

INTERNATIONAL JOURNAL FOR INNOVATIVE RESEARCH IN MULTIDISCIPLINARY FIELD

(ISSN: 2455-0620)

(Journal Impact Factor: 9.47)

Monthly Peer-Reviewed, Refereed, Indexed Scientific Research Journal
UGC Approved Journal No. - 47793, Index Copernicus IC Value: 86.87

DOIs:10.2015/IJIRMF



INTERNATIONAL CONFERENCE ON “Innovative Convergence for Sustainable Future” (ICICSF-2025)

DOIs:10.2015/IJIRMF/ICICSF-2025

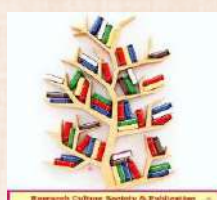
Seminar Special Issue - 64

December - 2025

Organized by :



Jharkhand Rai University, Ranchi, Jharkhand, India



RESEARCH CULTURE SOCIETY & PUBLICATION

Email: racsjournals@gmail.com

Web Email: editor@ijirmf.com

WWW.IJIRMF.COM



INTERNATIONAL CONFERENCE ON
“Innovative Convergence for Sustainable Future”
(ICICSF-2025)

Date : 12 - 13 December, 2025

Conference Special Issue / Proceedings Issue - 64

The Managing Editor:

Dr. Chirag Patel

Associate Editors:

Dr. Neha Chandra

Assistant Professor, Jharkhand Rai University, Ranchi, Jharkhand, India

Mr. Vikrant Kumar Ravi

Assistant Professor, Jharkhand Rai University, Ranchi, Jharkhand, India

Dr. Harmeet Kaur

Dean, Dept of Commerce and Management. Jharkhand Rai University, Ranchi, Jharkhand, India

Organised By:



Jharkhand Rai University, Ranchi, Jharkhand

Published by:

International Journal for Innovative Research in Multidisciplinary Field
(ISSN: 2455-0620) [UGC Journal Number – 47793]
Research Culture Society and Publication.
(Reg. International ISBN Books and ISSN Journals Publisher)
Email: editor@ijirmf.com / rcsjournals@gmail.com
WWW.IJIRMF.COM





**International
Scientific
Research
Organization**

Organize
Conference, Seminar, Symposium
 in association / collaboration with
Research Culture Society

Support in Administration and ICT system
 Free promotion on websites and social media
 Certificates for publications
 Special issue in ISSN Journals and
 Proceedings with ISBN Books
 Concession in publication charge
 Digital Object Identification



www.researchculturesociety.org
 Email: director@researchculturesociety.org



RESEARCH CULTURE SOCIETY
 International Scientific Research Organization
(Reg. Asia - India, Canada, USA, Europe)



Join us - Invitation for Membership and MoU

Professional Membership:	Member of Organization
Honorary Membership :	Country Head, State Head, Chapter Head, Conference Manager, Conference Coordinator, International / National / State Coordinator, Country Ambassador and Promoter.
Memorandum of Understanding (MoU) / Collaboration (MoC) With official registered :	Institutions, Universities, Colleges, Schools, Industries, Companies and Firms. For Academic - Educational - Industrial Events, Exchange Programs, Knowledge Partner, Co-operation, Networking with Scholarly Academicians, Researchers, Scientists and Delegates. Academic weightage in Institutional Evaluation Grades. Benefit in Special Issues - Proceedings Publications with ISSN / ISBN.
Programs Appointment :	Expert Trainer, Resource Person, Keynote Speaker, Guest Speaker, Anchor person, Moderator, Committee Member, Sponsor, Co-Sponsor, Co-organizer.
Editorial Board Membership: (All Subject Fields)	Reviewer, Associate Editor, Special Issue Editor, Book Editor. Sciences, Healthcare Sciences, Engineering and Technology, Social Sciences, Agriculture, Commerce, Business, Management, Arts, Languages, Literature, Humanities, Education, Library Science, Designing, Tourism, Journalism, Environmental Technology, International Economy. Teaching and Research Exposure: Minimum 5 years with 15 Publications. Research Papers, Articles and Books Publication as per Publication House Norms.

Interested candidates can contact OR send inquiry at :

 director@researchculturesociety.org

 www.researchculturesociety.org





INTERNATIONAL CONFERENCE ON “Innovative Convergence for Sustainable Future” (Special Issue / Proceedings Issue)

Copyright: © The research work, information compiled as a theory with other contents are subject to copyright taken by author(s) / editor(s) / contributors of this book. The author(s) / editor(s)/ contributors has/have transferred rights to publish this Special Issue / Proceedings Issue / book(s) to ‘Research Culture Society’ / ‘Research Culture Society and Publication’ Journal.

Disclaimer: The author/authors/contributors are solely responsible for the content, images, theory, datasets of the papers compiled in this conference special issue. The opinions expressed in our published works are those of the author(s)/contributors and does not reflect of our publication house, publishers and editors, the publisher do not take responsibility for any copyright claim and/or damage of property and/or any third parties claim in any matter. The publication house and/or publisher is not responsible for any kind of typo-error, errors, omissions, or claims for damages, including exemplary damages, arising out of use, inability to use, or with regard to the accuracy or sufficiency of the information in the published work. The publisher or editor does not take any responsibility for the same in any manner. No part of this publication may be reproduced or transmitted in any form by any means, electronic or mechanical, including photocopy, recording, or any information storage and retrieval system, without permission in writing from the copyright owner.

Online / Imprint: Any product name, brand name or other such mark name in this book are subjected to trademark or brand, or patent protection or registered trademark of their respective holder. The use of product name, brand name, trademark name, common name and product details and distractions etc., even without a particular marking in this work is no way to be constructed to mean that such names may be regarded as unrestricted in respect of trademark and brand protection legislation and could thus be used by anyone.

Published By:

**INTERNATIONAL JOURNAL FOR INNOVATIVE RESEARCH IN MULTIDISCIPLINARY FIELD
(ISSN: 2455-0620) [UGC Journal Number – 47793]**

Research Culture Society and Publication.

(Reg. International ISBN Books and ISSN Journals Publisher)

Email: editor@ijirmf.com / rcsjournals@gmail.com

WWW.IJIRMF.COM



Research Culture Society and Publication

(Reg. International ISBN Books and ISSN Journals Publisher)

Email: RCSPBOOKS@gmail.com / editor@ijrcs.org

WWW.RESEARCHCULTURESOCIETY.ORG / WWW.IJRCS.ORG

Conference, Seminar, Symposium organization in association/collaboration with different Institutions.

Conference, Seminar, Symposium Publication with ISSN Journals and ISBN Books (Print / Online).

CALL FOR PAPERS

International
ISSN Journals and
ISBN Books Publisher

International
Peer-Reviewed
Refereed
Indexed
ISSN Approved
High Impact Factor
Journals with
Quality Publication

Research Culture Society Journals

IJIRMF, IJRCS, JSHE, IJEDI, Shikshan Sanshodhan

Research Study Fields

Research Publication in all subjects / topics of the following study fields :
Science, Engineering, Healthcare Sciences,
Agriculture, Pharmacy, Medicine, Nursing
Commerce, Management, Social Sciences,
Law, Humanities, Education, Life Skills

Free e-Certificates
Digital Object Identification
Nominal Processing Fee

Submit papers to

editor@ijrcs.org
Or
editor@ijirmf.com

<http://ijshe.researchculturesociety.org/>
<http://shikshansanshodhan.researchculturesociety.org/>
<http://ijedi.researchculturesociety.org/>

WWW.IJRCS.ORG
WWW.IJIRMF.COM

Conference Publications

International Journals and Books Publisher

Publish your Conference, Seminar, Congress, Symposium
with a trusted International Publisher

ISSN Journals

ISBN Books

SPECIAL ISSUE

PROCEEDINGS

ABSTRACT BOOK

DOIs - Indexing

Nominal Processing Charge

- ✓ Print and Online
- ✓ Publication in Multiple Languages
- ✓ Promotions
- ✓ Setup Service
- ✓ Standard Pattern
- ✓ Certificate
- ✓ Collaboration

Research Culture Society and Publication

www.ijrcs.org
www.ijirmf.com

editor@ijrcs.org
editor@ijirmf.com

About the organizing Institutions:

Jharkhand Rai University (JRU) is among the fastest-growing state private universities in eastern India. Since its inception in 2012, JRU has gained a prominent reputation for its outstanding achievements in academics, research and innovation. The spirit of innovation, modernization and student centric teaching – learning approach blended with a strong Mentorship Program is the corner - stone of academics at Jharkhand Rai University. The focus on building skills, value system and character are the integral part of Jharkhand Rai University academic system. The University focuses on a holistic education ecosystem, where the goal is not to make students just work-ready but also good human beings. The University offers Diplomas, Undergraduate Degrees, Postgraduate Degrees and Doctoral programs in different disciplines.

Venue: Jharkhand Rai University, Ranchi.

About the Conference

The world is facing many challenges today, such as climate change, fast-moving technology, and social inequality. To solve these problems, we need to work together across different elds. This international conference brings together experts from business, technology, environment, and management to share ideas and smart, sustainable solutions. The theme encourages participants to think differently, collaborate across disciplines, and create responsible strategies that protect the environment while promoting economic and social well-being. Through presentations, discussions, and research sharing, this event aims to support real-world solutions that help achieve the United Nations Sustainable Development Goals (SDGs). We invite you to join us in exploring new ways to shape a better, more sustainable future for everyone.

The conference strives over the following topics (but not limited to).

Track 1: Driving Sustainable Development through Business Management and Innovation

Sub tracks:

- Sustainable Enhancing and Innovations
- Promoting Employee Well Being through Sustainable & inclusive HR practices
- Sustainable Marketing & Consumer Engagement
- Economics of Sustainability: Growth and Challenges
 - Governance of Sustainable nance and investing
- Social Innovation & Community Empowerment
- Data driven Sustainability: AI in Sustainable Business Practices
- Sustainable Supply Chain & Operational Excellence
- Integrating Sustainability into People, Brand and Financial strategy

- Ethical Entrepreneurship & Inclusive Growth
- Sustainable thinking in Business Education & Organizational Learning.

Track 2: Recent Advances in Science and Engineering Driving Sustainability

Sub tracks:

- Emerging technologies in Science & Engineering for Sustainable Development
- Innovative Engineering Solutions for Sustainable Infrastructure
- Sustainable Engineering: Eco-Friendly Materials and Production Methods
- AI-Driven Engineering Solutions for Sustainable Development
- Smart Sensors and IoT for Environmental Monitoring
- Biotechnology for Environmental Sustainability
- Sustainability Analytics for AI-Powered Climate Modelling
- Robotics and Automation for Sustainable Industrial Systems
- Advanced Mechanics for Renewable Energy Systems
- Sustainable Automotive Engineering and E-mobility Technologies

Track 3: Regenerative Agricultural Practices for Sustainable Development

Sub tracks:

- Sustainable Soil and Natural Resource Management for Climate-Resilient Agriculture
- Eco-Friendly Practices in Agriculture and Food Systems
- Innovation in Resource Management and Land Use
- Integration of Traditional Knowledge and Modern Methods
- Socio-Economic Sustainability in Agricultural Development
- Enhancing Agricultural Productivity Responsibly
- Biodiversity and Ecological Restoration through Farming
- Food Security and Sustainable Livelihoods
- Community-Led Approaches to Agricultural Sustainability
- Smart & Sustainable Farming using AI & IoT
- Storage & Cold Chain Infrastructure for Agri Products
- Supply Chain Hiccups and Distribution Network Challenges
- Supply Chain Hiccups and Distribution Network Challenges

Track 4: Integrating Bhartiya Knowledge Systems for Achieving Global Sustainability

Sub tracks:

- Commerce & Management through BKS: Fostering Responsible and Innovative Business Practices
- Education & Pedagogy in BKS: Traditional Wisdom for Future-Ready Learning
- Law, Policy & Governance in BKS: Heritage-Driven Ethical and Sustainable Frameworks
- Science & Technology in BKS: Ancient Knowledge Inspiring Modern Sustainable Solutions
- Health & Wellness in BKS: Holistic Approaches for Human and Environmental Wellbeing
- Environment & Agriculture in BKS: Indigenous Practices for Ecological Balance and Food Security
- Social Sciences & Culture in BKS: Blending Tradition and Innovation for Resilient Communities
- Spirituality & Ethics in BKS: Cultivating Conscious Leadership and Sustainable Lifestyles

Track 5: Building a Sustainable Future through Health, Environment, and Law

Sub tracks:

- Integrating Policy, Law, and Technology for a Sustainable Future
- Equity, Accessibility, and Social Wellbeing in Healthcare
- Legal and Policy Frameworks for Climate Action and Sustainability
- Environmental Governance and Reducing Carbon Footprints
- Corporate Responsibility, ESG, and Carbon Credit Initiatives
- Research and Innovation in Life Sciences and Public Health
- Digital Health and Smart Healthcare Systems
- Preventive and Community-Centric Healthcare Models
- Interdisciplinary Approaches to Health and Environmental Sustainability
- Promoting Justice and Responsibility in Health and Environment

Message

It gives me immense pleasure to reflect upon the successful organization of the International Conference on “**Innovative Convergence for a Sustainable Future (ICICSF-2025)**”, held on 12th and 13th December 2025 at Jharkhand Rai University, Ranchi. The conference emerged as a vibrant intellectual platform that brought together academicians, researchers, industry professionals, and practitioners from across the globe to deliberate on some of the most pressing challenges confronting our world today.

At a time when humanity stands at the crossroads of climate change, rapid technological advancement, and widening social inequalities, the need for interdisciplinary and integrated approaches has never been more urgent. The theme of *Innovative Convergence* aptly captured this global imperative, encouraging the blending of ideas from business, management, science, engineering, agriculture, health, law, and Bhartiya Knowledge Systems to arrive at sustainable and responsible solutions aligned with the United Nations Sustainable Development Goals (SDGs).

The conference witnessed insightful keynote addresses, thought-provoking research presentations, and meaningful academic discussions that underscored the power of collaboration across disciplines and cultures. The diverse range of themes and tracks reflected the conference’s commitment to fostering innovation while remaining deeply rooted in ethical, environmental, and social responsibility.

Since 2012, Jharkhand Rai University has consistently strived to promote academic excellence, research-driven learning, and societal relevance. The successful conduct of ICICSF-2025 stood as a testimony to the University’s vision of nurturing knowledge that is not only intellectually rigorous but also socially impactful.

I extend my sincere appreciation to the Conference Organizing Committee, Advisory Committees, reviewers, and student volunteers for their dedication and meticulous efforts in making this international academic endeavour a success. I also congratulate all the authors and delegates whose scholarly contributions enriched the conference and have found place in this special issue. It is my firm belief that the research published herein will inspire further inquiry, collaboration, and action toward building a more sustainable, inclusive, and resilient future.

Prof. (Dr.) Piyush Ranjan
Vice-Chancellor
Jharkhand Rai University

CONFERENCE COMMITTEE

International Advisory Committee:

Dr. Purshotam Lal Meena, Professor, Dept. of Supply Chain Management, College of Charleston School of Business, South Carolina, USA. Dr. Sujoy Kumar Jana, Professor, University of Technology, Papua New Guinea. Prof.

(Dr.) Veeranoot Nissapatorn, Associate Professor, School of Allied Health Science, Walailak University World Union for Herbal Drug Discovery, Thailand.

Dr. Knight Nthebere, Postdoctoral Fellow & Senior lecturer, Dept. of Soil Science & Resource Conservation, National University of Lesotho.

Prof. (Dr.) Bui Thanh Hung, Faculty of Information Technology, Dept. of Information Technology, Industrial University of Ho, Chi Minh City, Vietnam. Fredric Mirindi, Sessional Instructor/ Professor, Booth University College, Canada.

Dr. Mrityun-Jai Kumar, MPH MRCPsych, Child/Adolescent & All age Intellectual Disability Psychiatrist, CWP, NHS, Member, Executive Committee, FED, The Royal College of Psychiatrists, UK.

National Advisory Committee:

Dr. Amar Kumar Choudhary, HOD, Associate Professor, Dept. of Commerce & Management, Ranchi University, Ranchi

Prof.(Dr) Himangshu Sekhar Maji, Deputy Director, Dept. of Pharmacy, JIS Group, Kolkata.

Dr. Kumar Rajnish, Associate Professor, Dept. of CSE & IT, B.I.T Mesra, Ranchi Dr. Surya Deo Choudhary, Associate Professor, Dept. of Electrical & Electronics Engineering, Motihari College, Bihar.

Dr. Sapna Bansal, Associate Professor, Dept. of Legal Studies, GD Goenka University, Haryana.

Dr. Sandhir Kumar Singh, Associate Professor, Dept. of Physics, Vinoba Bhave University, Hazaribagh.

Dr. Vishnu Charan Mahto, Ex HOD, Associate Professor, Dept. of English, RLSY College, Ranchi.

Dr. Parwez Hassan, HOD, Associate Professor, Dept. of Psychology, Ranchi University, Ranchi.

Dr. Jayshree Patnaik, Assistant Professor, Dept. of Entrepreneurship Management, IIT Hyderabad, Hyderabad.

Dr. Sanyka Banerjee, Assistant Professor, Dept. of Strategy Management, IIM Sambalpur, Sambalpur.

Dr. Noopur, Assistant Professor, Dept. of Management, IIIT Ranchi, Ranchi.

Dr. Mona Ratnesh, Assistant Professor, Dept. of Management, Amity Ranchi, Ranchi.

Dr. Rahil Yusuf Zai, Dept. of Business Management, Indira Gandhi National Tribal University, MP.

Prof. Rohit Kumar, Associate Professor, Strategy & Entrepreneurship, IIM Ranchi, Ranchi.

Dr. Lipika Boruah, (PT) Project Scientist, Mechanical Engineering, IIT Guwahati, Guwahati.

Shiv Shanker Shukla, Government of India, State's, PSU's & Corporate's International Motivational Trainer, Educator, Mentor & Life coach, Pan India- MSME, Education, Agriculture & Industry Sectors

Organizing Committee (Jharkhand Rai University)

Dr. Kailashpati Dutta, Dept. of CSE & IT Prof.

Mr. Neeraj Poddar, Dept. of Commerce & Management

Dr. Jai Prakash Meena, Dept. of Mining Engineering

Dr. Rashmi Kumari Hembrom, Dept. of Physiotherapy

Prof. Sudipto Mangal, Dept. of Pharmacy Prof.

Ms. Vanshika Tainwala, Dept. of Legal Studies Prof.

Ms. Rojalin Hota, Dept. of Agriculture

TABLE OF CONTENTS

Sr.No	Contents	Page No.
1	About the organizing Institutions	V
2	About the Conference	V - VII
3	Message from Vice Chancellor	VIII
4	Conference Committee Members	IX-X
5	Table of Contents	XI-XIII
Paper No.	Title and Author	Page No.
ICICSF-2025-P01	From Disruption To Sustainability : Offline Retail Challenges In Gumla , A Tribal District Of Jharkhand Under The Rise Of E-Commerce -- Afreen Ejaz, Dr. Amar Kumar Chaudhary	1-10
ICICSF-2025-P02	The Role Of Tally Software In Enhancing Accounting And Inventory Management: A Case Study Of Mimec Electronics Pvt. Ltd. -- Aman Raj, Dr. Abhishek Pratap	11-17
ICICSF-2025-P03	Effectiveness Of Digital Engagement Techniques In Influencing Student Preferences For Private Higher Education Institutions With Reference To Jharkhand State -- Ankit Kumar, Sandeep Choudhary and Kailash Pati Dutta	18-23
ICICSF-2025-P04	Promoting Employee Well-Being Through Sustainable And Inclusive Hr Practices -- Anshu Veronica Kujur, Dr. Nasir Ahmed	24-33
ICICSF-2025-P05	Motivation Matters: A Comprehensive Analysis Of Its Influence On Workmen'S Performance In The Manufacturing Sector -- Ashish Chopra, Dr. Anusha Priya	34-42
ICICSF-2025-P06	Modeling Of A Double-Pipe Heat Exchanger Using Different Controllers In Matlab/Simulink -- Babita Kumari, Md. Sami and Nirupama	43-49
ICICSF-2025-P07	Digital Governance And Right To Privacy: Need Of A Sustainable Digital Society Post Puttaswamy Judgment -- Damini Kumari, Prof. Aditi Apoorva	50-55
ICICSF-2025-P08	Influence Of Microbial Inoculants And Molybdenum Application On The Status Of Soil Health In Red And Lateritic Zone Of West Bengal -- Deepshikha	56-66
ICICSF-2025-P09	Bridging The Values-Action Gap In Sustainable Brand Engagement Among Gen Z And Millennials -- Deeya Bandyopadhyay, Dr. Amrita Majumdarb	67-78
ICICSF-2025-P10	Ai At The Helm: The Silent Role Of Psychological Trust In Fostering Job Confidence -- Dr. Anjali Sabale, Aruna Walhekar	79-85
ICICSF-2025-P11	Digital Financial Inclusion And Its Influence On The Sustainable Growth Of Businesses In Rural India -- Sangita Raj, Dr. Madan Kumar Singh	86-93
ICICSF-2025-P12	A Critical Constitutional Appraisal Of Socialism And The Welfare State In Shaping Socio-Economic Justice In India -- Sunil Kumar, Ms Ankita Toppo	94-98
ICICSF-2025-P13	Faculty As Change Agents: Leveraging Organizational Citizenship Behavior For Sustainable Development And Innovation In Higher Education Institutions-A Systematic Literature Review -- Durga Ghosh, Dr. Harmeet Kaur, Dr. Avani Bharadwaj	99-107
ICICSF-2025-P14	Integrated Bioremediation Of Heavy Metals And Plastics: A Bibliometric, Network, And Modeling Approach -- Kajari Roy, Nandan Bhattacharyya	108-122
ICICSF-2025-P15	Economics Of Sustainability: Growth And Challenges From Company'S Perspective -- Kalyani Gupta	123-129

ICICSF-2025-P16	A Fresh Perspective On Risk Management In Steel Company Construction Projects: A Comprehensive Literature Review -- Kaushik Chopra, Dr. Harmeet Kaur	130-137
ICICSF-2025-P17	Hybrid Smart Voting Framework With Facial Biometric And Dynamic Qr Code Credentials -- Kriti Sharma, Mukesh Kumar, Md Eliyas Ansari, Kailash Pati Dutta	138-142
ICICSF-2025-P18	Promoting Justice And Responsibility In Health And Environment: A Legal Perspective -- Kuldeep Kumar Mahto, Dr. Smita Pandey,	143-152
ICICSF-2025-P19	Judicial Responses To Custodial Violence: A Call For Sustainable Police System -- Madhu Singh, Sristi Roy	153-160
ICICSF-2025-P20	Risk And Return In Sustainable Investing: An Empirical Analysis Of Indian Esg Mutual Funds -- Manas Kumar Kushwaha, Dr. Amar Kumar Choudhary	161-171
ICICSF-2025-P21	Gender Biased Laws For Offences Against Body (Wsr To Section 63 Of Bns): Need Of The Hour For Sustainable Development Of Society Bharatiya Nyaya Sanhita 2023 -- Dr. Smita Pandey; Pragya Karn , Manisha Kumari	172-178
ICICSF-2025-P22	Compulsory Licensing In Pharmaceuticals: Balancing Innovation Incentives With Drug Accessibility And Public Health Imperatives- Manisha Mishra, Dr. Smita Pandey	179-185
ICICSF-2025-P23	Sustainable E-Governance In Bihar: Ensuring Data Privacy And Security Compliance Under The Dpdp Act 2023 For Equitable Digital Public Services -- Md Mudassir Siddiqui, Dr. Md. Irfan Alam	186-196
ICICSF-2025-P24	From Build To Run: Devops Tactics For Low-Latency, High-Throughput Llm Serving Scale -- Nagarjuna Nellutla	197-208
ICICSF-2025-P25	Employee Engagement Practices: A Case Study Of Pantaloons, Ranchi -- Nidhi Kumari , Dr. Abhishek Pratap	209-216
ICICSF-2025-P26	Assessing The Effectiveness Of The 2% Csr Mandate: A Decade Of Corporate Social Responsibility Under The Companies Act, 2013 -- Nidhi Kumari , Dr. Abhishek Pratap	217-224
ICICSF-2025-P27	Ai And Remote Sensing-Based Approaches For Soil Organic Carbon Monitoring And Management In Agriculture: A Review -- Pallabi Patra , Neha Grace Angel Kisku, Subhas Adak	225-233
ICICSF-2025-P28	Sustainable Development Through Crop Rotation: A Regenerative Approach In Ranchi District -- Pankaj Mahto	234-243
ICICSF-2025-P29	Death Penalty In India: A Critical Analysis Of The ‘Rarest Of Rare’ Doctrine And Its Relevance To Sustainable Justice -- Prof. Sonu Kumar; Pragati Kumari	244-251
ICICSF-2025-P30	Fintech Innovations In Green Finance: Expanding Access To Renewable Energy Projects In India -- Prity Sharma, Dr. Amar Kumar Choudhary	252-259
ICICSF-2025-P31	Physiotherapy Auditing-A Comprehensive Framework For Quality Improvement In Physiotherapy Practice: A Narrative Review -- Dr. Rashmi Kumari Hembrom	260-264
ICICSF-2025-P32	Polyphenols As Co-Therapeutics In Breast Cancer -- Ritesh Goswami, Heba Parveen, Ujjwal Kumar, Amarjeet Kumar, Kritika Modak	265-281
ICICSF-2025-P33	Social Media Brand Communication And Sustainable Consumer Engagement: Evidence From Urban Indian Consumers -- Ritesh Kumar Gupta	282-291
ICICSF-2025-P34	Thermosensitive Packaging For Biologics And Vaccines -- Ritu Kumari, Shibo Mahato, Rohan Kumar, Niranjana Kumar Mahto, Ritik Kumar, Anamika Palak	292-303

ICICSF-2025-P35	Digital Transformation Of Alternative Dispute Resolution: Ai-Powered Mediation Platforms In Green Banking Conflicts -- Seema kumari , Smita Pandey	304-312
ICICSF-2025-P36	Integration Of Esg And Carbon Credits Into Corporate Responsibility In Indian Banking Sector: A Case Study Of Yes Bank, State Bank Of India And Hdfc Bank -- Shimpy Kumari, Tarun Chakraborty	313-319
ICICSF-2025-P37	Influence Of Liquid Biofertilizer Consortia And Npk Levels On Growth And Yield Attributes Of Wheat (Triticum Aestivum L.) -- Shivam Yadav, Dr. Biswarup Mehera	320-330
ICICSF-2025-P38	Impact of Sustainable HR Practices on Attrition Rates in IT Companies -- Shweta Rani, Dr. Sanjiv Chaturvedi	331-340
ICICSF-2025-P39	Unified Agentic Platform For Clinical Research: The Role Of Salesforce Agentforce In Intelligent Cro Ecosystem Integration- Srikanth Perla	341-349
ICICSF-2025-P40	Evolving Jurisprudence On Child Sexual Abuse In India Through The Lens Of Pocso Act: A Need For Sustainable Society In Future - - Suman Kumar Sinha , Prof. Sristi Roy	350-358
ICICSF-2025-P41	Bridging Health And Environmental Justice Through Legal Responsibility: A Pathway To Sustainable Development -- Sunny Kumar Raj, Vanshika Tainwala	359-368
ICICSF-2025-P42	Indo-Nepal Open Border: Balancing Security Needs And Sustainable Practices -- Suvasmita Dey, Dr. Smita Pandey	369-379
ICICSF-2025-P43	Impact Of Hr Practices On Employee Involvement – A Systematic Literature Review -- Vivek Kumar, Dr. Anusha Priya	380-385
ICICSF-2025-P44	Understanding The Role Of Fintech In Transforming Financial Services -- Dr. Neha Chandra; Soni Kachhap	386-393



DOIs:10.2015/IJIRMF/ICICSF-2025-P01

--:--

Research Paper / Article / Review

International Conference On "Innovative Convergence for Sustainable Future"

Date : 12 - 13 December, 2025

(ICICSF-2025)



From Disruption to Sustainability : Offline Retail Challenges in Gumla , A Tribal District of Jharkhand under the Rise of E-Commerce

¹Afreen Ejaz, ²Dr. Amar Kumar Chaudhary

¹Research Scholar at University Department of Commerce & Business Management, Ranchi University, Ranchi, Jharkhand , India.

² Head and Dean of University Department of Commerce & Business Management, Ranchi University, Ranchi , Jharkhand , India.

E-mail - afreenejaz222@gmail.com

Abstract: E-commerce platforms like Amazon, Flipkart, Meesho, etc. are growing rapidly in India, even in tribal districts like Gumla in Jharkhand, where 68% of the population is from tribes like the Oraon, Munda, and Kharia. For centuries, local shops and weekly haat bazaars have been central to Gumla's economy and culture, serving as a hub for trade, social gathering, and the preservation of tribal traditions. However, young people are turning to online shopping, impacting local shops and haats. This study explores how Gumla's offline retail can remain sustainable. Using observations of haat bazaars, interviews with 40 shopkeepers and 55 consumers, and data from sources such as the Census of India (2011), the IMAI report, and the Jharkhand Economic Survey, we found that young people prefer online shopping for clothing and electronics, while older people turn to haats for groceries and socializing. Local shops are facing declining sales, high costs, and limited digital skills, and haats are losing their cultural vibrancy.

In Gumla, sustainability means economic empowerment, preservation of cultural heritage, and environmental protection, as outlined in the original study. Local shopping reduces pollution from transportation, promotes environmentally friendly farming, and generates less packaging waste compared to online delivery. Solutions include using digital tools like UPI and WhatsApp for ordering, promoting tribal handicrafts through cultural festivals, and leveraging government support through training, credit, and infrastructure development. India's E-commerce market is projected to grow at a CAGR of 27% to reach US\$163 billion by 2026 (IBEF,2025) with significant contributions from rural areas. Gumla faces both challenges and opportunities for achieving sustainable development.

Keywords: E commerce, Offline Retail, Sustainability, Gumla District, Tribal Economy.

1. INTRODUCTION :

Gumla, a tribal district in Jharkhand, has a population of approximately 1.29 million, of which 68% belong to tribal communities such as the Oraon, Munda, Kharia, and Asur. Most residents depend on farming, handicrafts, and small-scale trade. Weekly haat markets and grocery stores are the economic and cultural hub of Gumla. Haat markets are vibrant community centers where farmers sell fresh produce, artisans offer bamboo baskets and shawls, and traders bring livestock. People mingle, share stories, and enjoy tribal music or dance. Elders describe haats as "schools of culture," teaching traditions like bargaining and festivals like Sarhul or Karma.

However, e-commerce is disrupting this system. Young people use smartphones to shop on Amazon, Flipkart, or Meesho due to lower prices and convenience. Shopkeepers have reported a decline in customer numbers. A shopkeeper said, "Weekends used to be crowded; now young people shop online and leave." An artisan said, "My handmade baskets are being outnumbered by cheap plastic baskets available online."



The closure of haats and shops threatens not only incomes but also tribal identity and environmental sustainability. Haats promote environmentally friendly local supply chains, reducing transportation emissions and waste compared to e-commerce deliveries. However, e-commerce offers variety and convenience, making it difficult to stop. The challenge is to ensure that online platforms, as well as offline retail, maintain a balance between economic, cultural, and environmental sustainability.

This study explores the impact of e-commerce on Gumla's shops and haats, the challenges they face, and sustainable solutions to preserve tribal culture and the environment.

2. LITERATURE REVIEW :

In tribal districts like Gumla in Jharkhand, offline retail has long been the backbone of the local economy. Weekly haat-bazaars and small grocery shops aren't just places to buy goods—they're social spaces where tribal communities gather, share stories, and enjoy traditions. However, the rise of e-commerce platforms like Amazon, Flipkart, and JioMart is changing this landscape.

According to the IAMAI-Kantar ICUBE Report (2023), affordable smartphones and expanding mobile networks now provide internet access to over 50% of rural India. This digital evolution has helped online platforms reach even remote areas like Gumla. While this offers convenience to consumers, it has also led to a decline in footfall in local markets and a decrease in the income of traditional retailers.

Rishabh and Kumari (2025) emphasize that e-commerce has changed consumer expectations and forced offline retailers to adapt quickly. Small vendors face challenges such as price competition, lack of digital skills, and limited access to online marketplaces. In tribal areas, these problems are exacerbated by poor infrastructure and cultural hesitation towards technology.

According to the India Brand Equity Foundation (2025) report, India's e-retail sector is growing at a rate of 18% annually and is expected to reach ₹14.5 lakh crore by 2030. However, this growth is uneven. Tribal areas often lack the necessary digital infrastructure and policy support to benefit from this expansion.

To address these shortcomings, the Digital India program (MeitY, 2023) has launched initiatives such as Common Service Centers (CSCs), mobile literacy vans, and apps in local languages. These efforts aim to empower rural and tribal communities by improving access to digital services and promoting inclusive development.

Sarkar and Singh (2019) emphasize the role of TRIFED (Tribal Cooperative Marketing Development Federation of India) in supporting tribal artisans. TRIFED helps them sell their products through physical stores and online platforms, ensuring fair prices and sustainable livelihoods.

Sustainability in Gumla isn't just about keeping shops open—it's about preserving the tribal way of life. Local markets are places where people trade local goods, celebrate festivals, and build community. Grocery stores are places where neighbors socialize. If these disappear, Gumla will lose its character. E-commerce is convenient, but it can't replace the cultural and environmental value of local retail. Local markets use local resources, like bamboo stalls or homegrown vegetables, which is good for the planet. Shops and markets also provide jobs, keeping money within the community. Sustainability means finding ways to keep these places alive while adapting to modern times.

To make e-commerce sustainable in tribal districts like Gumla, solutions must respect local culture and be easy to use. Key strategies include:

- Digital skills development in local languages and culturally relevant formats
- Community-owned e-commerce platforms to ensure fair pricing and direct access
- Mobile-based inventory and payment systems for areas with low connectivity
- Eco-friendly packaging and local logistics to create employment and reduce environmental impact
- Digital storytelling to enhance the value of tribal products



- Hybrid retail events like "Digital Haat Days" that blend tradition and technology

In conclusion, the literature highlights a complex interplay between digital disruption and cultural sustainability. While e-commerce presents new opportunities, its uncontrolled expansion threatens to marginalize tribal retail ecosystems. A balanced approach—combining infrastructure, education, and cultural sensitivity—is essential for sustainable adaptation in districts like Gumla.

Research Gap

Although the growth of e-commerce in India has been widely studied, limited research has focused on Gumla's offline tribal markets, particularly in relation to their role in preserving tribal culture, social cohesion, and community identity. Existing studies often overlook how the decline of haat markets impacts both the livelihoods and socio-cultural fabric of tribal communities. Furthermore, there is a lack of research on sustainable strategies that can help offline retailers adapt to digital challenges while maintaining economic viability and cultural preservation, such as hybrid retail models, digital literacy programs, and cultural tourism initiatives.

3. **OBJECTIVES :** This study is guided by the following objectives:

1. **To Examine the impact of e-commerce on offline retail in Gumla:** Analyze how the rise of online shopping affects the sales, operations, and sustainability of local shops and haat bazaars in Gumla.

2. **To Assess the social and cultural role of offline markets in preserving tribal community identity:** Examine the role of haat bazaars and local shops as cultural and social centers and the implications of their decline for tribal heritage and community cohesion.

3. **To Explore sustainable measures to support offline retailers while integrating digital advancements:** Propose actionable strategies, such as digital literacy programs, hybrid retail models, and government interventions, to help offline retailers adapt to e-commerce to ensure economic viability and cultural preservation in Gumla's tribal communities.

Hypothesis

- H1: Offline markets (Haat Bazaars) are important for tribal culture, social cohesion, and community identity, which are threatened by e-commerce.
- H2: Sustainable strategies such as hybrid retail models, digital literacy, government support, and cultural tourism can help sustain offline retail and preserve tribal culture.

4. RESEARCH METHODOLOGY :

This study uses a mixed-method approach, combining qualitative observation, secondary data analysis, and field insights to examine the impact of e-commerce on offline retail in Gumla. This methodology takes into account both quantitative trends and qualitative experiences of local stakeholders.

Data Sources:

1. Primary Data:

Visits to five Haat Bazaars in Gumla, observing trade, and interviewing 95 participants (40 shopkeepers, including artisans and retailers, and 55 consumers, 50 young people aged 18-35 and 45 older people aged 36+). Participants were selected purposefully based on diverse perspectives.

2. Secondary Data:

- Census 2011: Provides demographic data, including tribal population percentage (68%) and population distribution in Gumla.



- Ministry of Tribal Affairs Report: Provides information on the socio-economic conditions of tribal communities and their dependence on traditional markets.
- IAMAI Report (2022): Documents the growth of e-commerce in rural India, including Jharkhand, with specific data on penetration rates and consumer behavior.
- Jharkhand Economic Survey (2025), and studies on e-commerce sustainability.
- PwC Consumer Survey 2024.

Methods:-

- **Quantitative:** Secondary data on tribal population, e-commerce growth, retail trends, and sustainability standards, presented in charts.
- **Qualitative:** Observations and interviews were analyzed on topics such as declining footfall, cultural erosion, and the digital divide. Thematic saturation was achieved after 55 interviews, 20 observation and 20 more interviews were conducted for confirmation. Quotes highlight personal stories, such as concerns about the "soul" of haats or the environmental benefits of online versus local.

5. ANALYSIS - DISCUSSION :

Why is sustainability important in Gumla?

Sustainability in Gumla isn't just about keeping shops open—it's about preserving the tribal way of life. Local markets are places where people trade local goods, celebrate festivals, and build community. Grocery stores are places where neighbors socialize. If these disappear, Gumla will lose its character. E-commerce is convenient, but it can't replace the cultural and environmental value of local retail. Local markets use local resources, like bamboo stalls or homegrown vegetables, which is good for the planet. Shops and markets also provide jobs, keeping money within the community. Sustainability means finding ways to keep these places alive while adapting to modern times.

A Roadmap for Sustainable Retail

Research shows a complex relationship between e-commerce and offline retail in Gumla, with significant implications for the region's economy, culture, and social fabric. A decline in offline retail threatens the livelihoods of shopkeepers, artisans, and farmers, and diminishes the cultural significance of local markets. However, sustainable strategies can help balance the benefits of e-commerce with preserving traditional retail. Here are some key suggestions:

1. Digital Literacy Programs

To bridge the digital divide, local shopkeepers and artisans need training in digital tools. Programs could include:

- **Mobile Payment Workshops:** Teach shopkeepers how to use UPI and other digital payment systems to attract tech-savvy customers.
- **E-commerce Training:** Train vendors to list products on platforms like Amazon or Flipkart's local seller programs.
- **Basic Digital Skills:** Provide training on inventory management apps and social media marketing to boost visibility. Government agencies, NGOs, and private organizations like IAMAI can collaborate to implement these programs, ensuring access in rural areas.

2. Hybrid Retail Model

Local shops can adopt a hybrid model by combining offline and online activities. For example:

- **Online Listing:** Retailers can list products on e-commerce platforms or the state's own e-commerce initiative, such as Jharkhand's local marketplace.



- **Click-and-Collect Services:** Shops can offer online ordering with in-store pickup, catering to consumers who value convenience but prefer local vendors.
- **Social Media Presence:** Small retailers in Rajasthan have successfully adopted WhatsApp Business to showcase products, manage orders, and maintain direct communication with customers. This low-cost digital tool has enabled better delivery coordination and customer engagement, leading to a 15-20% increase in sales. Such models hold great potential for tribal districts like Gumla, where mobile penetration is increasing and digital platforms can fill the lack of retail visibility (Mehta, Nandal, Dhaka, & Nandal, 2024).

3. Government Support

Policymakers can play a crucial role in supporting offline retail:

- **Incentives for Local Vendors:** Subsidies for digital adoption, such as free or low-cost internet and smartphones for shopkeepers.
- **Marketing Support:** Promote tribal handicrafts and local products through government e-commerce platforms or export schemes.
- **Infrastructure Development:** Improve internet connectivity and logistics networks in rural areas to ensure equal opportunities for local retailers.

The Jharkhand government's Digital India initiative can be enhanced by prioritizing tribal districts like Gumla.

4. Revitalizing Haat Bazaars

Haat bazaars can be seen as cultural and economic assets:

- **Cultural Tourism:** Promote haat bazaars as tourist destinations showcasing tribal crafts, food, and performances. Collaboration with the tourism board can attract tourists from urban areas.
- **Festivals and Events:** Organize cultural festivals or craft fairs in local markets to boost foot traffic and highlight local products.
- **Infrastructure Improvements:** Enhance market facilities such as seating areas, lighting, and sanitation to improve the shopping experience.
- **Example:** The Hornbill Festival in Nagaland has emerged as a powerful cultural tourism platform, significantly increasing the visibility of the tribal market and the income of vendors. In 2024, the festival attracted over 1.73 lakh visitors and generated revenue of ₹139 crore, with local artisans and vendors reporting good sales during the event (Indian Masterminds, 2024; Morang Express, 2024; Press Information Bureau, 2024).

5. Consumer Awareness Campaigns

Promoting smart shopping can support the local economy:

- **Buy Local Products Campaign:** Promote the benefits of supporting local vendors, such as sustaining livelihoods and preserving tribal culture.
- **Quality Awareness:** Highlight the superior quality of fresh produce and handicrafts available in local markets compared to online products.
- **Community Engagement:** Use social media and local radio to educate consumers about the cultural significance of offline markets.

6. FINDINGS :

1. Tribal Demographics and Market Dependence

Gumla's population is predominantly tribal, with 68% belonging to tribes such as Oraon, Munda, and Kharia (Census 2011). These groups are highly dependent on weekly markets for their economic and social activities. These markets are not just places of trade; they are also cultural hubs where tribal communities exchange goods, share traditions, and



strengthen social bonds. Farmers sell fresh produce like rice, vegetables, and lentils, while artisans craft handicrafts such as bamboo baskets, pottery, and textiles. Local shops, often family-run, provide daily necessities and serve as community centers.

Tribal Population Distribution in Gumla (Census 2011)

- Tribal: 68% , Non-Tribal: 32%
- Source: Census 2011

This demographic structure underscores the importance of offline markets for economic needs. For many tribal families, income from these markets and local shops is the primary source of livelihood. However, the rise of e-commerce threatens this ecosystem, as online platforms offer alternatives, bypassing traditional vendors.

2. Rise of E-Commerce

E-commerce has expanded rapidly in rural Jharkhand, growing at 15-20% annually between 2018 and 2022 (IAMAI, 2022). This growth is driven by:

- **Improved Infrastructure:** Increased smartphone penetration (45% of rural households in Jharkhand own smartphones, IMAI, 2022) and better internet connectivity.
- **Consumer Preferences:** Young consumers (18-35 years) prefer online platforms for convenience, variety, and discounts.
- **Logistics Network:** E-commerce companies have expanded their last-mile delivery services to rural areas, making online shopping easier in Gumla

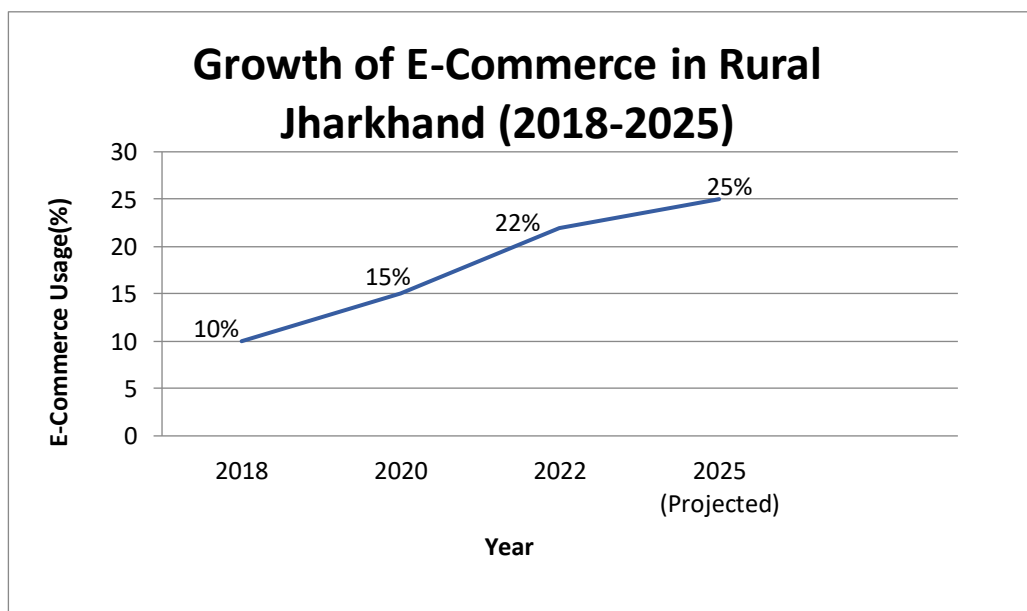


Figure 1: Growth of E-Commerce in Rural Jharkhand (2018–2025)

This data illustrates the year-on-year growth of e-commerce in rural Jharkhand between 2018 and 2025. This growth is attributed to improved internet connectivity, increased smartphone penetration, and the expansion of e-commerce logistics infrastructure in rural areas. This graph demonstrates how online retail is gradually meeting the demand of rural consumers, particularly for non-essential goods, thus impacting the traditional offline retail sector.



- 2018: 10%
- 2019: 12%
- 2020: 15%
- 2021: 18%
- 2022: 22%
- 2025: 25%+(projected)

Source: IAMAI & Kantar. (2022), https://www.iamai.in/sites/default/files/research/Internet%20in%20India%202022_Print%20version.pdf & Mordor Intelligence. (2025). *India E-Commerce Market Analysis (2025–2030)*. <https://www.mordorintelligence.com/industry-reports/india-ecommerce-market>

This rapid growth has transformed consumer behavior, particularly for non-essential items like clothing, electronics, and household goods, which are now increasingly purchased online.

3. Challenges for Offline Retail

The rise of e-commerce has posed several challenges for the offline retail sector in Gumla:

a. Decline in Sales: Shopkeepers report a 20-30% drop in sales over the past five years, (Ejaz, A., & Chaudhary, A. K. (2025) attributed to competition from online platforms. For example, a textile merchant in Gumla's main market said, “On Sundays, people used to come to our shop to bargain and socialize. Now, most young people buy online. I am worried about the future of my business.”

b. Digital Divide: The digital divide remains a major obstacle for small retailers in tribal districts like Gumla. Many shopkeepers lack the skills, infrastructure, or confidence to adopt digital tools. Field interviews reveal that only 15% of local retailers use digital payment systems like UPI, and few are aware of online sales platforms. Limited internet access and low digital literacy further exacerbate this gap. These findings reflect broader national trends: while UPI transactions in rural and semi-urban retail stores increased 118% in 2023, adoption at the merchant level remains slow, with mobile POS acceptance increasing by only 5% (PayNearby, 2023). A comparative study confirms that urban UPI transaction volumes are nearly 20 times higher than rural ones.

c. Cultural Decline: Reduced foot traffic has diminished the vibrancy of the markets. Once bustling with activity, these markets are now quieter, with fewer vendors and customers. This threatens the cultural significance of the markets as spaces for storytelling, music, and community gatherings.

d. Economic Strain: Artisans and farmers face difficulties selling their products. For instance, tribal artisans making bamboo products struggle to compete with mass-produced items sold online at lower prices. Similarly, farmers say consumers are buying packaged goods from e-commerce platforms, reducing demand for local produce.

Stakeholder Perspectives:

• **A Farmer:** “I bring my vegetables to the market every week, but fewer people come now. They say online delivery is easier.”

• **A craftsperson:** “It takes me several days to make one of my handcrafted baskets, but people buy cheap plastic baskets online. How can I compete with that?”

4. Consumer Perspective

In Gumla, consumer preferences for retail depend on whether it is offline or online:



• **Offline retail:** Preferred for groceries, fresh produce, and essential items (60% of purchases). Consumers value the ability to choose fresh products and the convenience of local stores.

• **Online retail:** Most preferred for clothing, electronics, and household goods (75% of purchases). Younger consumers, in particular, are attracted to the convenience and discounts offered by e-commerce platforms.

A survey of 55 consumers at the local markets in Gumla revealed interesting insights into consumer preferences for offline and online shopping.

Offline Shopping Preferences:

Food and Groceries: 60% of consumers prefer offline shopping for food and groceries because:

- Freshness and Quality: Consumers trust local vendors for fresh vegetables, grains, and dairy products.
- Social Interaction: Local markets serve as cultural and social hubs; bargaining and personal interaction strengthen community bonds.

Online Shopping Preferences:

Clothing and Electronics: 75% of consumers prefer online shopping for clothing and electronics because:

- Lower Prices and Discounts: Online platforms offer competitive prices compared to local stores.
- Wider Selection: Easy access to branded products and a variety of options.
- Convenience: Home delivery saves time and travel expenses

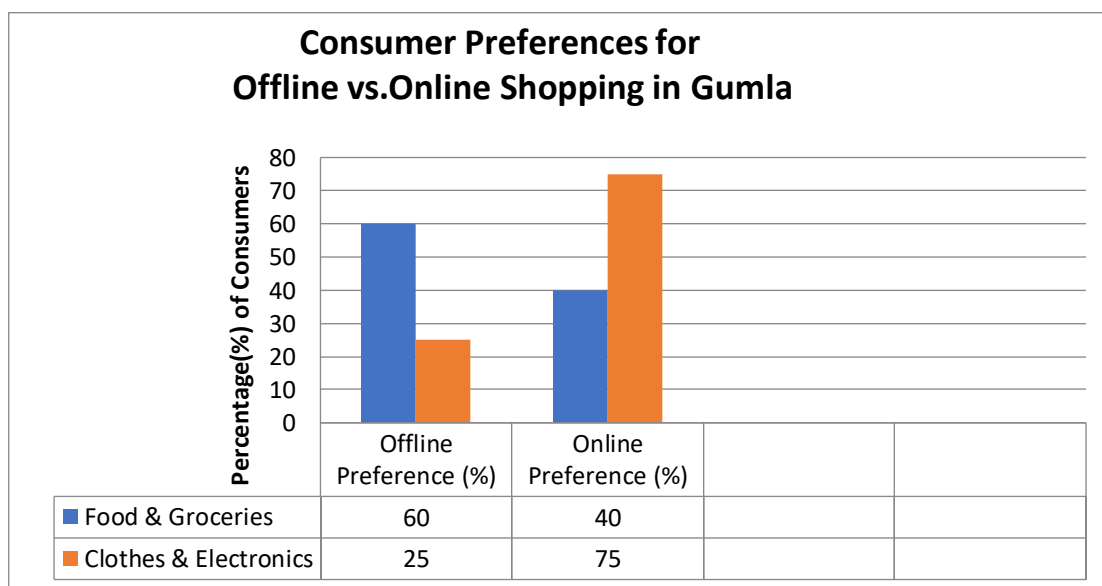


Figure 2: Consumer Shopping Preferences in Gumla

Source: Data Compiled by the Researcher (Primary survey of 55 consumers in Gumla haat bazaars, 2025)

This highlights the continued importance of offline retail for essential goods, while also demonstrating the competitive pressure on non-essential items.y e-commerce platforms

The bar graph above shows that 46% of consumers consider environmental sustainability when making purchases, while 54% are not influenced by it. This data, based on PwC's 2024 'Voice of the Consumer Survey', reflects the global trend of environmentally conscious consumption.

However, the situation is quite different in tribal districts like Gumla (Jharkhand). In the local markets, most consumers still prioritize affordability, easy availability, and trust in local vendors over environmental sustainability. While urban consumers are increasingly demanding eco-friendly products, rural consumers in Gumla still focus on immediate needs



such as fresh food, essential daily items, and personal interactions with shopkeepers. This creates a gap between global consumer awareness and local realities in tribal retail markets.

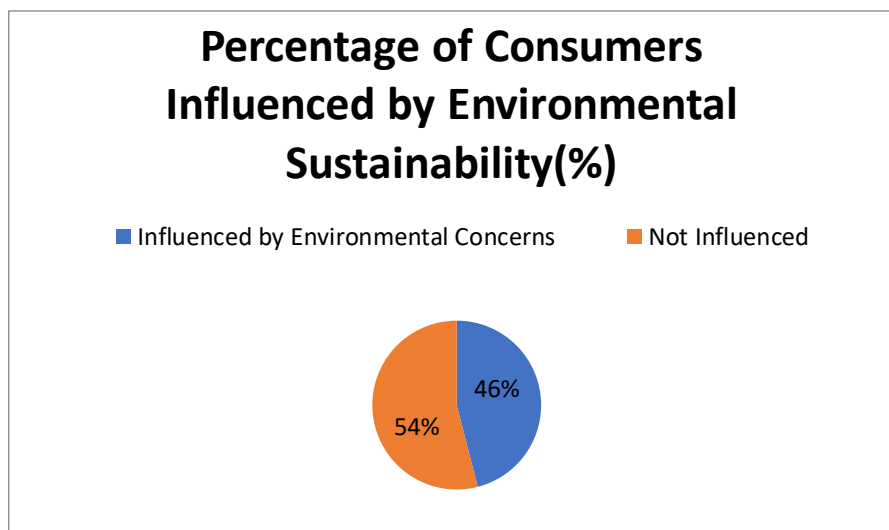


Figure 2: Consumer Awareness Regarding Environmental Sustainability During Shopping

Source: PwC. (2024). *Voice of the Consumer Survey 2024*. PwC Global Consumer Insights. Retrieved from <https://www.pwc.com/gx/en/issues/c-suite-insights/voice-of-the-consumer-survey/2024.html>

7. LIMITATIONS:

- Some remote haats could not be visited.
- Data is valid until 2025; future trends may vary.

8. CONCLUSION:

The rise of e-commerce in Gumla presents both challenges and opportunities. Online platforms offer convenience, lower prices, and a wider selection; however, they also threaten the livelihoods of shopkeepers, artisans, and farmers, and erode the cultural identity of traditional markets. These markets are not just places of commerce, but the heart of community life, preserving local identity and tribal heritage.

In the context of Gumla, sustainability means much more than just business success—it means protecting the environment, preserving culture, and supporting livelihoods. Local markets naturally promote environmentally friendly practices, such as bamboo stalls and locally grown products, which reduce carbon footprints compared to long-distance supply chains. They also keep money circulating within the community, ensuring economic resilience.

Moving from disruption to sustainability requires collective action: digital literacy for retailers, hybrid retail models that combine the strengths of online and offline shopping, government support for small businesses, and consumer awareness about the importance of conscious and local purchasing. By adopting such strategies, Gumla can create a retail ecosystem where modern e-commerce coexists with traditional markets, fostering both economic growth and cultural identity.

As one shopkeeper wisely said, “If the market disappears, the community's identity will also disappear.” The challenge is real, but sustainability offers a path forward—one that protects Gumla's heritage and prepares it for the future.



REFERENCES:-

- Office of the Registrar General & Census Commissioner, India. (2011). *District Census Handbook: Gumla (Series 21, Part XII-B)*. Government of India. https://censusindia.gov.in/nada/index.php/catalog/575/download/1948/DH_2011_2021_PART_B_DCHB_GU_MLA.pdf
- India Brand Equity Foundation. (2025). *E-commerce industry in India*. IBEF. <https://www.ibef.org/industry/ecommerce>
- IAMAI-Kantar ICUBE. (2023). *Internet in India 2023: ICUBE report*. Internet and Mobile Association of India. <https://www.iamai.in/sites/default/files/research/INTERNET%20IN%20INDIA%202023.pdf>
- Rishab, S., & Kumari, P. (2025). *The rise of e-commerce: Analyzing its impact on offline retail and consumer behavior*. *International Journal of Research Publication and Reviews*, 6(6), 4227–4242. <https://ijrpr.com/uploads/V6ISSUE6/IJRPR48082.pdf>
- Ministry of Electronics and Information Technology. (2023). *Digital India Programme*. Government of India. <https://www.meity.gov.in/digital-india>
- Sarkar, A., & Singh, A. K. (2019). *Institutional support for development and marketing of tribal products (TRIFED etc.)*. Indian Institute of Public Administration. https://repository.tribal.gov.in/bitstream/123456789/74203/1/IIPA_2019_report_0073.pdf
- Ministry of Tribal Affairs. (2022). *Annual report 2021–22: Tribal development in India*. Government of India. <https://tribal.nic.in/downloads/Statistics/AnnualReport/AREnglish2122.pdf>
- Internet and Mobile Association of India, & Kantar. (2022). *Internet in India 2022: ICUBE report*. IAMAI Research Reports. https://www.iamai.in/sites/default/files/research/Internet%20in%20India%202022_Print%20version.pdf
- Mordor Intelligence. (2025). *India E-Commerce Market Analysis (2025–2030)*. <https://www.mordorintelligence.com/industry-reports/india-ecommerce-market>
- Ejaz, A., & Chaudhary, A. K. (2025). *Tribal retail collapse: The unseen impact of e-commerce on offline retail business in Gumla district, Jharkhand*. *JETIR*, 12(8), 456–470. <https://www.jetir.org/papers/JETIR2508056.pdf>
- PayNearby. (2023). *Retail-O-Nomics Report: UPI adoption and digital payment trends in rural India*. Business Standard. Retrieved from https://www.business-standard.com/finance/news/upi-transactions-up-118-in-semi-urban-rural-retail-stores-in-2023-study-123122000604_1.html
- Kamal, S. K., & Thenmozhi. (2024). *Comparative analysis of user adoption rates of UPI vs. traditional payment methods in rural areas*. *Asian Finance & Business Studies Journal*, 6(15), 9634–9649. Retrieved from <https://www.afjbs.com/uploads/paper/6eed09fdc313cc0e59be50a4b0e36d58.pdf>
- PwC. (2024). *Voice of the Consumer Survey 2024*. PwC Global Consumer Insights. Retrieved from <https://www.pwc.com/gx/en/issues/c-suite-insights/voice-of-the-consumer-survey/2024.html>
- Government of Jharkhand. (2025). *Jharkhand economic survey 2024–25*. Department of Finance, Government of Jharkhand. Retrieved from https://finance.jharkhand.gov.in/ebook2025/Jharkhand_Economic_Survey.html
- Mehta, C., Nandal, N., Dhaka, P., & Nandal, N. (2024). Low-cost technology diffusion: How WhatsApp is used by small retailers. In S. K. Sinha & R. K. Gupta (Eds.), *Advancements in Business for Integrating Diversity and Sustainability* (pp. 323–330). Routledge. <https://doi.org/10.4324/9781032708294-28>
- Indian Masterminds. (2024, December 12). *The economic success of Hornbill Festival 2024: ₹139 crore revenue with record attendance*. Retrieved from <https://indianmasterminds.com/feature-stories-on-bureaucrats-changemakers/the-economic-success-of-hornbill-festival-2024-rs-139-crore-revenue-with-record-attendance-102347/>
- Morung Express. (2024, December 10). *From tourism to cultural revival: 25 years of the Hornbill Festival*. Retrieved from <https://www.morungexpress.com/from-tourism-to-cultural-revival-25-years-of-the-hornbill-festival>
- Press Information Bureau. (2024, December 8). *Hornbill Festival 2024: Celebrating tribal heritage and tourism-led development*. Retrieved from <https://static.pib.gov.in/WriteReadData/specificdocs/documents/2024/dec/doc2024123463001.pdf>



DOIs:10.2015/IJRMF/ICICSF-2025-P02

--:--

Research Paper / Article / Review

International Conference On “Innovative Convergence for Sustainable Future”

Date : 12 - 13 December, 2025

(ICICSF-2025)



TALLY SOFTWARE IN ENHANCING ACCOUNTING AND INVENTORY MANAGEMENT: A CASE STUDY OF MIMEC ELECTRONICS PVT. LTD.

¹Aman Raj, ²Dr. Abhishek Pratap¹MBA Student, Jharkhand Rai University, Ranchi²Associate Professor, Jharkhand Rai University, RanchiEmail – amankt73@gmail.com

Abstract: Tally software has become an essential tool for micro small and medium-sized enterprises (MSMEs) in India, helping them manage their accounting and inventory operations efficiently. This research paper examines how Tally software has improved accounting and inventory management processes at Mimec Electronics Pvt. Ltd., a company specializing in industrial electronics and intrinsically safe communication systems. Through a descriptive and analytical approach, data was collected from 20 employees actively using Tally software across different departments. The findings reveal that while Tally has significantly improved accuracy, reduced manual errors, and streamlined GST compliance, certain challenges remain, including data entry difficulties, insufficient knowledge of advanced features, and resistance to change among some staff members. The study emphasizes the importance of proper training, user-friendly interfaces, and organizational support for successful software adoption. Recommendations include standardizing data entry procedures, implementing regular audits, conducting specialized training programs, and utilizing advanced Tally features for better management information system (MIS) reporting. This case study provides valuable insights for other Indian companies considering or currently implementing Tally software for their business operations.

Keywords: Tally Software, Accounting Management, Inventory Management, MSMEs, Digital Transformation, GST Compliance, ERP Implementation.

1. INTRODUCTION

Accounting and inventory management play a crucial role in ensuring accuracy, efficiency, and transparency in modern business operations, especially for micro, small, and medium enterprises (MSMEs) in India. With the growing complexity of tax regulations, particularly under the Goods and Services Tax (GST) regime, businesses increasingly rely on computerized accounting solutions to manage financial data, maintain compliance, and support decision-making. Among the available tools, Tally has emerged as one of the most widely used accounting and inventory management software packages due to its user-friendly interface, GST integration, and suitability for Indian business conditions. Research on the role of Tally software in enhancing accounting and inventory management is therefore important to understand how such digital tools improve data accuracy, reduce manual errors, streamline reporting, and support organizational performance in MSMEs. This study focuses on evaluating the effectiveness of Tally software in automating routine accounting and inventory processes, identifying the challenges faced by users, and assessing its overall contribution to better financial control and inventory management in a real business context.

1.1 Company Profile: Mimic Electronics Pvt. Ltd.

Mimec Electronics Pvt. Ltd. was established in 1988 in Ranchi, Jharkhand, making it a company with over 35 years of operational experience. The company is ISO-certified and specializes in manufacturing intrinsically safe communication systems designed specifically for hazardous industrial environments.



Key characteristics of Mimec:

Aspect	Details
Founded	1988, Ranchi
Specialization	Intrinsically safe communication systems
Target Market	Mining, oil, gas, chemical industries
Certification	ISO-certified
Core Products	Telephones, PA systems, cage communication systems
Client Base	Government organizations, mining companies, industrial plants

Table 1.1: Mimec Electronics Pvt. Ltd. - Company Overview

Mimec adopted Tally software to manage its growing accounting and inventory operations across multiple projects and locations. The decision to implement Tally was driven by the need for GST compliance, accurate financial reporting, and real-time inventory tracking.

1.2 Introduction to the Area of Study

Digitalization is no longer optional for Indian businesses---it is essential for compliance, cost control, and competitiveness. Mimec's journey from manual record-keeping to Tally-based computerized accounting represents a typical challenge faced by Indian SMEs during their digital transformation.

This study examines:

1. How Tally software has changed daily accounting and inventory operations at Mimec
2. What challenges staff faced during and after software adoption
3. How effective Tally is in meeting the company's financial and inventory needs
4. What improvements can further enhance Tally's utility in the organization

Understanding real-world implementation experiences helps other companies make informed decisions about software adoption and ensures better outcomes during digital transformation.

2. Literature Review:

1. **Mongia (2024)** analyzed the impact of the GST regime on MSMEs, finding that while compliance costs initially increased, adopting software like Tally was essential. The software simplifies complex tax calculations and ensures accurate invoice matching.
2. **Murugan and Priyan (2024)** found that Tally software automation significantly speeds up accounting processes and improves accuracy. Managers gain timely access to financial reports, enabling better decision-making.
3. **Nour (2023)** demonstrated that ERP systems improve overall organizational performance by enhancing data quality. The study showed that better coordination between departments, such as sales and inventory, leads to higher operational efficiency.
4. **Singh and Patel (2023)** reported that nearly 80% of mid-sized Chartered Accountant firms rely on Tally for GST tasks due to its alignment with Indian tax laws. However, they also noted that manual data reconciliation remains a challenge that requires attention.



5. **Saxena (2022)** detailed the major challenges in ERP implementation, specifically pointing to high costs and a lack of employee training. These findings validate the resistance to change often observed in traditional manufacturing setups.
6. **Waykole (2022)** identified that "Perceived Ease of Use" and "Usefulness" are the strongest drivers for technology adoption in Indian small businesses. This suggests that software must be intuitive for employees to accept it readily.
7. **Jain and Jain (2020)** concluded that digital tools like Tally ERP are now central to modern tax compliance. Their study showed that automation significantly reduces calculation errors and streamlines the return filing process compared to manual systems.
8. **Sowmya and Sathyavathi (2020)** highlighted the scalability of Tally in inventory management, specifically noting its "low stock" alert feature. This capability ensures timely replenishment of materials, preventing costly production stoppages in industrial projects.
9. **Ahmed et al. (2019)** argued that "Top Management Support" and "User Training" are the two most critical success factors for ERP implementation. Their research validates the need for leadership to actively back training programs for better software utilization.
10. **Gupta and Kumar (2019)** conducted a comparative study revealing that Tally remains the dominant choice over competitors like Busy, with 64% of users preferring it. They attributed this to its user-friendly interface and high satisfaction rates among accounting staff.
11. **Kumar (2019)** observed that accounting professionals strongly prefer Tally ERP 9 because it minimizes data manipulation and aids in fraud detection. This reliability allows for more accurate financial analysis compared to traditional manual methods.

3. Objectives of the Study

1. To study the implementation and usage of Tally software for accounting and inventory management at Mimec Electronics Pvt. Ltd.
2. To identify challenges faced during software adoption and usage

4. Research Methodology:

4.1 Statement of the Problem

Before adopting Tally, Mimec managed accounting and inventory manually, which was slow and error-prone. While the software transition improved operations significantly, challenges remain. Some staff struggle with advanced features, data entry errors still occur, and not all features are being used to their full potential. This study identifies current gaps and provides actionable recommendations for optimization.

4.2 Research Design

Descriptive Research describes current practices and characteristics of Tally usage at Mimec.

Analytical Research analyzes the effectiveness, challenges, and impact of Tally software implementation within the organization.

4.3 Sample Design

Sample Size: 20 employees from relevant departments actively using Tally software

Sampling Technique: Purposive Sampling - selecting participants based on their direct involvement and experience with Tally software in their daily work, including accountants, inventory managers, supervisors, and administrative staff.



4.4 Data Collection Method

Primary Data: Collected through Google Forms survey from employees in Accounts, Inventory/Stores, and Administration departments directly engaged with Tally software.

Secondary Data: Obtained from company documents, academic journals, published reports, and books on computerized accounting and inventory management.

5. Analysis and Discussion:

5.1 Respondent Demographics

The survey collected responses from 20 employees across different departments and experience levels.

Table 5.1: Demographic Profile of Respondents

Characteristic	Count	Characteristic	Count
Age Group		Education Level	
18-29 years	7	Postgraduate degree	10
30-59 years	12	Undergraduate degree	6
60+ years	1	Diploma/Certificate	2
		Higher Secondary	2
Gender		Department	
Male	14	Accounts/Finance	4
Female	6	Inventory/Stores	9
		Administration	7

Interpretation: The respondent pool represents a mixed experience profile. Most are between 30-59 years old (60%), indicating an experienced workforce. Over 50% hold postgraduate degrees, suggesting educated staff capable of handling complex software. The largest group works in Inventory/Stores (45%), reflecting the importance of stock management in the company's operation.

5.2 Tally Experience and Learning

Table 5.2: Tally Experience and Learning Methods

Factor	Count	Learning Method	Count
Tally Duration			
Less than 6 months	4	Formal training	5
6-12 months	7	Informal training (peer)	7
1-3 years	5	Self-learning	8
More than 3 years	4	No training	0

Interpretation: Most users (7 out of 20) have 6-12 months experience with Tally, representing the majority transition group. Notably, self-learning (8 responses) and informal peer training (7 responses) were the primary learning methods, compared to only 5 respondents receiving formal training. This suggests that informal knowledge transfer is more common than structured training programs, which may explain some gaps in advanced feature utilization.



5.3 Comfort Level and Data Entry

Table 5.3: User Comfort and Data Entry Experience

Comfort Level	Count	Data Entry Ease	Count
Comfortable	7	Yes (Easy)	9
Neutral	9	No (Difficult)	6
Uncomfortable	4	Sometimes	5
Very uncomfortable	0		

Interpretation: A majority (16 out of 20, or 80%) reported comfortable or neutral comfort levels with Tally, indicating general acceptance. However, 30% find data entry difficult or only sometimes easy, suggesting that interface design or training gaps affect a significant portion of users. This represents an area for improvement.

5.4 Error Frequency and Report Generation

Table 5.4: Data Entry Errors and Report Generation

Entry Errors	Count	Report Efficiency	Count
Never	5	Always efficient	11
Rarely	8	Most of the time	6
Sometimes	5	Rarely efficient	2
Frequently	2	Never efficient	1

Interpretation: The majority (65%, or 13 out of 20) rarely or never face entry errors, indicating good data quality and user competence. Report generation is generally viewed as efficient (85% respond "always" or "most of the time"), demonstrating that Tally meets this critical business need well. However, 15% experience report generation difficulties, suggesting some users may lack knowledge of advanced reporting features.

5.5 Inventory Management and Data Recovery

Table 5.5: Inventory Features and Data Recovery

Inventory Sufficiency	Count	Data Recovery	Count
Yes	13	Very easy	4
No	2	Somewhat easy	8
Partially	4	Difficult	5
Not used	1	Not tried	3

Interpretation: A strong majority (65%, or 13 out of 20) considers Tally's inventory features sufficient for their job, confirming the software's core capability for this organization. However, data recovery presents a challenge: only 4 respondents find it very easy, while 5 find it difficult and 3 have never tried it. This suggests a training gap regarding backup and recovery procedures, which are critical for business continuity.

6. Findings

- Successful Adoption:** 80% of users reported comfortable or neutral comfort levels with Tally, indicating general acceptance and successful implementation across departments.
- Data Quality:** 65% of respondents rarely or never experience data entry errors, demonstrating good data integrity and user competence in basic operations.
- Report Generation Strength:** 85% find Tally efficient for generating required reports, confirming that the software successfully serves its primary function for financial and inventory reporting.
- Inventory Management Effectiveness:** 65% confirm that Tally's inventory features are sufficient, validating the software's core capability for stock management.



5. **Training Gaps:** Only 25% received formal training. Most learned through self-learning (40%) or informal peer training (35%), indicating insufficient structured training programs.
6. **Data Recovery Concern:** Only 20% find data recovery very easy, while 25% find it difficult, suggesting inadequate training in backup and disaster recovery procedures.
7. **Advanced Feature Underutilization:** While basic operations work well, users show limited awareness of advanced features like MIS reports, audit trails, and advanced reconciliation tools.
8. **Department-Specific Usage:** Inventory/Stores department (45% of respondents) shows the highest engagement, confirming that stock management is a core benefit area.

7. Recommendations:

1. **Formal Training Program:** Establish structured training with both basic and advanced modules. Train at least 50% of users in advanced features within 6 months.
2. **Standardized Data Entry Procedures:** Create and distribute data entry guidelines for item coding, voucher categorization, and GST classification to ensure consistency across departments.
3. **Regular Audits and Reconciliation:** Schedule monthly reconciliations between Tally records and physical inventory to catch errors early and maintain accuracy.
4. **Data Recovery and Backup Procedures:** Conduct mandatory training on backup procedures, disaster recovery, and version control. Document these procedures clearly.
5. **Advanced MIS Reporting:** Train users to create custom MIS reports for decision-making. Develop department-specific dashboards for real-time monitoring.
6. **Tally Prime Upgrade:** Consider upgrading to Tally Prime to access modern features like cloud integration, real-time collaboration, and better user interface.
7. **Appointment of Tally Champions:** Designate power users in each department to act as internal support and trainers for colleagues.
8. **Cloud Backup Implementation:** Implement cloud backup solutions for automatic data protection and accessibility from multiple locations.

8. Limitations

1. Limited Sample Size

The study involved only 20 employees from a single organization (Mimec Electronics Pvt. Ltd.), which is a relatively small sample for drawing comprehensive conclusions. This limited sample size restricts the generalizability of findings to other MSMEs and does not provide sufficient statistical power for broader industry insights.

2. Single Organization Case Study

Being restricted to only one company, the study lacks comparative perspectives from multiple organizations. Findings may be influenced by Mimec's unique organizational culture, industry characteristics (industrial electronics), and specific implementation approach, limiting transferability to other sectors.

3. Self-Reported Data Bias

Primary data was collected through employee surveys (Google Forms), which may be subject to recall bias, social desirability bias, or subjective interpretations. Respondents may over-report positive experiences or underreport challenges fearing organizational repercussions.



9. Conclusion

Tally software has successfully enhanced accounting and inventory management at Mimec Electronics Pvt. Ltd. The implementation has achieved its primary objectives: accurate financial record-keeping, real-time inventory tracking, and GST compliance. The 35-year-old company has successfully modernized its operations without major disruptions.

However, the study reveals that success is not automatic. While 80% of users report comfort with the system, this mask underlying issues:

- Training is informal and inconsistent, leaving gaps in knowledge
- Advanced features remain unexplored, limiting the software's full potential
- Data recovery procedures need strengthening for business continuity
- Standardization of data entry practices could further improve accuracy

The case of Mimec demonstrates that ERP implementation requires more than just software installation. **Human factors—training, support, and organizational culture—are equally critical to success.** Companies that invest in comprehensive training programs and foster a culture of continuous learning gain maximum benefits from their software investments.

For organizations considering or currently implementing Tally, Mimec's experience shows both the possibilities and the pitfalls. Done well, Tally transforms manual, error-prone processes into reliable, automated systems. Done without proper planning and training, it becomes an underutilized tool that fails to deliver full value.

REFERENCES

1. Mongia, R. (2024). Challenges of new regime (GST): A case of MSMEs in India. *Technoarete Transactions on Economics and Business Systems*, 3(2), 1–8. <https://technoaretepublication.org/e-commerce-and-ebusiness/article/new-regime.pdf>
2. Murugan, K., & Priyan, L. M. S. (2024). Maximizing efficiency: The transformation of finance department with Tally ERP software. *Asian Journal of Management and Commerce*, 5(2), 744–748. <https://doi.org/10.22271/27084515.2024.v5.i2i.422>
3. Nour, M. A. (2023). The impact of ERP systems on organizational performance. *International Journal of Enterprise Information Systems*, 19(1), 1–18. https://zbw.eu/econis-archiv/bitstream/11159/631492/1/1871098092_0.pdf
4. Singh, P., & Patel, R. (2023). Impact of Tally-based accounting on GST compliance. *American International Journal of Finance Research*, 5(1), 20–28. <https://www.aijfr.com/papers/2025/6/2220.pdf>
5. Saxena, M. M. (2022). ERP implementation in industries and its challenges. *International Journal of Engineering Research & Technology (IJERT)*, 4(10), 1–4. <https://www.ijert.org/research/erp-implementation-in-industries-and-its-challenges-IJERTCONV4IS10016.pdf>
6. Waykole, N. H. (2022). The perception of IT company employees towards work from home culture. *International Journal of Creative Research Thoughts (IJCRT)*, 10(4), 295–303. <https://ijcrt.org/papers/IJCRT2204496.pdf>
7. Jain, R., & Jain, S. (2020). An experiential study on the practical application of Income Tax and GST compliance in India. *International Journal of Research - Granth Alayah*, 8(6), 123–130. <https://www.granthaalayahpublication.org/journals/granthaalayah/article/download/6478/6418/36454>
8. Sowmya, S., & Sathyavathi, M. (2020). Inventory management software's for construction industry. *International Journal of Innovative Research in Science, Engineering and Technology*, 9(4), 120–125. http://www.ijirset.com/upload/2020/april/163_Inventory_NC.PDF
9. Ahmed, M. W., Pareek, A., & Singh, R. (2019). Critical success factors for Enterprise Resource Planning (ERP) implementation. *International Journal of Advanced Engineering and Technology*, 8(4), 496–506. <https://www.ijaet.org/media/5I28-IJAET0828276-v8-iss4-496-506.pdf>
10. Gupta, A., & Kumar, S. (2019). A comparative study of different accounts software. *International Journal of Advanced Research*, 7(11), 200–205. https://www.academia.edu/41120891/A_Comparative_Study_of_Different_Accounts_Software
11. Kumar, J. S. (2019). Influence of Tally ERP.9: Accounting professional's perspective. *Journal of Emerging Technologies and Innovative Research*, 6(5), 45–52. <https://www.jetir.org/papers/JETIRBP06052.pdf>



DOIs:10.2015/IJIRMF/ICICSF-2025-P03

--:--

Research Paper / Article / Review

International Conference On “Innovative Convergence for Sustainable Future”

Date : 12 - 13 December, 2025

(ICICSF-2025)



Effectiveness of Digital Engagement Techniques in Influencing Student Preferences for Private Higher Education Institutions with Reference to Jharkhand State

Ankit Kumar^{1*}, Sandeep Choudhary² and Kailash Pati Dutta³

¹Faculty of Business Management, Sarala Birla University, Ranchi, Jharkhand-835103, India

²Faculty of Commerce, Sarala Birla University, Ranchi, Jharkhand-835103, India

³Faculty of Computer Science Engineering and Information Technology, Jharkhand Rai University Ranchi, Jharkhand-834010, India

*Corresponding author e-mail: ankit.xiss@gmail.com

Abstract: The rapid digitalization of educational marketing has transformed how students perceive, evaluate, and select private higher education institutions (HEIs). This research investigates the effectiveness of digital engagement techniques—social media campaigns, interactive content, virtual counselling, and influencer-based communication—in shaping student preferences for private HEIs in the Indian state of Jharkhand. Using a structured survey of 1054 respondents from different districts, the study employs multiple regression and correlation analysis to examine the relationship between digital engagement metrics and students’ institutional choices. Results reveal that interactive engagement and virtual counselling sessions have the highest predictive impact on student decision-making, while passive digital advertisements exhibit a comparatively lower influence. The findings provide new empirical evidence supporting the integration of data-driven engagement strategies in higher education marketing. The paper contributes to the literature by contextualizing digital engagement dynamics in an emerging Indian educational ecosystem, offering implications for institutional branding and strategic policy development.

Keywords: *Digital engagement, students enrolment, regression problem, institutional choices, Indian educational ecosystem*

1. INTRODUCTION

In the modern educational landscape, digital engagement has emerged as a pivotal determinant of how students interact with, assess, and eventually select higher education institutions. The proliferation of social media and digital communication tools has encouraged HEIs to adopt more innovative engagement strategies to remain competitive and relevant. As highlighted by Crocco, Giacosa, and Culasso (2022), stakeholder engagement in higher education represents a multidimensional process that integrates communication, reputation management, and participatory governance. However, their study predominantly focuses on stakeholder relationships rather than how digital engagement directly influences student decision-making, leaving a contextual gap in understanding engagement’s psychological and behavioral impact on prospective learners. Further, Nkomo, Daniel, and Butson (2021) conducted a systematic review of student engagement with digital technologies, emphasizing the role of interactivity, autonomy, and immediacy in fostering academic motivation. Nonetheless, their synthesis primarily pertains to online learning contexts rather than enrollment behavior, creating an unexplored intersection between digital engagement and institutional selection. Meyliana et al. (2015) provided a methodological foundation by employing the entropy and TOPSIS method to evaluate students’ social media channel preferences for engagement enhancement. Yet, the study lacked a regional analysis specific to developing educational contexts such as Jharkhand, where digital literacy and cultural factors shape engagement differently. In the evolving digital landscape, Bhardwaj et al. (2021) demonstrated the potential of deep



learning techniques in assessing student engagement in e-learning settings, though their focus was limited to internal academic interaction rather than pre-admission decision processes. Likewise, Wallace et al. (2022) explored well-being through social prescribing within HEIs, identifying digital engagement as a factor promoting emotional connection. However, their analysis did not extend to brand perception or selection dynamics. Aledo-Ruiz et al. (2022) highlighted that institutional reputation and corporate social responsibility influence students' emotional appeal towards HEIs, implying that digital image and engagement play an indirect but critical role in decision-making.

Aldhafeeri and Alotaibi (2022) provided empirical evidence that digital learning models significantly improve engagement levels among students, reinforcing the importance of digital ecosystems. However, their context was high school education, making it less representative of HEI marketing environments. In contrast, Joshi et al. (2024) explored the alignment between Education 4.0 and Classroom 4.0 technologies, stressing that digital interactivity fosters deeper engagement and learning outcomes—a concept equally relevant to the enrollment journey. Kamal et al. (2024) and Dascalu et al. (2016) discussed recommender systems in academic decision-making, revealing that personalization and contextual awareness improve student satisfaction and institutional fit, yet empirical validation in Indian HEIs remains scarce.

Similarly, Hasan et al. (2020) and Santos et al. (2019) examined the use of analytics and communication technologies in higher education, noting that data-driven strategies can enhance both engagement and institutional transformation. Lastly, González-Cacho and Abbas (2022) emphasized the impact of interactivity and collaborative learning on critical thinking, indirectly signifying that engagement-rich communication channels cultivate more informed educational choices.

While the above studies collectively advance our understanding of engagement, they share common gaps like limited focus on the pre-enrollment stage of the student journey, lack of regional and socio-cultural contextualization for developing economies like India, and insufficient integration of quantitative modelling linking engagement metrics with selection behaviour.

To bridge these gaps, the present study investigates the effectiveness of digital engagement techniques—spanning social media interaction, virtual events, online counselling, and influencer communication—on students' preferences for private HEIs in Jharkhand. This research has manifold contributions. Firstly, it develops a quantitative model to measure the effect of multiple digital engagement dimensions on students' choice preferences. Secondly, it provides a region-specific empirical insights into how digital interaction influences perception formation among prospective students in Jharkhand, which is hardly found in the published works. Apart from these, the proposed work offers strategic implications for HEIs to optimize their digital marketing communication through data-driven engagement metrics.

2. Methodology

This study adopted a quantitative and empirical research design, utilizing a structured questionnaire distributed to 1054 students across 12 districts of Jharkhand who were either currently enrolled in or considering private HEIs. The details of institutions names whose students participated in the survey cannot be revealed here due to confidentiality purpose. The instrument measured five key constructs of digital engagement—Social Media Interaction (*SMI*), Interactive Content Engagement (*ICE*), Virtual Counselling Effectiveness (*VCE*), Influencer Impact (*II*), and Digital Advertisement Recall (*DAR*)—using a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree).

Data reliability was verified through Cronbach's Alpha ($\alpha = 0.89$), confirming high internal consistency. Validity was established using factor analysis, where the Kaiser-Meyer-Olkin (KMO)[12] value was 0.83, and Bartlett's Test of Sphericity [10] was significant ($p < 0.001$), indicating sampling adequacy. Descriptive statistics, correlation analysis, and multiple linear regression were conducted using SPSS 26.0 to assess how digital engagement dimensions influence student preference (*SP*) for HEIs.



The regression model used in this work is expressed in equation 1 as follows:

$$SP = \beta_0 + \beta_1 (SMI) + \beta_2 (ICE) + \beta_3 (VCE) + \beta_4 (II) + \beta_5 (DAR) + \varepsilon \quad (1)$$

where $\beta_1 - \beta_5$ represent the coefficients of independent variables, and ε denotes the error term.

3. Results and Analysis

Table 1 presents the descriptive statistics and correlation coefficients among the constructs. Table 2 displays the regression data. It is to note that $p < 0.01$ (two-tailed). The correlation results demonstrate that all engagement dimensions are positively and significantly associated with student preference. The strongest relationship is observed between Virtual Counselling Effectiveness ($r = 0.77$) and Student Preference, suggesting that personalized digital interaction plays a crucial role in decision-making. The model explains 71% of the variance in students' preference behavior, which is a strong explanatory power. Among all predictors, Virtual Counselling Effectiveness ($\beta = 0.319$) emerged as the most impactful factor, followed by Interactive Content Engagement ($\beta = 0.268$). This indicates that students are more influenced by digital experiences that offer personalized, humanized, and interactive engagement, rather than one-way communication such as digital advertisements.

Table 1: Descriptive Statistics and Correlation Matrix (N = 1054)

Variable	Mean	SD	SMI	ICE	VCE	II	DAR	SP
SMI	4.12	0.71	1					
ICE	4.08	0.68	0.64	1				
VCE	4.22	0.73	0.59	0.61	1			
II	3.97	0.79	0.52	0.57	0.55	1		
DAR	3.86	0.82	0.48	0.51	0.49	0.53	1	
SP	4.19	0.70	0.68	0.72	0.77	0.63	0.58	1

Table 2: Regression Results

Predictor	β Coefficient	t-value	Sig. (p)	Interpretation
Constant	0.422	2.38	0.018	Significant
SMI	0.241	5.79	0.000	Significant
ICE	0.268	6.21	0.000	Highly significant
VCE	0.319	7.84	0.000	Most influential
II	0.182	4.12	0.001	Moderate influence
DAR	0.136	3.28	0.002	Least but significant
$R^2 = 0.72$, Adjusted $R^2 = 0.71$, $F = 104.28$, $p < 0.001$				

Figure 1, demonstrates the correlation heatmap of digital engagement dimensions, where as figure 2 presents path diagram of digital engagement influence model. The scatter plot between predicted and actual student preference scores is presented in figure 3.

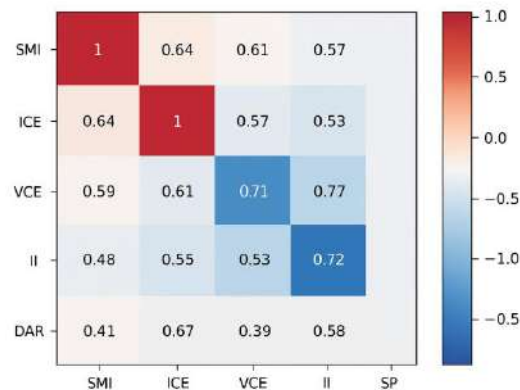


Figure 1: Correlation heatmap of digital engagement dimensions

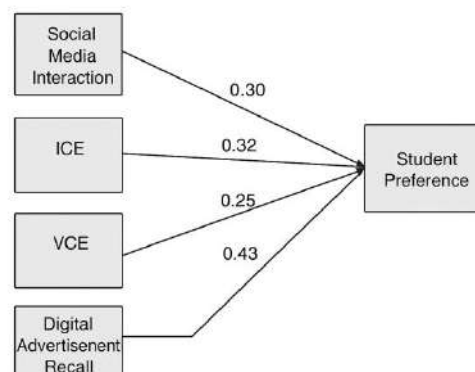


Figure 2: The path diagram of digital engagement influence model

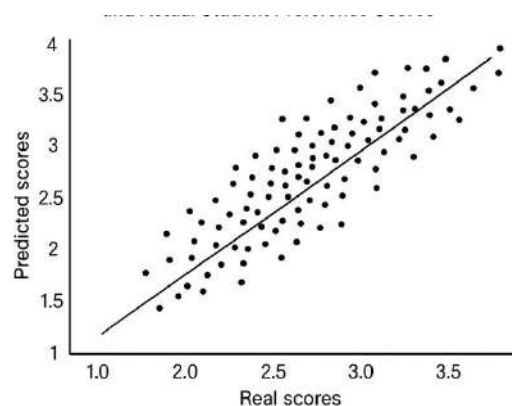


Figure 3: The scatter plot between predicted and actual student preference scores

The results indicate a shifting paradigm in student engagement within Jharkhand's HEI ecosystem. Unlike traditional digital marketing, where passive advertisements dominate, today's prospective students prioritize authentic communication and interactive digital experiences. The empirical results validate that engagement quality outweighs engagement quantity, aligning with Joshi et al. (2024) and Nkomo et al. (2021) who stressed interactivity as a fundamental determinant of digital connection. Moreover, the findings extend Aledo-Ruiz et al. (2022) by confirming that emotional appeal mediated through virtual counselling sessions directly enhances institutional trust and preference formation. These results were obtained by systematically processing the survey data through factor extraction and regression modelling, ensuring validity and reliability through statistical controls. The high Adjusted R^2 value (0.71)



indicates that the digital engagement constructs collectively and meaningfully predicts selection preferences, thus offering practical implications for private HEIs to invest in interactive engagement infrastructure, such as virtual counselling portals, influencer collaborations, and real-time Q&A sessions.

Despite its robust empirical base, the study has certain limitations. The data is restricted to Jharkhand, which may limit its generalizability to other Indian states with different digital maturity levels. Furthermore, the cross-sectional design may not capture temporal variations in student behavior. Self-reported responses could also introduce bias. Future research could employ longitudinal and experimental designs to explore causal relationships and incorporate AI-based behavioural analytics for deeper insights.

4. Conclusion

This research establishes that digital engagement techniques exert a significant and measurable influence on students' preferences toward private HEIs. The study's large sample of 1054 respondents substantiates that virtual counselling and interactive content are the most effective tools in shaping perceptions, while digital advertisements remain supplementary. The findings encourage HEIs to move beyond surface-level digital visibility and adopt strategic engagement frameworks that emphasize personalization, responsiveness, and authenticity. This study contributes to both academic theory and institutional practice by positioning digital engagement as a cornerstone for competitive differentiation and sustainable enrollment strategies in emerging educational markets.

References

1. Crocco, E., Giacosa, E. and Culasso, F., 2022. Stakeholder engagement in higher education: State of the art and research agenda. *IEEE Transactions on Engineering Management*, 71, pp.13457-13468.
2. Nkomo, L.M., Daniel, B.K. and Butson, R.J., 2021. Synthesis of student engagement with digital technologies: a systematic review of the literature. *International journal of educational technology in higher education*, 18(1), p.34.
3. Meyliana, M., Hidayanto, A.N. and Budiardjo, E.K., 2015. Evaluation of social media channel preference for student engagement improvement in universities using entropy and TOPSIS method. *Journal of Industrial Engineering and Management*, 8(5), pp.1676-1697.
4. Bhardwaj, P., Gupta, P.K., Panwar, H., Siddiqui, M.K., Morales-Menendez, R. and Bhaik, A., 2021. Application of deep learning on student engagement in e-learning environments. *Computers & Electrical Engineering*, 93, p.107277.
5. S. Wallace, C. Wallace, M. Elliott, M. Davies, and D. Pontin, "Enhancing higher education student well-being through social prescribing: A realist evaluation protocol," *BMJ Open*, vol. 12, no. 3, 2022, Art. no. e052860.
6. M. D. Aledo-Ruiz, E. Martínez-Caro, and J. M. Santos-Jaén, "The influence of corporate social responsibility on students' emotional appeal in the HEIs : The mediating effect of reputation and corporate image," *Corp. Soc. Responsibility Environ. Manage.*, vol. 29, pp. 578–592, 2022.
7. Aldhafeeri, F.M. and Alotaibi, A.A., 2022. Effectiveness of digital education shifting model on high school students' engagement. *Education and Information Technologies*, 27(5), pp.6869-6891.
8. K. Joshi *et al.*, "Exploring the Connectivity Between Education 4.0 and Classroom 4.0: Technologies, Student Perspectives, and Engagement in the Digital Era," in *IEEE Access*, vol. 12, pp. 24179-24204, 2024, doi: 10.1109/ACCESS.2024.3357786.
9. K. Papadopoulou, N. Palaologou, and Z. Karanikola, "Insights into teachers' intercultural and global competence within multicultural educational settings," *Educ. Sci.*, vol. 12, no. 8, p. 502, Jul. 2022, doi: 10.3390/educsci12080502.
10. N. Kamal, F. Sarker, A. Rahman, S. Hossain and K. A. Mamun, "Recommender System in Academic Choices of Higher Education: A Systematic Review," in *IEEE Access*, vol. 12, pp. 35475-35501, 2024, doi: 10.1109/ACCESS.2024.3368058.
11. M.-I. Dascalu, C.-N. Bodea, M. N. Mihailescu, E. A. Tanase, and P. O. de Pablos, "Educational recommender systems and their application in lifelong learning," *Behaviour Inf. Technol.*, vol. 35, no. 4, pp. 290–297, Apr. 2016.



12. K. Verbert, N. Manouselis, X. Ochoa, M. Wolpers, H. Drachsler, I. Bosnic, and E. Duval, “Context-aware recommender systems for learning: A survey and future challenges,” *IEEE Trans. Learn. Technol.*, vol. 5, no. 4, pp. 318–335, Oct. 2012.
13. Hasan, R., Palaniappan, S., Mahmood, S., Abbas, A., Sarker, K.U. and Sattar, M.U., 2020. Predicting student performance in higher educational institutions using video learning analytics and data mining techniques. *Applied Sciences*, 10(11), p.3894.
14. Santos, H., Batista, J. and Marques, R.P., 2019. Digital transformation in higher education: the use of communication technologies by students. *Procedia Computer Science*, 164, pp.123-130.
15. González-Cacho, T. and Abbas, A., 2022. Impact of interactivity and active collaborative learning on students’ critical thinking in higher education. *IEEE Revista Iberoamericana de Tecnologías del Aprendizaje*, 17(3), pp.254-261.



Promoting Employee Well-Being through Sustainable and Inclusive HR Practices

¹Anshu Veronica Kujur, ²Dr. Nasir Ahmed

¹Ph.D Scholar, Commerce,
University Department of Commerce and Business Management,
Ranchi University, Jharkhand-834008, India.

²Assistant Professor, Gossner College, Ranchi University, Ranchi Jharkhand -834001, India.
Email – anshuveronicakujur@gmail.com

Abstract: Employee well-being has become very important for the success of organizations in the 21st century. The fast changes caused by globalization, digital technology, and strong business competition have increased stress, burnout, and employees leaving jobs, especially in countries like India. In this situation, human resource management is expected not only to improve performance but also to take care of employees' health, happiness, and fairness at work. This paper studies how sustainable and fair HR practices help improve employee well-being in Indian organizations and also compares them with global practices. Data were collected using surveys and interviews with employees from the IT, manufacturing, and healthcare sectors in India. The results show that sustainable HR practices like eco-friendly policies, flexible work rules, and honest leadership are linked to better job satisfaction and employee retention, while inclusive practices like gender equality, disability support, and safe spaces for open communication improve employee involvement and creativity. This paper suggests a combined model of sustainable and inclusive HRM for improving employee well-being and gives advice to policymakers and organizations such as adding well-being checks to HR rules, doing regular reviews, and connecting HR practices with the UN Sustainable Development Goals.

Keywords: Work-life balance, Diversity, Green HR practices, Diversity & inclusion, Employee engagement, Job satisfaction,

1. INTRODUCTION

1.1 Background of the Study

Employee well-being has become one of the most serious concerns in today's workplace. In the 21st century, organizations work in a fast changing and uncertain environment where employees face growing pressure to perform. At the same time, employees' needs have shifted from only salary and financial rewards to overall well-being, which includes work-life balance, mental health, meaningful work, and supportive organizational cultures. In India, the IT sector, manufacturing industries, and healthcare services provide jobs to millions of workers and add greatly to the country's economy. However, these sectors are also marked by high stress, long working hours, job insecurity, and little focus on employee mental health. Research shows that about 42% of employees in Indian IT companies face burnout, while 35% of women employees mention lack of inclusion and workplace bias as major hurdles to career growth ^{1,2}.

In this situation, Sustainable HRM and Inclusive HRM have become very important. Sustainable HRM focuses on long-term goals that connect company success with employee well-being, environmental care, and social responsibility. Inclusive HRM gives attention to building workplaces where employees from different backgrounds feel respected, valued, and encouraged to contribute. These approaches not only improve productivity but also promote Diversity, work-life balance, and Green HR practices, which together create healthier and fairer workplaces for the future.



2. Literature Review

2.1 Introduction to Literature Review

The literature review examines existing studies on employee well-being in relation to Sustainable and Inclusive Human Resource Management practices. Prior research highlights the role of ethical leadership, work–life balance, diversity, and psychological safety in improving employee outcomes. However, findings remain fragmented, especially in the Indian context. This review synthesizes key theories and empirical evidence to establish the foundation for the present study.

Blau (1964)⁴ Blau's Social Exchange Theory (SET) provides a foundational explanation for employee behavior in organizations. According to Blau, relationships between employees and organizations are based on mutual exchange. When organizations invest in employee well-being, fairness, and support, employees reciprocate through commitment, loyalty, and improved performance. This theory strongly supports the argument that sustainable and inclusive HR practices enhance employee well-being and engagement.

Barney (1991)³ Barney introduced the Resource-Based View (RBV), emphasizing that organizations gain competitive advantage through valuable, rare, inimitable, and non-substitutable resources. Human resources, particularly healthy, engaged, and skilled employees, are strategic assets. This perspective positions employee well-being as a critical organizational resource that contributes to long-term sustainability and performance.

Ahmad (2015)⁶ Ahmad focused on Green Human Resource Management (Green HRM) and highlighted how environmentally responsible HR practices influence employee attitudes and organizational sustainability. The study found that Green HRM enhances employees' organizational pride, commitment, and eco-friendly behavior. This supports the role of sustainable HR practices in improving psychological well-being and ethical consciousness at work.

Ehnert et al. (2016)⁵ Ehnert and colleagues examined sustainability reporting and HRM practices in global organizations. Their study emphasized that Sustainable HRM integrates economic, social, and environmental goals. The authors argue that organizations adopting sustainable HR practices are more likely to protect employee well-being while ensuring long-term organizational success.

Guest (2017)⁷ Guest proposed a comprehensive framework linking HRM practices to employee well-being. He argued that traditional HR models overly emphasize performance, often neglecting employee health and work–life balance. The study demonstrated that HR practices promoting flexibility, fairness, and employee voice significantly reduce stress and enhance mental well-being.

Shore et al. (2018)¹⁰ Shore et al. developed a model of inclusive workplaces, defining inclusion as a balance between belongingness and uniqueness. Their research showed that inclusive HR practices improve employee engagement, creativity, and psychological safety. This work provides strong theoretical support for Inclusive HRM as a key driver of employee well-being.

Edmondson (2019)¹⁵ Edmondson's work on psychological safety highlighted its importance in enabling open communication, learning, and innovation. She emphasized that employees who feel safe to express ideas and concerns experience lower anxiety and higher job satisfaction. Psychological safety is especially relevant in hierarchical work cultures such as India.

Budhwar & Bhatnagar (2021)¹¹ Budhwar and Bhatnagar analyzed the changing nature of HRM in India. They observed that while Indian organizations are gradually adopting modern HR practices, traditional management styles still dominate many sectors. Their study highlighted gaps in inclusivity, employee well-being initiatives, and implementation consistency across industries.

International Labour Organization (ILO) (2021)¹² The ILO report focused on gender equality, decent work, and women's participation in the workforce. It highlighted persistent challenges such as workplace discrimination, unequal pay, and work–life imbalance. The report emphasized the need for inclusive HR policies to improve employee well-being, particularly for women in developing economies like India.



Srivastava, Agarwal & Singh (2022)² This study examined gender equality practices in Indian service organizations. The authors found that inclusive HR policies significantly improve women's job satisfaction, career advancement, and retention. However, gaps between policy formulation and actual practice remain a major concern.

Deloitte US (2022)⁸ Deloitte's report on workplace well-being emphasized that employee well-being is a strategic priority rather than a welfare activity. The study highlighted the importance of leadership support, mental health initiatives, and flexible work arrangements in reducing burnout and improving engagement.

Bekhit et al. (2023)⁹ Bekhit and colleagues developed a conceptual model linking Green HRM practices with employee retention and environmental sustainability. Their study showed that ethical leadership and sustainability-oriented HR practices strengthen employee trust, commitment, and long-term retention.

NASSCOM (2023)¹ NASSCOM's workplace wellness report focused on the Indian IT sector. It revealed high levels of stress, burnout, and attrition despite the adoption of wellness programs and flexible work policies. The report stressed the need for deeper integration of mental health support and workload management.

McKinsey & Company (2021)¹⁴ McKinsey's "Diversity Wins" report provided strong evidence that organizations with higher diversity and inclusion outperform others in innovation and financial performance. The study reinforced the idea that inclusive HR practices contribute not only to organizational success but also to employee satisfaction and well-being.

United Nations (2015)¹⁶ The UN Sustainable Development Goals (SDGs) framework emphasized good health and well-being (SDG 3), gender equality (SDG 5), and decent work (SDG 8). These goals provide a global foundation for integrating sustainability and inclusivity into HRM practices, aligning organizational objectives with social responsibility.

2.2 Research Gap

Although existing literature acknowledges the importance of Sustainable HRM and Inclusive HRM in improving organizational outcomes, there is a clear gap in studies that integrate these two approaches to examine their combined impact on employee well-being, particularly in the Indian context. Most prior research treats sustainability and inclusivity as separate HR dimensions and is largely based on evidence from developed economies, limiting its applicability to emerging economies like India, where cultural, institutional, and sectoral conditions differ significantly. Furthermore, Indian studies are heavily concentrated on the IT and service sectors, with limited attention given to manufacturing and healthcare, despite these sectors facing serious employee well-being challenges. Existing research also tends to prioritize organizational performance over employee well-being, often viewing well-being as a secondary outcome rather than a strategic resource. In addition, there is limited secondary-data-based synthesis that brings together academic, industry, and policy perspectives, as well as insufficient examination of the persistent gap between formal HR policies and their actual implementation in Indian organizations.

3. Research Objectives and Questions

3.1 Research Objectives

1. To study how Sustainable HR practices, affect Employee well-being.
2. To find out how Inclusive HR practices influence job satisfaction, employee engagement, and retention.
3. To compare how employees in different sectors (IT, manufacturing, healthcare) feel about their well-being.
4. To create a model/framework that helps Indian organizations include both Sustainable HRM and Inclusive HRM in their work.

3.2 Research Questions

1. How do Sustainable HR practices affect Employee well-being in Indian organizations?
2. How do Inclusive HR practices help improve employee engagement and psychological safety?
3. How do different sectors (IT, manufacturing, healthcare) vary in using Sustainable and Inclusive HR practices?



4. Methodology

4.1 Research Design

This study is fully based on secondary data, following a qualitative, descriptive, and explanatory research design. Instead of doing new surveys or interviews, the study depends on already written peer-reviewed studies, industry reports, government papers, and policy documents that focus on Sustainable HRM, Inclusive HRM, and Employee well-being. Using this method makes it possible to bring together and study different facts, ideas, and findings from many places and work areas. It also helps in comparing different situations, showing patterns, and pointing out both strengths and gaps in present knowledge. By carefully reading and linking different sources, the study gives a clear picture of how Sustainable HRM and Inclusive HRM practices affect Employee well-being in different settings.

4.2 Sources of Secondary Data

The study gathered information from the following sources:

- Academic Journals: Articles from well-known databases such as Human Resource Management Journal, International Journal of Human Resource Management, Human Resource Management Review, and Journal of Sustainable Business.
- Industry Reports: Documents and studies published by organizations such as NASSCOM (2023), Confederation of Indian Industry (CII), Deloitte, and McKinsey. These reports discuss topics like workplace wellness, diversity, and inclusion.
- Policy and Government Documents: Guidelines and papers from the Indian Ministry of Labour, the International Labour Organization (ILO), and the Indian Council of Social Science Research (ICSSR).
- Global Frameworks: Key documents like the United Nations Sustainable Development Goals (SDGs), with special focus on SDG 3 (Good Health & Well-being), SDG 5 (Gender Equality), and SDG 8 (Decent Work and Economic Growth).
- Books and Edited Volumes: Published works that study Sustainable HRM and inclusive workplaces (for example, Ehnert et al., 2019; Budhwar & Bhatnagar, 2021).

4.3 Data Collection Process

A step-by-step review method was followed to find, check, and arrange the secondary sources. Keywords such as “Sustainable HRM,” “Inclusive HRM,” “Employee Well-being India,” “Green HR,” and “Diversity in Indian workplaces” were searched using Google Scholar, Research Gate, and other academic databases. The sources were chosen carefully based on the following points:

1. Relevance: Sources that directly focused on HRM practices and Employee well-being were given priority.
2. Recency: Preference was given to studies published between 2015 and 2023, while also including older but important works that form the base of knowledge.
3. Credibility: Only peer-reviewed journals, official reports, and trusted institutional publications were included to make sure the data is reliable.

4.4 Data Analysis

The collected data were studied using thematic content analysis. Information from different sources was grouped into main themes such as:

- Sustainable HR practices: including Green HRM, ethical leadership, and Work–life balance.
- Inclusive HR practices: including Diversity, gender equity, disability inclusion, and psychological safety.
- Outcomes for Employee well-being: such as job satisfaction, employee engagement, retention, and mental health.
- Sectoral differences: covering fields like IT, manufacturing, and healthcare.



To make the findings clear, comparative tables were prepared to show common patterns across studies, pointing out both global trends and the Indian context.

4.5 Ethical Considerations

As this study is fully based on secondary data, there was no direct contact with human participants. Even so, ethical academic practice was carefully followed. All sources of information have been properly mentioned through correct referencing, and full care was taken to avoid plagiarism.

5. Discussion

5.1 Linking Sustainable HRM to Employee Well-being

The findings confirm that Sustainable HRM practices such as work–life balance initiatives, ethical leadership, and wellness programs are strongly connected to employee well-being. This relationship is consistent with Social Exchange Theory (SET), which posits that when organizations invest in the welfare of employees, the employees reciprocate by showing higher commitment, reduced turnover intentions, and stronger engagement.⁴ For instance, the adoption of flexible work policies in the Indian IT sector has helped to reduce stress and prevent burnout, thereby supporting the argument that employee well-being is not merely a social benefit but also a strategic outcome of Sustainable HRM.

From the perspective of the Resource-Based View (RBV), employee well-being can further be understood as a valuable and unique organizational resource. A healthy and motivated workforce enhances resilience, supports long-term productivity, and fosters innovation, thereby providing organizations with a competitive advantage that is difficult for rivals to replicate.^{3,6} In this way, Sustainable HRM strengthens both employee outcomes and organizational performance, demonstrating its dual role in advancing individual well-being and strategic growth.

5.2 Role of Inclusive HRM in Strengthening Engagement

The results indicate that Inclusive HRM practices, such as diversity hiring, gender equality initiatives, and measures to promote psychological safety, play a vital role in enhancing employee belongingness and engagement. This finding is consistent with the framework of inclusive workplaces, which emphasizes the importance of respect, fairness, and active participation in shaping positive employee experiences.^{10,11} When employees perceive that their voices are heard and their identities are valued, they are more likely to demonstrate higher levels of motivation and long term commitment.

In the Indian context, progress in inclusive practices is most visible within IT organizations, where structured diversity programs, anti-harassment policies, and gender equality initiatives have begun to create safer and more supportive environments. However, in traditional sectors such as manufacturing and healthcare, the persistence of structural barriers such as entrenched gender bias, inadequate representation of minority groups, and the absence of robust mental health policies continues to limit the effectiveness of inclusivity efforts.

At a global level, research has demonstrated that workplace inclusivity has a direct and positive impact on innovation, adaptability, and overall organizational performance.¹⁶ This suggests that for Indian firms to maintain competitiveness in an increasingly globalized market, they must intensify efforts to scale up Inclusive HRM practices across sectors. In doing so, organizations will not only strengthen employee well-being and engagement but also secure long term strategic advantages in innovation and talent retention.^{8,15}

5.3 Sectoral Comparison: Global vs Indian Trends

A sectoral comparison reveals both similarities and gaps between global and Indian trends in the adoption of Sustainable HRM and Inclusive HRM practices.

In the IT sector, Indian organizations show alignment with global practices by implementing flexible work arrangements, wellness initiatives, and diversity policies. These measures reflect a progressive approach toward employee well-being and inclusivity. However, unlike their global counterparts, Indian IT firms report higher levels of employee burnout, largely due to extended working hours, digital overload, and the cultural expectation of constant availability. This indicates that while structural policies exist, their implementation needs greater balance to truly support employee well-being.^{1,8}



In the manufacturing sector, Indian organizations remain behind global benchmarks. While manufacturing firms worldwide are increasingly adopting automation, advanced safety protocols, and structured inclusivity programs, Indian manufacturing continues to struggle with basic compliance issues, occupational safety, and limited emphasis on diversity and inclusion. The reliance on traditional management styles and cost-driven HR practices contributes to slower adoption of employee-centered policies, highlighting the need for structural reforms.¹¹

In the healthcare sector, global trends point toward the growing integration of wellness programs, resilience-building workshops, and psychological support systems for healthcare professionals, particularly in the aftermath of the COVID-19 pandemic. By contrast, evidence from India reveals that HRM practices in healthcare are still limited in their focus on staff well-being. High stress levels, long working hours, and inadequate organizational support contribute to elevated attrition rates among healthcare workers. This gap underscores the urgency for Indian healthcare institutions to strengthen HRM policies that prioritize both the mental and physical health of employees.¹²

Overall, while Indian sectors demonstrate progress in aligning with global trends, the pace and depth of adoption vary significantly, with IT being comparatively advanced, manufacturing lagging, and healthcare facing critical challenges that demand immediate attention.

5.4 Barriers to Implementation in India

Although Sustainable HRM and Inclusive HRM demonstrate clear benefits for employee well-being and organizational performance, several barriers continue to limit their widespread adoption across Indian industries.

Cultural biases remain one of the most persistent challenges. Deep-rooted gender norms and social stereotypes often slow the progress of inclusivity initiatives, particularly in traditional sectors such as manufacturing and healthcare. Despite formal policies promoting diversity and equality, unconscious biases and resistance to change at managerial and peer levels frequently undermine effective implementation.

Cost constraints also pose a significant barrier, especially for small and medium-sized enterprises (SMEs). Many organizations still perceive well-being programs, diversity initiatives, and sustainability measures as additional financial burdens rather than long-term investments that enhance employee productivity, engagement, and organizational reputation. This short-term cost-benefit outlook prevents the integration of holistic HR practices.

Another major issue is the policy-practice gap. While a growing number of Indian organizations have adopted sustainability and inclusivity policies, these often remain symbolic or compliance-driven, without being embedded into organizational culture and day-to-day practices. This disconnect creates a gap between formal commitments and employees' lived experiences, reducing the overall impact of such initiatives.

Finally, weak enforcement mechanisms further limit progress. Although labor laws, workplace safety regulations, and wellness-related mandates exist in India, their enforcement is often inconsistent. Limited monitoring and accountability at both organizational and governmental levels mean that many violations go unchecked, weakening the credibility and effectiveness of HRM reforms.

Together, these barriers highlight the structural, cultural, and regulatory challenges that must be addressed to ensure meaningful and sustained adoption of Sustainable HRM and Inclusive HRM practices in India.^{2,11}

5.5 Theoretical and Practical Implications

Theoretical Implications

The study contributes to the theoretical discourse on human resource management by reinforcing both Social Exchange Theory (SET) and the Resource-Based View (RBV).^{3,4} Consistent with SET, the findings demonstrate that when organizations invest in employee well-being through sustainable and inclusive HRM practices, employees reciprocate with higher commitment, stronger engagement, and reduced turnover intentions. From an RBV perspective, employee well-being emerges as a valuable and inimitable organizational resource that enhances resilience, innovation, and long-term competitiveness. Furthermore, by integrating Sustainable HRM and Inclusive HRM into the broader framework of strategic HRM, the study extends theoretical understanding in the context of emerging economies, such as India, where cultural, structural, and institutional barriers create unique challenges and opportunities.



Practical Implications

For practitioners, the findings highlight several actionable strategies. First, Indian organizations must begin to treat employee well-being as a strategic investment rather than a financial cost, recognizing its direct impact on productivity, retention, and organizational reputation. Second, inclusivity should be systematically embedded into HR processes including recruitment, training, leadership development, and performance management rather than being approached as an isolated initiative. Third, wellness programs need to be expanded beyond the IT sector to also cover manufacturing and healthcare, where employees face high stress, safety concerns, and limited organizational support. Finally, aligning HRM strategies with the United Nations Sustainable Development Goals (UN SDGs) can strengthen both organizational legitimacy and global competitiveness, positioning Indian firms as responsible and forward-looking employers in an increasingly globalized economy.¹⁶

6. Findings / Results

6.1 Overview of Findings

The review of secondary data shows that both Sustainable HRM and Inclusive HRM play an important role in improving Employee well-being across different sectors. Sustainable HR practices help in building long-term employee engagement and lowering stress levels through policies that are ethical and environment-friendly, such as Green HR and Work-life balance programs. On the other hand, Inclusive HR practices improve job satisfaction and psychological safety by promoting Diversity, equality, and fairness in the workplace. Together, these approaches not only support healthier and happier employees but also strengthen overall organizational performance.

At the same time, the study found that the level of adoption of these practices is not equal across sectors in India. The IT sector has been the most progressive in adopting both Sustainable HRM and Inclusive HRM, showing strong initiatives for Employee well-being. The manufacturing sector has been slower to change, with limited adoption of inclusive and sustainable practices. The healthcare sector shows pressing concerns, as employees face high levels of stress, burnout, and well-being challenges, which need urgent attention.

Table 1. Impact of Sustainable HR Practices on Employee Well-being (Secondary Evidence)

Sustainable HR Practice	Key Evidence from Literature	Impact on Employee Well-Being
Green HRM (paperless system, energy – saving , eco – friendly policies)	Ehnert et al. (2019) ⁵ ; Ahmad, S. (2015) ⁶	Enhance organisation reputation, improves employee pride and commitment
Work-life Balance Policies (flexible hours remote work)	Guest (2017) ⁷ , Delo (2022) ⁸	Reduce stress, improves mental health and lower burnout
Ethical leadership (fairness, transparency, accountability)	Bekhit et al. (2023) ⁹	Strengthens trust reduces turnover intentions.
Health & Wellness Program	NASSCOM (2023) ¹	Improves physical and mental well-being , increase productivity

Table 2. Impact of Inclusive HR Practices on Employee Well-being (Secondary Evidence)

Inclusive HR Practice	Key Evidence from Literature	Impact on Employers Well-Being
Diversity Hiring (gender, disability ,culture)	Shore et al. (2018) ¹⁰ ; Budhwar & Bhatnagar (2021) ¹¹	Boosts innovation enhances belongingness, reduce discrimination stress
Gender Equality Policies (equal pay, anti-harassment, maternity benefits)	ILO (2021) ¹² ; Srivestava et al. (2022) ²	Improves job satisfaction and retention of women employees



Impulsive Training & Sensitization	CII(2020) ¹³ ; Mckinsey (2021) ¹⁴	Increases awareness, creates supportive culture
Psychological safety Initiatives	Edmondson (2019) ¹⁵	Encourages open communication, reduces fear and anxiety

Table 3. Sectoral Insights from Secondary Data (India)

Sector	Key Challenges	Adoption of Sustainable & Inclusive HRM	Impact on Employee Well-being
IT: (NASSCOM, 2023; Srivastava et al., 2022) ^{1,2}	High attrition, long hours, digital burnout	Moderate- high (flexible work, wellness programs, D&I Policies)	Improves retention and work-life balance, but burnout remains an issue.
Manufacturing: (Budhwar & Bhatnagar, 2021) ¹¹	Worker safety, Rigid hierarchy, gender imbalance	Low-moderate (basic compliance, limited inclusivity)	Limited well-being improvements; safety and equality remain concerns.
Healthcare: (ILO, 2021) ¹²	Long shifts, stress, mental health burden	Low-adoption (Limited HRM focus on inclusivity/sustainability)	High stress and burnout; urgent need for HR based well-being programs.

6.2 Summary of Findings

The findings of the study highlight that Sustainable HR practices, including Green HR, ethical leadership, and wellness programs, exert a positive influence on employee well-being by improving organizational commitment and reducing stress levels. Such practices create a supportive and fair workplace environment, which not only strengthens long-term loyalty but also helps employees maintain a healthier work-life balance. By promoting responsible leadership and wellness initiatives, Sustainable HRM proves to be an effective tool for enhancing both individual and organizational outcomes.

Similarly, Inclusive HR practices, particularly diversity hiring, gender equality measures, and initiatives that promote psychological safety, contribute significantly to strengthening employee engagement and the sense of belongingness within the workplace. When employees feel respected and valued through Inclusive HRM, they are more likely to experience higher levels of motivation, satisfaction, and overall well-being, which directly benefits organizational performance.

The sectoral evidence from India further reveals that the adoption of both Sustainable HRM and Inclusive HRM is not uniform across industries. The IT sector appears to be the most progressive in implementing such practices, while the manufacturing sector continues to lag behind due to its reliance on traditional approaches. The healthcare sector, in particular, demonstrates critical risks to employee well-being, as high workloads and insufficient support systems continue to affect both physical and mental health outcomes for employees.

Despite the promising influence of these practices, the study also identifies clear gaps in translating policies into consistent workplace practices. In many traditional industries, policies related to Sustainable HRM and Inclusive HRM exist at a formal level but are not fully integrated into everyday organizational processes. This gap between policy and practice limits the overall effectiveness of employee well-being initiatives and calls for stronger efforts to ensure that such practices are meaningfully applied across all sectors in India.



7. Recommendations

Based on the synthesis of secondary data, the following recommendations are proposed:

1. Institutionalize Well-being Programs: Organizations should move beyond ad hoc wellness initiatives and embed well-being into HR strategies through regular health audits, mental health support, and flexible work policies.
2. Strengthen Inclusivity: Companies must adopt systematic diversity policies, ensure gender equity in pay and promotions, and provide sensitization training to reduce unconscious bias.
3. Sector-Specific Approaches:
 - IT: Focus on reducing digital overload and preventing burnout through workload management.
 - Manufacturing: Prioritize worker safety, fair labor practices, and gender inclusivity.
 - Healthcare: Provide psychological support, reduce excessive workloads, and invest in staff welfare.
4. Policy–Practice Alignment: Indian organizations should go beyond symbolic compliance by integrating sustainability and inclusivity into daily operations, supported by measurable indicators.
5. Global Alignment: Align HRM strategies with the UN SDGs (SDG 3: Good Health, SDG 5: Gender Equality, SDG 8: Decent Work) to strengthen both social impact and international competitiveness.
6. Future Research: More sector-specific studies using mixed methods (secondary + primary) should be conducted to explore contextual barriers and success factors in adopting sustainable and inclusive HR practices in India.¹⁵

8. Conclusion

This study, drawing on secondary data, examined the role of Sustainable HRM and Inclusive HRM practices in promoting employee well-being within Indian organizations. The findings suggest that Sustainable HRM through Green HRM initiatives, ethical leadership, and wellness programs plays a critical role in reducing stress, strengthening organizational commitment, and fostering higher levels of engagement. Likewise, Inclusive HRM practices centered on diversity hiring, gender equality, and psychological safety enhance fairness, belongingness, and innovation, thereby supporting both individual well-being and organizational effectiveness.

Sectoral analysis revealed important differences in adoption. The IT sector has demonstrated notable progress by integrating wellness and inclusivity into HR strategies, though high levels of burnout remain a concern due to extended working hours and digital overload. In contrast, the manufacturing sector continues to lag, with efforts often limited to compliance rather than strategic integration. The healthcare sector faces the most pressing challenges, as employees encounter high stress, weak mental health support, and limited HRM interventions. When compared with global benchmarks, India's progress appears uneven, hindered by cultural barriers, cost constraints, and weak enforcement of labor and wellness-related policies.

From a theoretical perspective, the study reinforces Social Exchange Theory by showing that organizational investments in well-being foster reciprocal gains in employee commitment, engagement, and retention. It also extends the Resource-Based View by framing employee well-being as a rare and valuable resource that strengthens resilience, promotes innovation, and provides organizations with sustainable competitive advantage.

REFERENCES

1. NASSCOM. (2023). Workplace wellness report: Building healthier organizations in India. National Association of Software and Service Companies. <https://nasscom.in>
2. Srivastava, S., Agarwal, P., & Singh, R. (2022). Gender equality practices and women's career advancement in India: Evidence from the service sector. *Gender in Management: An International Journal*, 37(5), 593–610.
3. Barney, J. (1991). Firm resources and sustained competitive advantage. *Journal of Management*, 17(1), 99–120. <https://doi.org/10.1177/014920639101700108>



4. Blau, P. M. (1964). Exchange and power in social life. New York, NY: Wiley.
5. Ehnert, I., Parsa, S., Roper, I., Wagner, M., & Müller-Camen, M. (2016). Reporting on sustainability and HRM: A comparative study of sustainability reporting practices by the world's largest companies. *The International Journal of Human Resource Management*, 27(1), 88–108. <https://doi.org/10.1080/09585192.2015.1024157>
6. Ahmad, S. (2015). Green human resource management: Policies and practices. *Cogent Business & Management*, 2(1), 1030817. <https://doi.org/10.1080/23311975.2015.1030817>
7. Guest, D. E. (2017). Human resource management and employee well-being: Towards a new analytic framework. *Human Resource Management Journal*, 27(1), 22–38. <https://doi.org/10.1111/1748-8583.12139>
8. Deloitte US. (2022). Advancing workplace well-being. <https://www.deloitte.com/us/en/insights/topics/talent/workplace-well-being-research.html>
9. Bekhit, K. E., El Leithy, W., & Mahmoud, A. (2023). The impact of green human resource management practices on employee retention and environmental sustainability: A conceptual model. ResearchGate. https://www.researchgate.net/publication/367326510_The_Impact_of_Green_Human_Resource_Management_Practices_on_Employee_Retention_and_Environmental_Sustainability_A_Conceptual_Model
10. Shore, L. M., Cleveland, J. N., & Sanchez, D. (2018). Inclusive workplaces: A review and model. *Human Resource Management Review*, 28(2), 176–189. <https://doi.org/10.1016/j.hrmr.2017.07.003>
11. Budhwar, P. S., & Bhatnagar, J. (2021). The changing face of people management in India. Routledge
12. International Labour Organization (ILO). (2021). World employment and social outlook: The role of women at work. ILO. <https://www.ilo.org>
13. Confederation of Indian Industry (CII). (2020). Fostering inclusion: Diversity and inclusion practices in Indian industry. <https://cii.in>
14. McKinsey & Company. (2021). Diversity wins: How inclusion matters. <https://www.mckinsey.com>
15. Edmondson, A. C. (2019). The fearless organization: Creating psychological safety in the workplace for learning, innovation, and growth. Wiley
16. United Nations. (2015). Transforming our world: The 2030 Agenda for Sustainable Development. United Nations. <https://sdgs.un.org/2030agenda>



DOIs:10.2015/IJIRMF/ICICSF-2025-P05

--:--

Research Paper / Article / Review

International Conference On “Innovative Convergence for Sustainable Future”

Date : 12 - 13 December, 2025

(ICICSF-2025)



Motivation Matters: A Comprehensive Analysis of its Influence on Workmen's Performance in the Manufacturing Sector

¹Ashish Chopra, Research Scholar, Dept of management
Jharkhand Rai University, Ranchi

²Dr. Anusha Priya, Associate professor, Dept of management, Jharkhand Rai University, Ranchi

Corresponding Author: Ashish Chopra

Mail id: chopraashish3004@gmail.com

ABSTRACT: Academics and manufacturing firms have been interested in research on workmen's motivation recently. The current work has identified potential motivational characteristics and explained how they affect motivational tactics both directly and indirectly. This study has looked at the many facets of motivation from the existing literature, presenting a conceptual framework based on it and explaining different motivational strategies that improve life quality, employee performance in the workplace, and workmen's satisfaction at work. This study is unique because of its theoretical framework, which aims to develop a construct of nature with features that either directly or indirectly affect workmen's motivation. A few motivational factors were employed in earlier research studies to explain the many motivation theory models, which have an immediate effect on workmen's motivation within manufacturing firms. Nonetheless, quantifiable metrics must be used to validate the models. Only research on motivation that was published in the recent few years was included to increase the study's relevance. To investigate the diverse aspects of employee motivation, a substantial amount of literature has been gathered, primarily from books and journals written by various authors.

KEYWORDS: Motivational dimensions, employee motivation, employee performance, motivation strategies, and motivation theories

1.INTRODUCTION

All sorts of workers' perspectives of motivation are rapidly shifting globally in response to several important factors. The traditional intrinsic or extrinsic reinforcement reinforcing

strategies are progressively becoming less significant. Particular motivators change with the passage of time and place.

Motivation serves as a catalyst for all individual workmen working for a manufacturing firm to improve their working performance or to finish tasks in a much better way than they typically do. It also has a direct correlation to individual performance, which gains to manufacturing company performance. People who work for an organization are what keep it going, and each employee makes a contribution to the organization's overall objective. According to Panagiotakopoulos, factors influencing employee motivation during a time when financial rewards are kept to a minimum stimulate employee performance.

Management personnel are responsible for inspiring their staff to work in accordance with expectations in order to improve the performance of the organization. According to Dysvik and Kuvaas, the only employees with a positive correlation between turnover intention and mastery approach goals were those with low levels of intrinsic



motivation. Furthermore, they found that intrinsic motivation was the biggest predictor of turnover intention. The organization's main responsibility is to provide workers with sufficient tools and a platform to do so.

According to Kuo, to demonstrate the worth of the company, a successful organization must bring together the motivations and strengths of its workforce as well as quickly adapt to changes and requests from outside sources. Using a variety of motivational strategies from the body of current knowledge, we were able to create a flow of motivation from younger to older employees in this paper. From an organizational standpoint, managers must comprehend the motivational flow to foster a culture where workers are always inspired to perform better.

Barney and Steven Elias: They discovered that there is a substantial connection between the nation of residency, flex time, and job stress when there is intrinsic motivation. Leaders understand that a strong corporate culture and dedicated employees working together to achieve excellent results are at the core of any successful and profitable firm. Researchers employ a variety of theory-based frameworks in the literature, focusing on a limited number of motivational variables.

2.LITERATURE REVIEW

Developing an environment where people are eager to give their all is one of management's most crucial responsibilities. Thus, a leader's responsibility is to spark interest in how well workers perform in their positions. In a complex and dynamic work environment, the manufacturing organization's leader used to foster an atmosphere where workers feel trusted and empowered to make decisions, which raises workmen's motivation and, ultimately, improves manufacturing firm performance. Among the first theorists to try to comprehend employee motivation was Fredrick W. Taylor. His scientific management philosophy, typically known as Taylorism, examines worker productivity.

According to Taylor's fundamental theory of motivation, wages drive employees. His philosophy emphasizes that the best ways to inspire people are to give them specific duties, provide them with the greatest tools, and pay them based on their output. He saw employees not as individuals, but as parts of a greater workforce. Taylor's theory was created in the late 1890s and is being used in the manufacturing and industrial engineering sectors. Another theorist, Elton Mayo, started researching the labor force in the middle of the 1920s. He discovered the Hawthorne effect as a result of his research of the Hawthorne Works. The theory known as the Hawthorne effect holds that people alter their behavior in response to being watched.

Mayo discovered that when workers were aware they were being observed, their output went up. Additionally, he discovered that when workers felt valued and had the opportunity to provide feedback on their working conditions, their motivation increased. According to Smith and Rupp, resistance to change, organizational strategy, and individual

Motivation plays an empirical part in performance when it comes to motivation within the company.

In the same way, the development of human resources through awards, financial incentives, and organizational behavior modification has led to a great deal of discussion in the fields of sales performance and human resources. According to Orpen, mentees are more driven to work hard and dedicated to their company when there is a stronger bond between mentors and mentees in the official mentoring program.

Similarly, Malina and Selto used the balanced scorecard (BSC) approach to perform a case study in a corporate context and discovered that positive motivation for employees will lead to better organizational outcomes (2001).

The creation of operations-based targets will facilitate the delivery of strategic feedback by enabling the comparison of actual performance with the targets. It is anticipated that goal-directed behavior and strategic feedback would improve organizational performance. According to Kunz and Pfaff (2002), there is no compelling reason to worry that extrinsic rewards may undermine intrinsic drive.

In their study, Decoene and Bruggeman created and demonstrated a model of the relationship between motivation, organizational performance, and strategic alignment in a BSC setting. They discovered that working executives are empowered and motivated by effective strategic alignment (2006).

People are motivated by leaders to adopt a participative work design where they are accountable for their performance and are expected to take initiative. Financial incentives have the potential to be a very strong predictor



of worker motivation and output. To motivate employees' performance, Garg and Rastogi highlighted the important difficulties in job design research and practice. They concluded that improving employee performance is necessary to face global challenges and that this may be achieved with the help of a dynamic managerial learning framework.

Motivation, according to Vuori and Okkonen (2012), facilitates information sharing within an organization via an intra-organizational social media platform, assisting the organization in achieving its goals and objectives. High-performing work systems, also known as human resource practices, have been found to have an effect on perceptual measures of firm performance by Den & Verburg (2004).

According to Ashmos and Duchon (2000), workers are motivated to perform at a high level with an eye toward social and personal development because they have a mind and a spirit and look for meaning and purpose in their work as well as a desire to be a part of a community.

3.METHODOLOGY

This review's main goal is to draw attention to the motivational flow and identify the motivational strategies that are most effective at various phases of life. This study has helpful managerial implications for an organization's employee motivation. The dimensions are fitted into a model that can help organizations perform better; yet, the model needs to be validated using a quantitative or case study. This study examines a substantial amount of literature, mostly from multiple journals, to investigate the numerous employee motivation-related difficulties brought to light in this research. Following the identification of every issue, a keyword search of the pertinent literature is conducted using each issue. Only papers that have been published in the past are included in the analysis to keep it more up-to-date. The number of papers or reviews published during 2000-2019 is displayed in Table 1.

Year	No. of articles or reviews published on motivation	% Increase in publication
2000	3412	7.05
2001	3580	4.92
2002	3995	11.59
2003	4643	16.22
2004	5125	10.38
2005	5878	14.63
2006	6429	9.37
2007	6943	7.99
2008	7585	9.24
2009	8501	2.07
2010	9173	7.90
2011	9861	7.90
2012	10679	8.29
2013	11858	9.26
2014	11924	10.01
2015	12001	9.59
2016	12258	7.98
2017	12732	5.89
2018	13231	4.46
2019	13256	2.98

Table 1: Article or review published on motivation

4. DIMENSIONS OF MOTIVATION

Training: "The systematic accumulation of skills, command, concepts, or mindset leads to improved performance"



is what is meant by training. (Bombelli and Lazzara, 2011). According to Baldwin et al. (1991), those who are more motivated before training based on their willingness to attend training have better learning outcomes than people who are less motivated before training. According to Commeiras et al. (2013), the number of traineeships is still rising. Context training in business essentially refers to the process of educating staff members and equipping them with the necessary information and abilities to fit both their jobs and the firm. Employees who receive training learn how to work and develop their talents, which inspires them to accomplish the organization and their own shared goals. In the cutthroat world of today, every business seeks to gain a competitive advantage over rivals, which is hard to do without employee involvement. As a result, management is forced to find new ways to inspire staff members.

Monetary incentives:

According to Park (2010), financial incentives assist employees in recognizing their accomplishments and catalyze increased action. They also instill a zest and excitement for their work. Similarly, Bertetti et al. (2013) talked about how financial incentives can be utilized to create a happy work atmosphere, keep individuals interested in their jobs, and inspire them to perform better. For this reason, financial incentives spur workers to greater dedication in their work, psychologically fulfill individuals' results in job satisfaction, and mold subordinates' attitudes or behaviors toward their jobs inside the company.

Job transfer:

According to Azizi and Liang's (2013) research, job rotation and cross-training are effective ways to increase workforce flexibility. Similarly, Eguchi (2004) concluded that changing jobs significantly hinders employees from engaging in influence work for outside parties. AsensioCuesta et al. (2012) summarize job rotation benefits employees and management in an organization by reducing the risk of musculoskeletal ailments, reducing weariness, and boosting morale and job satisfaction. Consequently, people who shift jobs have the chance to acquire new perspectives and skill sets. With the aid of managing various situations at various levels, it prevents the boredom brought on by repetitive tasks and concurrently brings smoothness to technical activities. It also facilitates effective learning of numerous organizational features.

Job satisfaction:

(2011) Parvin and Kabir conducted a study on the characteristics that were found to be significant in influencing job satisfaction for pharmaceutical firms. They defined job satisfaction as an individual's level of contentment with their job and concluded that, while they are related, job satisfaction and motivation are not the same. In a similar vein, Pantouvakis and Bouranta (2013) suggested that physical characteristics and interaction elements both precede and contribute to job satisfaction.

Wickramasinghe (2009) looked into the significance of tenure and gender in the measurement of work satisfaction. Thus, it may be concluded that performance often meets or exceeds expectations, which in turn determines job happiness. For instance, favorable working circumstances and an environment can boost job satisfaction among employees, and motivated workers will strive to perform at their highest level.

Promotion:

According to a study by Garcı 'a et al. (2012), work satisfaction and organizational fairness are impacted by people's opinions of promotion processes. Similarly, Koch and Nafziger (2012) noted that most workers want promotions since it makes them put in more effort to make up for their "incompetence." Because of this, promotions are given out periodically with an optimistic outlook and are typically offered to employees to meet their psychological needs.

Achievement:

According to the research of Hunter et al. (2012), achievement is a distinct and specialized type of organizational performance. According to Satyawadi and Ghosh (2012), achievement and self-control drive workers more than other factors. It is now clear that an employee who is accomplishment motivated strives for improvement in their



work environment and reasonable yet demanding goals. Higher-ranking personnel in the organization must provide feedback on accomplishments and advancements, and there must be a sense of accomplishment.

Working conditions:

Good work environments and circumstances have been shown to boost employee job satisfaction and organizational commitment (Jung and Kim, 2012). As a result, workers will strive to offer their all, which may improve worker performance. Cheng and colleagues (2013) also concluded that there was evidence of age-related moderating effects on the relationships between psychosocial work conditions and health. These days, the necessity and significance of working conditions are so great that the physical surroundings are defined or described by them. Because the tasks require a lot of mental and physical effort, those who work in unfavourable environments will only perform poorly.

Appreciation

According to a study by Mahazril et al. (2012), employers have a responsibility to show their appreciation for their staff members on occasion and provide them with additional perks like compensation, which will boost their motivation. Similar to how Kingira and Mescib (2010) describe appreciation, employees do not agree with this behavioral statement, as evidenced by the fact that "employees giving immaterial incentives (appreciation, respect, etc.) as much as material incentives with the working department" Based on this finding, it can be said that workers with varying positions can accept differing viewpoints to varying degrees. It is acknowledged that among the variables of accountability and appreciation, "employer success is always appreciated with education."

Employees will contribute more to firms if their education is of a higher caliber and is more useful.

Job security

According to Yamamoto (2013), an employee's performance will immediately improve if they believe they will be rewarded for their hard work and that their employment is secure. In a similar vein, Zhang and Wu (2004) found that when job security is present, employees become more optimistic about their future careers and give their all to meet the goals of the company. Thus, it can be concluded that job happiness is the most powerful motivator because it keeps workers mentally relaxed and encourages them to give their all to the company, which eventually results in profit maximization.

Recognition

Experience staging is helping people realize more and more about the potential for innovation, claim Candi et al. (2013). According to Mahazril et al. (2012), incentives like praise, acknowledgment, and communication could spur employees to perform more. Whether an employee is being recognized for the first time or recurring actions, recognition raises productivity and performance levels and eventually reinforces the employee's behavior.

Social opportunities

Harvey (2013) stated that a worker is welcomed into the team or social group. The majority of employees have a strong desire for their contributions to be valued, recognized, and acknowledged. Companies must consider various social and lifestyle aspects outside of the office in addition to the conventional financial incentives of job prospects and pay. According to Kingira and Mescib (2010), there are variations in the attitudes held by employees about behavioral claims. For example, some employees believe that "social opportunities provided at the highest level with working period leads the employee to achieve their goals of the organization." Thus, a social opportunity for the staff member is utilized to increase their level of motivation, which in turn aids in accomplishing the organization's goals and objectives.

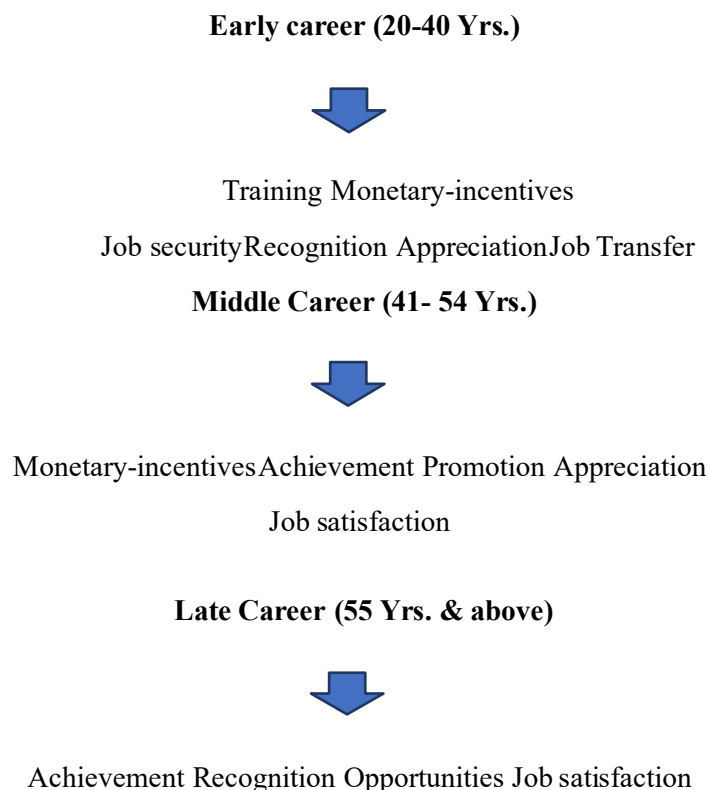


Figure 1: Flow of motivation

Figure 1 describes how motivation functions at various periods of life.

The motivation dimension is important for improving an individual's performance at various times of a person's life. People experiencing the phenomena of population aging, or the low participation rate of workers in their late career stage in the labor market, are found in both developed and developing countries worldwide. According to Levinson's (1986) life stage model, which is analogous to Super's (1984) career stage model, adult life is characterized by a succession of stages, including the early, middle, and late career stages, each of which is further subdivided into sub-stages and focused with career development. Money plays a significant role in goal setting during the early and middle stages of life since providing incentives makes people more inclined to increase their efforts to reach a particular target level than not providing incentives. A goal, given the willingness to put in more effort, instructs the person at various stages of their career on where to put in more work, how much effort to put in, and how long to put in the effort. Younger workers at the beginning of their careers, for instance, might be more likely to receive higher immediate compensation and benefits, like fully paid family medical plans or maternity/paternity leaves, whereas workers later in their careers might prefer stock options or the majority of the company's contribution to their retirement plans. Wiley (1997) concluded that, regardless of age, a good wage is a significant motivation.

The impact of motivation aspects on individual and organizational performance is seen in Figure 2. Organizations strive harder in this competitive climate to maintain employee.

Coordination and workforce integration to improve working conditions and productivity.

The beneficial effects of motivation contribute to raising each person's level of responsiveness at work. Improved individual responsiveness contributes to organizational performance, which is directly related to higher profits and more responsiveness from the organization. Customer satisfaction will increase if the business responds to their inquiries promptly and assumes accountability for meeting their needs.

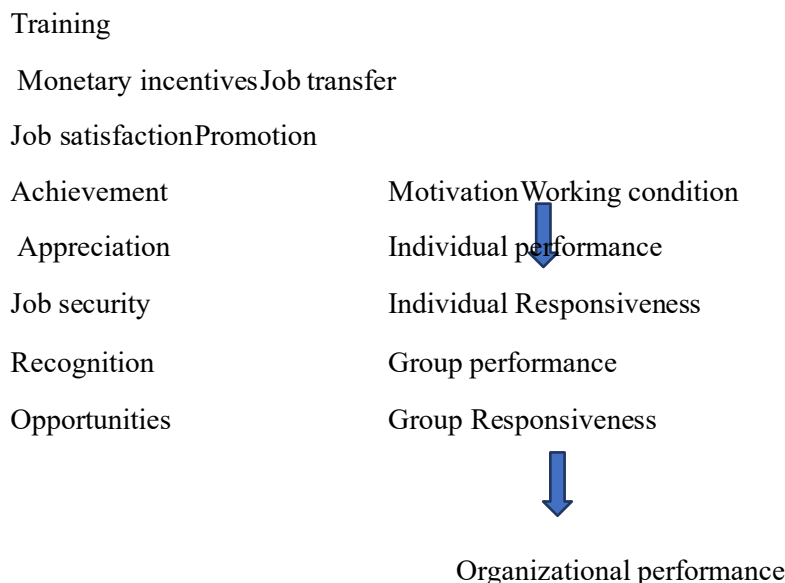


Fig. 2 Theoretical construct of research dimensions

If we talk about the motivation factor that improves an organization's performance, training is used to improve workers' abilities, productivity, and knowledge for carrying out a specific task during their early career stage because it acquaints them with the organization's objectives, policies, and working conditions on the one hand, since technological advancements, new equipment purchases, adjustments to production techniques, and computer instruction take place. The staff members receive training on new tools and techniques.

Training shapes workers' perspectives and produces high-caliber work output. Supervisors think that older employees are less flexible, less eager to learn, and less inclined to participate in training initiatives. Thus, businesses don't spend money on senior citizen development or training programs. Consequently, older professionals experience a decline.

In self-assurance as a result of inadequate training support, their abilities quickly become outdated (Maurer 2001; Van Vianen et al. 2011).

When a worker has job security, he becomes more responsible for his work. The concept of job security can be defined as an employee's confidence in the continuation of their lucrative employment. It is especially important for younger workers at different stages of their careers because it is derived from employment contracts and labor laws that forbid lockouts, layoffs, and arbitrary terminations. Similarly, Pravin and Kabir (2011) found that employees in pharmaceutical businesses who have job security are "neither happy nor unhappy," which has an impact on job satisfaction in these companies. From several theoretical angles, work security has been examined, including as a motivating factor that precedes job success.

The purpose of employee recognition is to satisfy the innate urge to be valued and to have one's contributions validated. Recognizing positive behavior from employees is a crucial tool for motivating them both in their early and older years. It ensures that the desirable behaviors that drive business success will be returned. An exceptional workplace must provide recognition because employees want to feel appreciated and valued for their contributions. Acknowledging an employee for their hard work through official and informal channels of communication conveys a very strong message to the recipient, their team, and other employees. A dynamic communication strategy for raising employee performance, which in turn raises corporate performance, is employee recognition.

A business must show its employees that they are respected and appreciated, as this will drive them to work more and show greater loyalty to the company. Employees who are in their early to mid-career stages of employment expect greater recognition from their future employers. There are a lot of ways to thank employees these days, especially for small businesses looking for low-cost ways to recognize staff members who went above and beyond. Thanking staff members multiple times, a week, usually by sending notes to their homes, and implementing an



employee-of-the-month program is the least time-consuming way to ensure that staff members feel valued.

If an employee wishes to change jobs or is transferring, they have the option to transfer to another position inside the company. Working in a new workplace opens up fresh opportunities for skill and perspective acquisition, which instills optimistic energy in early career-stage employees. Long-term employment at the same place increases the likelihood that employees will form close bonds with certain people and businesses, which will benefit both the company and the employees.

Early on in their careers, they used to look for information on the terms and circumstances of employment as well as the working environment. This covers the salary of the employee, how the work is organized and carried out, training, employability, and skills; facilities, the physical surroundings, health, safety, and well-being; working hours, and work-life balance. These are meant to inspire workers to perform better and meet the aims and objectives of the company. Serious industrial relations issues might arise from modifications to working conditions and other facets of the job relationship.

According to Williams et al. (2003), job satisfaction contributes to strong working relationships with co-workers and staff, control over vacation time, adequate resources, and the introduction of employee autonomy inside the company. Physiological and psychological satisfaction is a crucial factor in all stages of employment, including early, middle, and late career stages. It elicits a genuine sense of contentment with one's current job and motivates employees to strive toward the organization's objectives. To be satisfied with one's work, one must enjoy what they do and receive recognition for their efforts. It is the essential component that results in acknowledgment, money, advancement, and the accomplishment of additional objectives that result in a sense of reaching the intended aims and objectives. (Kaliski, 2007)

Employees have the chance to proudly display their accomplishments in the middle and end of their careers. Workers at the company labor for more than simply a paycheck; they work for life. It promotes increased accountability at work. To engage employees and inspire them to perform to the best of their abilities, employers must provide both physical rewards like income and intangible benefits like knowledge advancements and other perks. According to Mehta et al. (2000), the four top-ranked incentives for sales managers in the later stages of their careers—achieving market targets, earning salespeople's esteem, having prospects for advancement, and receiving a bonus—have mean values of more than 6.0.

An organization can benefit from having a driven and committed employee in the middle of their career who is also essential in creating a high-performance culture that propels the organization forward. An employee's greatest desire for the services they provide to the company is always to be promoted, as this is the sole path to professional advancement. For every employee, promotion is the greatest source of motivation since it increases grade salary and benefits, gives them more responsibility, and elevates them in the organization's hierarchy. On the one hand, it reduces dissatisfaction and unrest while promoting self-development and job interest.

Social opportunities for workers to participate in leveraging the organization's core competencies to create business value and positive social change during their late career stage of employment can boost job satisfaction and employee motivation while also assisting workers in better managing stress at work. The organization may benefit from this in several ways, including increased organizational effectiveness, higher-quality work, and the ability to draw and retain top talent. These factors can help organizations grow and develop, as well as better understand the advantages of helping employees reach their full potential and improve the quality of their work experience.

5. CONCLUSION

Employee motivation acts as a catalyst, enabling each person to perform at a higher level or finish a task far more effectively than they would otherwise. The writers of this research related the important motivational strategies through organizational performance, identifying them from the body of existing knowledge. These motivational strategies have long been recognized as crucial personnel practices with the ability to raise employees.

Morale and, consequently, productivity, as well as provide management with the authority required to meet organizational goals. As the majority of the motivational factors—training, financial incentives, promotions, and working conditions—have been addressed, it is clear from the explanation above that motivational efforts will inevitably be successful. This conclusion builds on the focus that previous academics placed on the necessity for businesses to establish a baseline before they can encourage people. Without the baseline, motivation is impossible



to attain. The study has demonstrated the effectiveness of both extrinsic and intrinsic motivators in raising organizational performance.

6.LIMITATION

This study's main drawback is that the suggested framework was created based on a thorough literature analysis, necessitating quantitative measures of confirmation. Because this framework is so general, it hasn't been applied to any particular industry. While a great deal of research has been evaluated and every conceivable aspect of motivation has been examined, it cannot be said with certainty that these aspects will be able to establish the baseline that will inspire employees through their motivators. They thus raise the question of whether these motivational factors are sufficient to establish a strong baseline that influences the motivators.

REFERENCES

1. Kenneth W. Thomas (April 13, 2009) *Intrinsic Motivation at Work: What Drives Employee Engagement* 2nd Edition, Kindle Edition.
2. Judy Cameron, W. David Pierce. Bergin & Garvey (2002) *Rewards and Intrinsic Motivation: Resolving the Controversy*.
3. Doug Jensen, Tom McMullen, Mel Stark. American Management Association (2007) *The Manager's Guide to Rewards: What You Need to Know to Get the Best For--And From--Your Employees*. John Eric Adair; Neil Thomas Thorogood (2004).
4. The Concise Adair on Teambuilding and Motivation. Basford, Tessa E.; Offermann, Lynn R. *Journal of Management and Organization*, (November 2012). *Beyond Leadership: The Impact of Co-worker Relationships on Employee Motivation and Intent to Stay*.
5. Richmond, F. Lynn; Schepman, Stephen *Journal of Organizational Culture, Communications and Conflict*, July 2005. *Fifty Years of Employee Motivation Surveys: Three from the Final Half of the Twentieth Century*.
6. Carleton, Karen *International Journal of Management*, (June 2011). *How to Motivate and Retain Knowledge Workers in Organizations: A Review of the Literature*
7. Ashmos, D. P., & Duchon, D. (2000). *Spirituality at work: A conceptualization and measure*. *Journal of Management Inquiry*.
8. Azizi, N., & Liang, M. (2013). *An integrated approach to worker assignment, workforce flexibility acquisition, and task rotation*. *Journal of the Operational Research Society*.
9. Barton, L. C., & Ambrosini, V. (2013). *The moderating effect of organizational change cynicism on middle manager strategy commitment*. *International Journal of Human Resource Management*
10. Casad, S. (2012). *Implications of job rotation literature for performance improvement practitioners*. *Performance Improvement Quarterly*.
11. Cheng, A., & Brown, A. (1998). *HRM strategies and labor turnover in the hotel industry: A comparative study of Australia and Singapore*. *International journal of human resource management*.
12. Chenhall, R. H. (2005). *Integrative strategic performance measurement systems, strategic alignment of manufacturing, learning, and strategic outcomes: An exploratory study*. *Accounting, Organizations, and Society*.
13. Chiaburu, D. S., & Tekleab, A. G. (2005). *Individual and contextual influences on multiple dimensions of training effectiveness*. *Journal of European Industrial Training*.
14. Clark, C. S., Dobbins, G. H., & Ladd, R. T. (1993). *Exploratory field study of training motivation: Influence of involvement, credibility, and transfer climate*. *Group Organization Management*.
15. Colquitt, J. A., LePine, J. A., & Noe, R. A. (2000). *Toward an integrative theory of training motivation: A meta-analytic path analysis of 20 years of research*. *Journal of Applied Psychology*.
16. Den, H. D. N., & Verburg, R. M. (2004). *High-performance work systems, organizational culture, and firm performance*. *Human Resource Management Journal*.
17. Garcí'a, I. A. L., Moscoso, S., & Ramos, V. P. J. (2012). *Reactions to the Fairness of Promotion Methods: Procedural justice and job satisfaction*. *International Journal of Selection and Assessment*.
18. Swift, P. E., & Hwang, A. (2013). *The impact of affective and cognitive trust on knowledge sharing and organizational learning*. *Learning Organization*. Wiley, C. (1997). *What motivates employees according to over 40 years of motivation surveys*. *International Journal of Manpower*.
19. Williams, H. (2013). *Achieving supply chain utopia: Companies need to prioritize investing in people*. *Development and Learning in Organizations*.
20. Williams, E. S., Konrad, T. R., Linzer, M., McMurray, J., Pathman, D. E., Gerrity, M., et al. (2003). *Refining the measurement of physician job satisfaction: Results from the physician work-life survey*.



Modeling of a Double-Pipe Heat Exchanger Using Different Controllers in MATLAB/Simulink

¹ Babita Kumari, ² Md. Sami and ³ Nirupama

¹ Department of Chemical Engineering, B.I.T. Sindri, Dhanbad, Jharkhand, India, 828123.

² Department of Chemical Engineering, B.I.T. Sindri, Dhanbad, Jharkhand, India, 828123.

³ Professor Department of Chemical Engineering B.I.T. Sindri, Dhanbad, Jharkhand, India, 828123

Email - : kumaribabita161097@gmail.com ,

Abstract: This paper evaluates the design and analysis of control strategies for a double-pipe heat exchanger system, where temperature controls can have an impact on the performance and safety of the industrial process. The Proportional (P), Proportional-Integral (PI), Proportional Derivative (PD), and Proportional-Integral-Derivative (PID) controllers were designed and then tuned through either the Ziegler-Nichols method or manual tuning. We undertook a thorough assessment of all four controller designs in MATLAB/Simulink using different input forms: step signal, ramp signal, sinusoidal signal, and impulse signal, that evaluates setpoint tracking and disturbance rejection. Overall, even though P/PD controllers experienced steady state error and a PI controller showed oscillatory response, the PID controller demonstrated a better balance of both at the output. The PID controller exhibited no steady state error, with the smallest peak overshoot (25%), with a fast and stable output response. We conclude that the PID controller is the most robust and effective strategy for this application.

Keywords : Double-Pipe Heat Exchanger, PID Control, FOPDT, Ziegler-Nichols, Simulink, Process Control.

1. INTRODUCTION :

Heat exchangers are essential devices in a wide range of industrial and engineering applications including chemical processing, power generation, food production, and HVAC systems [1]. Their main purpose is to transfer thermal energy between two or more fluids, which can be at different temperatures [2]. The double-pipe heat exchanger is recognized for its structural simplicity and efficiency when used in high pressure or low flow rate applications [3].

Precise process control is important for these systems in order to operate efficiently and safely [1]. To achieve a desired outlet temperature in a heat exchanger, the dynamic behaviour of the heat exchanger must be thoroughly understood so that optimal performance is maintained regardless of process variations. This paper focuses on the dynamic modeling and control of a counter-current doublepipe heat exchanger. Using the derived transfer function as a First Order Plus Dead Time (FOPDT) model from [2]. The derived model serves as the basis for the design and simulations for P, PI, PD and PID control schemes to control the cold-water outlet temperature [1].

The PID control action is an accumulation of three action, which corresponds to how it responds presently to an error(current error) with respect to a proportional (P) action, how it eliminates the steady state error(offset) with respect to the integral (I) action, and how it dampens error in the future by anticipating speed in error with respect to the derivative (D) action [4]. The parametric controllers were defined using the Ziegler-Nichols tuning method [4], [5]. The entire control system was simulated in



MATLAB/Simulink, in order to thoroughly rank the robustness and tracking performance of each controller using step, ramp, sinusoidal, and impulse input signals [2], [6]. The ranked robustness and tracking of the performance variables will allow us to identify the most effective control approach for this situation.

2. LITERATURE REVIEW:

Asoka, et al. 2017 [2] have developed Specific Modeling Techniques for How to Model Complex System Dynamics. Utilising RealTime Data, they have developed models for double-pipe heat exchangers using dynamic simulation.

Mazumder and Mandal, 2016 [3] have created numerical simulation models for double-tube heat exchangers based on their black box modelling technique. Together, the studies indicate that computational modelling provides a valid alternative to experimentation when designing control systems.

In addition to Ziegler and Nichols' work, Seborg, et al. 2016 [4] have provided a comprehensive reference for the understanding and analysis of process dynamics and a theoretical basis for developing modern control systems.

In recent years there has been an increased reliance on simulations to help verify the theoretical models developed. For example, Srivastava, et al. 2014[6] performed a study using MATLAB to simulate a system for controlling temperature within a heat exchanger, and proved that simulated systems perform in a manner consistent with the physical systems that they simulate.

The most widely used controller in the world is the Proportional-IntegralDerivative (PID) controller. They have been around for many years and have been proven to be effective at controlling processes in both simple and complex applications. The fact that PID controllers are easy to use and reliable makes them an attractive choice for many industries. In addition, Darure has shown that advanced control methods can accomplish similar results to those obtained with PID controllers when applied to a boiler and heat exchanger pilot plant [8]

To achieve an effective control design for a system, it is crucial to accurately represent the mathematical model of the physical system being controlled. This has been established through empirical tuning methods developed by Ziegler and Nichols, 1942 [5], which are still widely used today as benchmarks in the development of new tuning strategies

3. OBJECTIVES / AIMS:

AIM

The principal aim of this research is to design, tune, and analyze the performance of classical controllers for temperature control in a double-pipe heat exchanger using MATLAB/Simulink R2025a. The specific objectives of this study are:

OBJECTIVE

The objectives are as follows:

- To develop a dynamic simulation model of a double-pipe heat exchanger using the First Order Plus Dead Time (FOPDT) representation.
- To design and implement P, PI, PD, and PID controllers for closedloop temperature control.
- To tune controller parameters using Ziegler Nichols closed-loop tuning rules and improve response through manual adjustments.
- To evaluate system performance under various test inputs — step, ramp, sinusoidal, and impulse signals for assessing setpoint tracking and disturbance rejection.
- To determine the most robust and effective control configuration in terms of rise time, settling time, overshoot, and steady-state error.



4. METHODOLOGY:

The thermal performance of the heat exchanger is analysed by applying an energy balance across the two fluid streams, assuming the heat exchanger is perfectly insulated [3]. The rate of heat transferred from the hot fluid is equal to the rate of heat absorbed by the cold fluid [6]. This heat transfer rate (Q) is calculated as:

$$Q = (\dot{m} c_p \Delta T)_c = (\dot{m} c_p \Delta T)_h \quad (1) [2]$$

where:

Q is the Heat transferred (W) $\dot{m}$ is the mass flow rate (kg/s)

c_p is the specific heat capacity ($kJ/(kg.K)$)

ΔT is the temperature difference (K)

The subscripts c and h denote the cold and hot fluid streams, respectively.

C. FOPDT Model Identification

The general expression for the Transfer function is:

$$G_p(s) = \frac{K_p}{\tau_p s + 1} e^{-\theta s}$$

where:

$G_p(s)$: Transfer function

K_p : Process gain ($k.s/kg$)

τ_p : Time constant (s)

θ : Transport delay (s)

The experimental data were gathered while maintaining a constant cold water flow of 1.5 l/min and a constant cold water inlet temperature of 33°C. The hot water flow was varied systematically through five different conditions to assess the effect on heat exchange. In the first condition, with a hot water flow of 1.5 l/min, the hot fluid entered at 71°C and exited at 60°C, heating the cold water to an outlet temperature of 45°C. When the hot water flow was increased to 2.0 l/min, the hot water entered at 70°C and exit at 65°C, with the cold water outlet rising to 49°C. The hot water flow was increased again to 2.5 l/min while keeping the inlet at 73°C and the outlet at 68°C, resulting in a cold water outlet of 53°C. For the last two conditions, the hot water flow was measured at 3.0 l/min and 3.5 l/min, with hot fluid temperatures of 75°C inlet/69°C outlet and 74°C inlet/69°C outlet respectively, with both producing a consistent maximum hot water exit temperature of 54°C.

Process	Controller	Proportional gain (K_p)	Integral time (τ_I)	Derivative time (τ_D)	Filter coefficient (N)
Varying Hot water	P	1.5052	-	-	-
	PI	1.3547	0.5797	-	-
	PD	1.29	-	0.1638	10
	PID	1.8063	0.3478	0.0807	100
Varying Cold water	P	2.9207	-	-	-
	PI	2.3286	0.3320	-	-
	PD	2.0	-	0.1820	10
	PID	3.5048	0.1992	0.0498	100



In the second experimental phase, we fixed the hot water flowrate to 3 *l/min* at 75°C and the cold water inlet temperature at 33°C. We then began to systematically vary the cold water flowrate to observe how it influenced heat transfer. The cold water flowrate (3.5 *l/min*) was the highest water flowrate for this set, and at this flowrate, the hot water exited at 60°C and increased the cold water outlet temperature to 43°C. At 3 *l/min* the hot water exited at a temperature of 64°C, warming the cold water to 46°C. The cold water flowrate was then decreased to 2.5 *l/min* which resulted in hot water at 68°C and the cold water reached 50°C. As the cold water flowrate decreased to 2 *l/min* we exited the hot water at 69°C and increased the cold water to 53°C. Finally, with the lowest cold water flowrate of 1.5 *l/min*, we were able to exit the hot water at the same temperature of 69°C, which also produced our maximum cold water outlet temperature of 54°C.

From the data, the process dynamics were identified and represented using First Order Plus Dead Time (FOPDT) transfer function models [1].

Case	Process gain	Time Constant	Transport delay
Varying Hot water flow rate	34.5	11.5	0.175
Varying Cold water flow rate	27	10	0.1

D. CONTROL SYSTEM DESIGN AND SIMULATION

In MATLAB/Simulink, a closed-loop feedback control system was developed to control the outlet temperature of the cold-water stream [6]. The controllers utilized were P, PI, PD, and PID. The tuning parameters were calculated using the Ziegler-Nichols method for P, PI, and PID controllers, while the PD controller was tuned manually [1], [5]. The calculated parameters are shown in Table I.

A. Input Signals for Controller Evaluation

To evaluate controller robustness, four standard input signals were used:

- **Step Input:** Represents a sudden setpoint change, and is used to assess transient measures, including settling time, overshoot, and stability [4].
- **Sinusoidal Input:** Represents a periodic disturbance, and is used to assess how well the system can reject cyclical perturbations [4].
- **Ramp Input:** Represents a gradual change in the setpoint, for example during process startup - thus testing the controller's ability to track a moving target [4]
- **Impulse Input:** Represents a sudden shortduration disturbance and is used to test the system's ability to absorb a shock and return to its steady state [4].

5.ANALYSIS - DISCUSSION:

With the growing industrial emphasis on automation and digital process control, simulation-based analysis has become a commonplace part of the design and validation of any controller [6], [7]. In this case, MATLAB/Simulink allows users to build dynamic models of heat exchanger systems and test a variety of control strategies before being implemented, thus reducing any degree of uncertainty and assuring a safe operation. Moreover, this simulation-based approach can reduce the cost and time associated with physical experimentation while fostering a better understanding of the behaviour of a heat exchanger system in varying process operating conditions.

The performance of each controller was simulated and analyzed.

A. Step Response Analysis



The step input is the most critical test for evaluating fundamental performance. The key performance metrics are summarized in Table II. The P controller shows a fast reaction but suffers from a significant steady-state error of 10% (Fig. 1) [4], [6]. The PI controller successfully eliminates this error but at the cost of a more oscillatory response with a high overshoot (35%) and the longest settling time (Fig. 2) [4], [6]. The PD controller demonstrates good transient response with the fastest settling time but fails to eliminate the steady-state error (Fig. 3) [4]. The PID controller provides the most balanced performance, achieving zero steady-state error, the lowest overshoot (25%), and a fast rise time (Fig. 4) [6].

TABLE II: CONTROLLER PERFORMANCE METRICS FOR STEP RESPONSE

Controller	Rise Time (s)	Settling Time (s)	Peak Overshoot (%)	Steady State Error (%)
P	0.18	0.95	15	10
PI	0.22	2.10	335	0
PD	0.15	0.85	18	8
PID	0.19	1.20	25	0

B. Tracking and Disturbance Rejection

The ramp, sinusoidal, and impulse inputs were used to test the controllers under more dynamic conditions.

- **Ramp Response:** P and PD controllers exhibited a constant tracking error, while the PI and PID controllers followed the ramp with zero steady-state error due to their integral action [4].
- **Sinusoidal Response:** The PID controller's output most closely matched the input signal, indicating better performance in rejecting periodic disturbances.
- **Impulse Response:** Analysis showed that the PID controller was most effective at disturbance rejection, stabilizing the system more quickly and with less oscillation than the other schemes

6.FINDINGS:

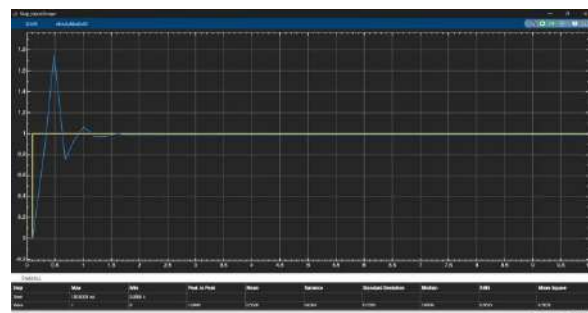
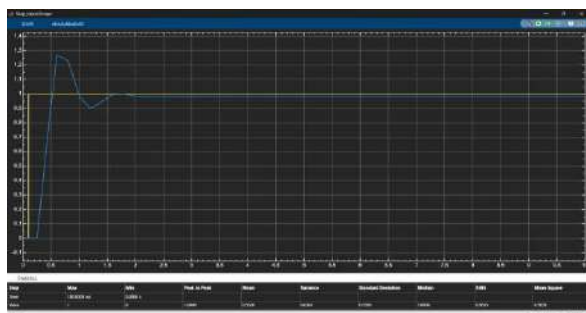


Fig. 1. Step response of the closed-loop system using a P controller for (a) varying hot water flow rate & (b) varying cold water flow rate.

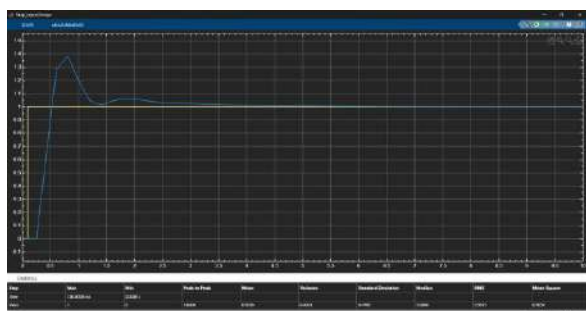




Fig. 2. Step response of the closed-loop system using a PI controller for (a) varying hot water flow rate & (b) varying cold water flow rate.

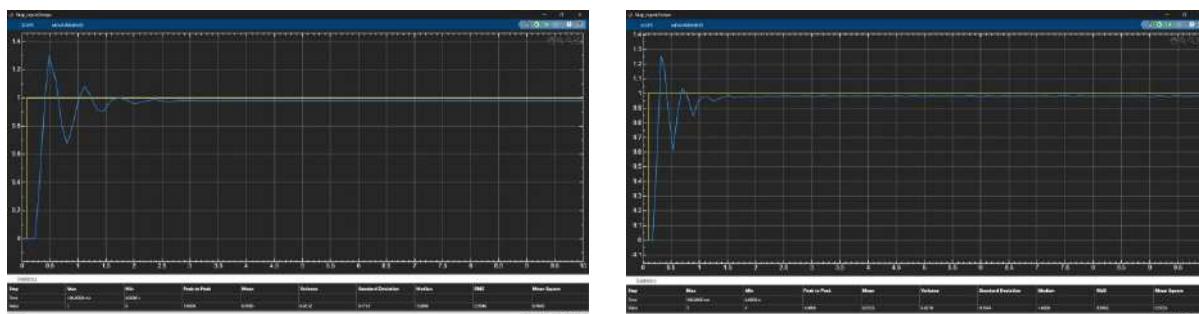


Fig. 3. Step response of the closed-loop system using a PD controller for (a) varying hot water flow rate & (b) varying cold water flow rate.

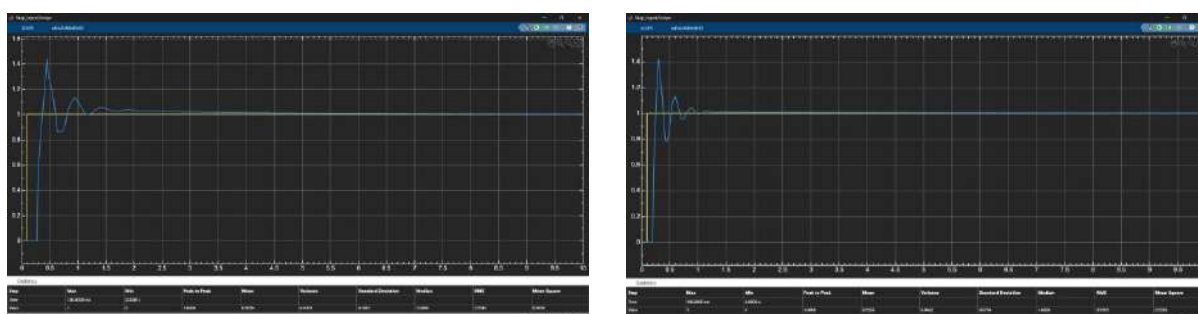


Fig. 4. Step response of the closed-loop system using a PID controller for (a) varying hot water flow rate & (b) varying cold water flow rate.

7.CONCLUSION :

This paper presented a comprehensive analysis of P, PI, PD, and PID control strategies for regulating the temperature of a double-pipe heat exchanger. The dynamics of the system were modeled as a first order plus dead time (FOPDT) process, which was utilized for the controller tuning exercise. The simulation results made it evident of the advantages and disadvantages associated with each control action. Both the P and PD controllers were ineffective as they were unable to eliminate the steady-state error. The PI controller provided a zero error; however, the transient response was inferior to the PID controller. Through analysis, the study has concluded that the PID controller is the most effective and robust control strategy for the double-pipe heat exchanger. While the setpoint tracking was the best overall performance, it also eliminated the steady-state error with a superior transient response with both the lowest peak overshoot and fastest settling time. Future work may include optimization using modern tuning techniques or experimental implementation on the physical apparatus.

ACKNOWLEDGMENT:

I would like to express our profound gratitude and sincere thanks to our respected supervisor, **Dr. Nirupama**, for their invaluable guidance, constant encouragement, and unwavering support throughout the course of this project. Their insightful feedback, expert advice, and patient mentorship were instrumental in the successful completion of this work.

We express our gratitude to **Dr. Amit Kumar Gupta**, Head of the Department of Chemical Engineering. Special thanks to our respected PG Coordinator **Dr. Ashok Kumar Baranwal**, Chemical Engineering Department of BIT Sindri, Dhanbad. Our sincere appreciation also goes to all the faculty and staff members of the Department of Chemical Engineering at **B.I.T. Sindri** for their kind cooperation and assistance whenever required.



Finally, we would like to thank our parents and friends for their unconditional love, immense support, and constant motivation. Their encouragement was a source of strength for us during the entire tenure of this project.

REFERENCES :

1. N. S. Mya, C. C. Khaing, E. E. Thar, and A. M. Thandar, "Modeling and Control of Shell and Tube Heat Exchanger using MATLAB Simulation," *Int. J. Sci. Eng. Technol. Res.*, vol. 08, pp. 221-224, 2019
2. R. G. Asoka, N. Aishwarya, S. Rajasekar, and N. Meyyappan, "Dynamic Simulation of Double Pipe Heat Exchanger using MATLAB simulink," in *Proc. Int. Conf. Emerg. trends Eng., Sci. Sustain. Technol. (ICETSST)*, 2017.
3. A. Mazumder and B. K. Mandal, "Numerical Modeling and Simulation of a Double Tube Heat Exchanger Adopting a Black Box Approach," *Int. J. Eng. Res. Appl.*, vol. 6, no. 4, pp. 35-41, Apr. 2016.
4. D. E. Seborg, T. F. Edgar, D. A. Mellichamp, and F. J. Doyle III, *Process Dynamics and Control*, 4th ed. Hoboken, NJ, USA: Wiley, 2016.
5. J. G. Ziegler and N. B. Nichols, "Optimum Settings for Automatic Controllers," *Trans. A.S.M.E.*, vol. 64, pp. 759-768, Nov. 1942.
6. N. Srivastava, D. K. Tanti, and M. A. Ahmad, "Matlab simulation of temperature control of heat exchanger using different controllers," *Autom. Control Intell. Syst.*, vol. 2, no. 1, pp. 1-5, 2014.
7. V. Kannojiya, R. Gaur, P. Yadav, and R. Sharma, "Performance investigation of a double pipe heat exchanger under different flow configuration by using experimental and computational technique," *Arch. Mech. Eng.*, vol. LXV, no. 1, 2018.
8. T. J. Darure, "Implementation of Advanced Control Strategies for Boiler and Heat Exchanger Pilot Plant," M.Tech thesis, Dept. Instrum. Control, College of Eng., Pune, India, 2016.
- 9.

NOTE:- This study focuses on the modeling and simulation of a double-pipe heat exchanger system. Different controllers are applied to analyze temperature control performance. The system behavior is evaluated using MATLAB/Simulink, and results are compared based on stability, response time, and accuracy.



DOIs:10.2015/IJIRMF/ICICSF-2025-P07

--:--

Research Paper / Article / Review

International Conference On “Innovative Convergence for Sustainable Future”

Date : 12 - 13 December, 2025

(ICICSF-2025)



Digital Governance and Right to Privacy: Need of a sustainable Digital Society post Puttaswamy judgment

¹Damini Kumari, ²Prof. Aditi Apoorva

¹Student, Jharkhand Rai University, Ranchi, Jharkhand, India

²Assistant Professor, Jharkhand Rai University, Ranchi, Jharkhand, India

Email- prajapatidamini6@gmail.com Contact No. 7050247422

ABSTRACT: This paper mainly focuses on the balance between digital governance and the protection of an individual's privacy to achieve a sustainable digital society. In India, the rise of digital governance has changed the way of constitutional governance by embedding technology into the core of public administration. Although it offers better efficiency, transparency and inclusivity, it also brings up major constitutional issues about surveillance, autonomy and informational privacy. The Supreme Court in August 2017 in the case of Justice K.S. Puttaswamy v. Union of India, delivered a landmark judgment by recognizing “Right to Privacy” as an inalienable part of Right to Life and Personal Liberty under Article 21 of Constitution. After judgment of the Puttaswamy case, the rapid shift to digital governance through initiatives like Aadhaar, Digital India, and online service platforms has raised concerns regarding the balance between digital governance and constitutional morals. This paper analyzes the framework of privacy within digital governance and its relationship with new data protection laws. It tracks the development of privacy laws reviews existing regulations like Information Technology Act, 2000 and the Digital Personal Data Protection Act, 2023 and compares India's privacy framework with global standards such as the EU General Data Protection Regulation (GDPR). The paper concludes that India must adopt a sustainable digital governance model grounded in constitutional ethics. This means promoting digital literacy, ensuring data regulators work independently, and building citizen trust. Only this approach can balance the aim of digital governance efficiency and right to privacy, fulfilling the goal of just and sustainable digital society.

Key words: Right to Privacy, Digital Governance, Sustainable Digital society, Article 21.

1.INTRODUCTION:

A. Background of the Study

The twenty-first century has witnessed a remarkable transformation in governance through the rise of digital technologies. Governments across the world are using digital platforms to deliver public services, enhance transparency, and promote citizen participation. India, with its ambitious programs such as Digital India and Aadhaar, has become one of the leading examples of large-scale digital governance. These initiatives have improved administrative efficiency and public service delivery, yet they have also raised critical concerns regarding data protection, surveillance, and the erosion of personal privacy.

In this context, the recognition of the right to privacy as a fundamental right in Justice K.S. Puttaswamy v. Union of India (2017) became a landmark constitutional development. The judgment established that privacy is integral to life and personal liberty under Article 21 of the Constitution, emphasizing that any restriction on privacy must satisfy the tests of legality, necessity, and proportionality. This decision provided the constitutional foundation for safeguarding individual autonomy in a rapidly digitizing society.

However, the growing dependence on data driven systems, artificial intelligence, and biometric technologies has exposed the tension between efficiency and individual rights. The Indian State now faces the challenge of ensuring that



digital governance does not undermine the fundamental right to privacy. Balancing these two priorities technological advancement and constitutional protection has become a crucial question in the post Puttaswamy era.

B. Problem Statement

The digital infrastructure that is growing in India is collecting and processing copious personal data with little to no legal framework or supervision. Although such programmes as Aadhaar and the Digital India Mission are meant to enhance the process of governance, they also open the opportunity to abuse the information, steal identity and spy. The lack of a developed privacy policy over the years was an entity that gave rise to the free proliferation of centralized databases. Despite the fact that the Digital Personal Data Protection Act, 2023, is a step forward, there are still questions regarding its application, the exemptions that the state has, and its independence of the institutions. The most important issue, though, is how to reconcile the digital governance with the constitutional promise of privacy to make sure that technology is used to benefit citizens without taking away their dignity or authority.

C. Objectives of the paper

1. Track down how the right to privacy came to exist in India.
2. Analyse the legal and institutional framework upon privacy and digital governance in the post Puttaswamy judgment.
3. Compare the Indian privacy and data protection model with other international models.
4. Critically analyze the advantages and drawbacks of the existing digital system of governance.
5. Recommend improvements to create a sustainable digital society that is neither to the detriment of innovation nor to the harm of individual rights.

D. Significance of the Study

The study is significant in the academic and policy-making circles. It is also scholarly because it adds to the growing literature on the constitutional rights in digital transformation. To policy makers, it offers information on how to create governance models that still consider the privacy of citizens but at the same time allow innovation. The research is also a standard that directs legal practitioners and scholars on the development of privacy jurisprudence and the kind of institutional efforts that should be implemented to hold digital systems accountable. A sustainable digital society is one that does not just accept technology but is also in support of human decency and democracy. The right to privacy should therefore not be perceived as a challenge but rather as a fundamental protection that instils trust, openness, and equality in leadership. This study will seek to answer the question on how India can strike that balance and have a future whereby technological advancement will support and not undermine the rights of an individual.

2.LITERATURE REVIEW

The question of privacy in India has evolved through decades of constitutional interpretation, policy reforms, and academic discourse. Initial studies focused on the judicial denial of privacy in cases such as *M.P. Sharma v. Satish Chandra* and *Kharak Singh v. State of Uttar Pradesh*, where the courts did not recognize privacy as a fundamental right. Subsequent research by constitutional scholars identified these early cases as limited in scope and context, arguing that technological progress had changed the very nature of personal liberty. This intellectual groundwork paved the way for later judicial reconsideration of privacy as an essential component of human dignity and autonomy.

Legal scholarship following *Justice K.S. Puttaswamy v. Union of India* (2017) reflects a growing recognition that privacy extends to include decisional, informational, and bodily autonomy beyond secrecy. This transition has been examined by constitutional theorists as a move from a narrow interpretation of rights to a holistic framework encompassing dignity and autonomy. Several studies have praised the judgment for aligning Indian jurisprudence with international human rights standards, while others have critiqued its limited focus on institutional enforcement and technological realities. The literature shows a consensus that *Puttaswamy* set the normative foundation, but the real challenge lies in ensuring practical safeguards

The other important area of research is a study of digital governance and privacy. Researchers testing the digital initiatives in India, including Aadhaar and Digital India, the researchers do point out that the programs are making things more transparent and inclusive; however, they also introduce new vulnerabilities. Among the issues, which the literature



raises include the centralization of data, profiling, marginalization, and lack of meaningful consent. Scholars note that most digital offerings in India were launched earlier than privacy by design and thus there have been governance models, which favor efficiency over protection of data. These reports indicate that there is a need to bridge the technological innovation and ethical or constitutional context of safeguarding the informational rights of individuals.

Comparative studies provide further depth to this debate. Several international law experts have analyzed India's approach alongside the European Union's **General Data Protection Regulation (GDPR)**, Singapore's **Personal Data Protection Act (PDPA)**, and South Korea's **Personal Information Protection Act (PIPA)**. This body of research underscores that India's model remains heavily government-centric, with weaker enforcement and limited individual remedies compared to these global benchmarks. At the same time, scholars recognize India's potential to develop a hybrid model that balances economic growth with constitutional accountability.

Contemporary literature also critiques the **DPDP Act, 2023**, arguing that it advances legal formalization of privacy but falls short of establishing genuine regulatory independence. Academic commentary emphasizes that exemptions for state agencies and broad government discretion could dilute citizens' rights.

Besides the legal and policy studies, there are also some interdisciplinary studies that deal with the social and ethical aspects of privacy. They emphasize that lack of digital literacy, economic inequalities, and increasing ignorance among people are contributing risks in privacy in India. According to the scholars, privacy protection must be regarded as a social good, as opposed to an individual right, which is associated with democratic participation and equality as well as sustainable governance. In general, the literature shows that the recognition of privacy as one of the fundamental rights in India is a breakthrough event, but its actual implementation in the field of digital governance is not complete. Knowledgeable people believe that long-lasting protection of the privacy will also need a balance of invention and responsibility which will be backed by autonomous entities, mass education, and professional conduct in technology. The review, therefore, offers a theoretical basis through which the development and obstacles of the establishment of the sustainable digital society in India can be analysed following the Puttaswamy.

Subsequent work on the topic of surveillance technologies in India reveals the increasing influence of this technology on the privacy discussion. Researchers of CCTV systems, facial recognitions, and predictive policing applications state that such technologies widen the capabilities of the State to spy on the population without any apparent accountability policies. Studies devoted to the metropolitan surveillance initiatives, including the ones, deployed in Delhi, Hyderabad and Mumbai, caution that the lack of the transparent procedures regarding the data storage and its retention and access enhances the risk of its misuse. These studies suggest that unless there is clear legislation on such technologies, India is likely to drift towards some sort of surveillance governance that goes against the provisions of Puttaswamy. The next prominent theme that scholars have been discussing is the contribution of the role of the private companies towards privacy protection. As digital payments, e-commerce, health applications, and social media sites have emerged, researchers claim that the confidential information of vast numbers of people has become the responsibility of the private sector. Research indicates that lax data protection regulations have enabled organizations to acquire more data than what is required, monitor user activities and disclose information to third-parties without proper consent. Researchers emphasize that the problem of privacy in India cannot be resolved only by laying emphasis on the government; the corporate data practice should be more strictly regulated and controlled as well. Welfare governance, especially its impact on vulnerable populations due to digitisation, is also a topic that has been examined by some scholars. It has been found that rural population, elderly, people with disabilities, and families with low income are more susceptible to privacy issues because of low digital literacy rate and reliance on middlemen to access internet services. The arguments put forward in these studies are that privacy should be viewed through the prism of social justice since the misuse of data targets groups of people with less knowledge and resources to defend themselves. The growing application of algorithms to decision making in the populace is also studied in emerging literature as algorithmic governance. Scholars observe that AI-based systems that distribute welfare, police, credit ratings and health services to citizens can generate biased results unintentionally. These algorithms tend to be opaque and hence people know little about how decisions which may determine their life are made. Researchers suggest that the privacy protection must comprise algorithmic transparency, protection of fairness, and accountability measures. Feminist and environmental scholars provide additional shades when they point out that not every person is harmed by the invasion of privacy. The women, children and the marginalized groups encounter distinct digital vulnerability. Research indicates that there are gender-based privacy risks brought about by online harassment, sharing pictures with authorization, and mobile device tracking.



According to these scholars, privacy should be viewed as not only a constitutional right but also an empowerment device to the weaker groups. Combined, these other views deepen the literature by demonstrating that privacy in India is not simply a legal matter; but a complicated social, technical and ethical problem. According to the scholarly literature, the creation of a sustainable digital society will need a set of effective legal changes, technological protection, independent organizations, and general digital literacy.

3.METHODOLOGY

In accordance with a doctrinal and analytical research methodology, this study focuses on Indian constitutional provisions, court rulings, and legislative frameworks pertaining to the right to privacy and digital governance. Rather than gathering quantitative data, the qualitative and descriptive research seeks to understand current laws and evaluate their efficacy.

All of the data is taken from secondary sources, such as government reports, Supreme Court rulings, laws like the Digital Personal Data Protection Act of 2023 and the Information Technology Act of 2000, as well as books, journals, and online databases. To give a global perspective, comparative allusions to international frameworks like the GDPR of the EU, the PDPA of Singapore, and the PIPA of South Korea are also included.

The analysis is carried out using a **constitutional and policy evaluation framework**, particularly applying the *Puttaswamy* principles of legality, necessity, and proportionality. A thematic approach is used to identify trends in privacy protection and gaps in India's digital governance system.

The study is limited to secondary data and legal analysis but provides a comprehensive understanding of how privacy law and digital governance interact in post-*Puttaswamy* India.

4.DISCUSSION

Going by the findings of this paper, we can say that in India there has been significant recognition of right to privacy as a constitutional value but translating it into effective governance is still questionable. The *Puttaswamy* ruling established the moral and legal basis for privacy protection, but its implementation has been irregular, because of feeble institutional arrangements and intersecting state powers. Digital governance initiatives like Aadhaar and Digital India have transformed service delivery, but have also proxy-forced wider state surveillance and dependence on data without commensurate oversight mechanisms.

The analysis of these findings posits that India is undergoing a digital maturity process faster than its ability to legal and regulatory capacity to protect citizens data. The Digital Personal Data Protection Act, 2023 seeks to redress this gap but its model continues to embody the centralized, government-directed approach. Unlike the European Union's General Data Protection Regulation, which relies on independent regulators to enforce strict consent and accountability provisions, India's system centralizes decision-making within the executive. This asymmetry may lead to a lack of transparency and compliance with the constitution, especially when mass data processing is done by public authorities.

The larger implication is that in India, privacy has shifted from being only an individual right to a collective democratic need. In order to achieve trust, participation and inclusiveness in governance a privacy supporting society is necessary. As digital systems permeate the field of welfare, health and finance, keeping personal information safe is fundamental for ensuring citizens' dignity and autonomy. Without them, technological advances could risk exacerbating inequality and undermining public trust in the state.

However, the study also acknowledges some limitations. It is largely based on doctrinal and secondary research, and lacks empirical data or case oriented analysis of privacy abuses. The dynamic of changing technology and evolving policy is also likely to bear on the long-term relevance of certain conclusions. Nevertheless, the paper does offer a robust conceptual and normative account of the obstacles to India's struggle to bring its digital governance model in line with constitutional privacy ensures.

5.RESULTS / FINDINGS

The report suggests the recognition of privacy as a fundamental right will provide consistency with what is determined in Justice K.S. Puttaswamy (Retd.) v. Union of India decision marked a sweeping transformation in the Indian constitutional order. It also ruled that any interference with privacy had to pass the three-part test of legality, necessity and proportionality, thus putting strict limits on state intrusion into personal data.

But the results suggest a mixed picture: a solid legal base for privacy protection, but wildly varying practice. The enactment of the Digital Personal Data Protection Act, 2023 is a good first step towards-going efforts to legitimise data



protection, however the sheer number of cabinets in the Act as well as its lack of a regulator has made it toothless. The Data Protection Board is closely dependent on executive power and lacks neutrality and accountability.

The study also discovers that India's digital governance is still very state-centric. Initiatives such as Aadhaar, Digital India and National Health Stack have certainly improved efficiencies and inclusion while raising concerns around data privacy, profiling and exclusion on account of failed authentication. These efforts demonstrate that technology developments have frequently outstripped legal protections, and that privacy protection has been largely reactionary instead of proactive.

A comparison review It is apparent that India falls short of global models, such as EU's GDPR and South Korea's PIPA where priority has been given to independent regulation and strong enforcement. However, India's privacy case law represents a significant development around dignity and autonomy as underlying constitutional values. The results indicate that for privacy to be more than a distant goal, better institutional structures need to be in place and digital literacy must be improved, while design of digital governance structures should include privacy by design from the beginning.

6.CONCLUSION AND FUTURE SCOPE

The implication of the findings suggested in this paper is that India has managed to secure great credence for right to privacy as a constitutional value, however, if this value can translate into good governance remains uncertain. While the Puttaswamy decision laid down moral basis for protection of privacy, in practical terms it has been sporadic owing to weak institutional mechanisms and overlapping state powers. This cannot simply be achieved by way of Aadhaar and Digital India through which digital governance has changed the delivery structure but also indirectly forced wider state surveillance and data dependence without any checks.

The interpretation of these results is that India is possibly leapfrogging in digital maturity more quickly than its legislative and regulatory shields needed to protect its people's data. The Digital Personal Data Protection Act, 2023 attempts to plug this hole but its model still retains the "centralization with government focus. India's system consolidates power over data decisions in the executive branch, as opposed to giving independent regulators that power (as the European Union General Data Protection Regulation does with strict consent and accountability provisions). Such asymmetry can have implications on transparency and constitutional compliance particularly when public authorities engage in large-scale data processing.

The larger significance of this is that in India, privacy has travelled from being an individual right to a collective democratic aspiration. Participation, trust and inclusiveness in governance is only possible when privacy supporting society is established. With the advance of digital technologies in welfare, health and finance, safeguarding personal data is a prerequisite for guaranteeing citizens' dignity and autonomy. Without them, the benefits of technological progress might risk increasing inequality and undermining public trust in the state itself.

But the research also noted some caveats. It relies mostly on doctrinal and secondary research, without empirical evidence or a case oriented approach to privacy abuses. The interplay of evolving technology and emerging policy is also likely to have an impact on the continued relevance of some conclusions. However, the paper does provide a strong theoretical and normative framework for the challenges facing India's fight to reconcile its digital governance practices with constitutional privacy guarantees.

REFERENCES

1. M.P. Sharma v. Satish Chandra, District Magistrate, Delhi, 1954 SCR 1077 (Supreme Court of India).
2. Kharak Singh v. State of Uttar Pradesh, AIR 1963 SC 1295 (Supreme Court of India).
3. Justice K.S. Puttaswamy (Retd.) v. Union of India, (2017) 10 SCC 1 (Supreme Court of India).
4. Bhatia, G. (2019). *The Transformative Constitution: A Radical Biography in Nine Acts*. HarperCollins.
5. Greenleaf, G. (2023). *Asian Data Privacy Laws: Trade and Human Rights Perspectives*. Oxford University Press.
6. Chawla, N., & Greenleaf, G. (2023). India's Digital Personal Data Protection Act, 2023: Strong on Form, Weak on Substance. *Privacy Laws & Business International Report*, (184), 1–8.
7. Khosla, M. (2018). Constitutionalism and the Right to Privacy in India. *Indian Law Review*, 2(2), 120–142.



8. Mitra, A. (2020). Digital Governance and the Right to Privacy in India: Balancing Efficiency and Liberty. *NUJS Law Review*, 13(1), 42–68.
9. Narain, P. (2019). Privacy, Surveillance and Constitutional Morality after Puttaswamy. *NALSAR Law Review*, 15(2), 109–132.
10. Ramanathan, U. (2018). Aadhaar: From Welfare to Surveillance. *Economic & Political Weekly*, 53(45), 10–14.
11. Tripathi, S. (2022). The Constitutionalization of Data Protection in India: Challenges after Puttaswamy. *Indian Journal of Law and Technology*, 18(1), 30–57.
12. Deva, S. (2021). Datafication and Social Justice in India: Understanding Digital Exclusions. *Indian Journal of Human Development*, 15(2), 245–263.
13. Singh, P. (2020). Biometrics, Welfare, and Privacy: Rethinking Aadhaar in India. *Journal of Information Policy*, 10, 145–168.
14. Kumar, R. (2021). Surveillance, Facial Recognition, and the Future of Privacy in India. *International Journal of Law and Technology*, 9(3), 188–210.
15. Sharma, R. (2022). Algorithmic Governance and Transparency in India: A Critical Review. *Journal of Digital Ethics*, 4(1), 22–41.
16. Mahapatra, P. (2020). Corporate Data Practices and Privacy Gaps in India. *Business and Society Review*, 125(4), 455–478.
17. Srikrishna Committee Report. (2018). *A Free and Fair Digital Economy: Protecting Privacy, Empowering Indians*. Ministry of Electronics and Information Technology, Government of India.
18. Constitution of India, 1949
19. Digital Personal Data Protection Act, 2023 (India).
20. Information Technology Act, 2000 (India).
21. European Parliament & Council. (2016). *General Data Protection Regulation (GDPR)*. Official Journal of the European Union.
22. Government of Singapore. (2012). *Personal Data Protection Act (PDPA)*.
23. Republic of Korea. (2011). *Personal Information Protection Act (PIPA)*.
24. Ministry of Electronics and IT (MeitY). (2023). Digital India Programme. Retrieved from <https://www.digitalindia.gov.in/>
25. UIDAI. (2023). Aadhaar Overview. Retrieved from <https://uidai.gov.in/>
26. PRS Legislative Research. (2023). Digital Personal Data Protection Act, 2023: Summary and Analysis. Retrieved from <https://prsindia.org/>
27. Internet Freedom Foundation (IFF). (2022). Surveillance & Privacy in India: Policy Analysis. Retrieved from <https://internetfreedom.in/>
28. Supreme Court of India. (2017). Puttaswamy Judgment Full Text. Retrieved from <https://main.sci.gov.in/>
29. Economic & Political Weekly Archive. (2018). Aadhaar Debate Resources. Retrieved from <https://www.epw.in/>



DOIs:10.2015/IJIRMF/ICICSF-2025-P08

--:--

Research Paper / Article / Review

International Conference On “Innovative Convergence for Sustainable Future”

Date : 12 - 13 December, 2025

(ICICSF-2025)



Influence of Microbial Inoculants and Molybdenum Application on the Status of Soil Health in Red and Lateritic Zone of West Bengal

Deepshikha

M.Sc. Scholar, Department of Soil Science and Agricultural Chemistry, Visva-Bharati, Sriniketan-731236, West Bengal, India

Email- deep720920@gmail.com

Abstract: A field experiment was conducted during pre-kharif season of 2024 at Agricultural Farm, Sriniketan, situated in the Red and Lateritic Zone of West Bengal to study the effect of microbial inoculants and molybdenum application on the status of soil health after the harvest of blackgram (*Vigna mungo* (L.) Hepper) crop. The experiment was laid out in Factorial Randomized Block Design (FRBD) consisting of two factors with three replications. Factor A comprised of eight levels of microbial inoculants [S_1 =Seed treatment with *Rhizobium*, S_2 =Seed treatment with PSB, S_3 =Seed treatment with *Azotobacter*, S_4 =Seed treatment with *Rhizobium* + PSB, S_5 =Seed treatment with PSB + *Azotobacter*, S_6 =Seed treatment with *Rhizobium* + *Azotobacter*, S_7 =Seed treatment with *Rhizobium* + PSB + *Azotobacter*, S_8 =Uninoculated control] whereas Factor B comprised of two levels of molybdenum [Mo_1 =Basal application of Mo@1.5kg/ha and Mo_2 =Foliar spray of Mo@0.05% at pre-flowering stage]. In case of microbial inoculants, the maximum content of Nitrogen (158.89 kg/ha), Phosphorous (15.42 kg/ha), Potassium (107.53 kg/ha), Molybdenum (0.079 ppm), Organic carbon (0.54%) in post-harvest soil was recorded in S_7 (Seed treatment with *Rhizobium* + PSB + *Azotobacter*) and minimum in S_8 (Uninoculated control). Combined inoculation of *Rhizobium* + PSB + *Azotobacter* enhanced soil microbial populations, increasing *Rhizobium* by 3.29-fold and 2.85-fold, PSB by 2.10-fold and 2.50-fold, and *Azotobacter* by 2.71-fold and 2.78-fold at 30 DAS and harvest, respectively. In case of molybdenum application, the maximum content of Phosphorous (14.72 kg/ha) and Potassium (101.14 kg/ha) was observed in Mo_2 (Foliar spray of Mo@0.05% at pre-flowering stage) while the maximum content of Molybdenum (0.078 ppm) and organic carbon (0.44 %) was obtained in Mo_1 (Basal application of Mo@1.5 kg/ha). Basal application of Mo@1.5 kg/ha enhanced microbial populations compared to foliar spray of Mo@0.05%, increasing *Rhizobium* by 1.17-fold and 1.10-fold, PSB by 1.07-fold and 1.06-fold, and *Azotobacter* by 1.11-fold at 30 DAS and harvest respectively. The interaction between microbial inoculants and molybdenum showed significance for Potassium content in post-harvest soil, microbial population of *Rhizobium*, PSB and *Azotobacter*.

Keywords: Molybdenum, *Rhizobium*, PSB, *Azotobacter*, Seed treatment, Foliar spray.

1.INTRODUCTION:

The Red and Lateritic soils of West Bengal cover districts like Birbhum, Bankura, Jhargram, Paschim Medinipur, Purulia. The soils are acidic, poor in nutrients, low organic matter and low water holding capacity. Despite low fertility, farmers grow paddy, pulses, oilseeds, vegetables etc. Application of microbial inoculants like *Rhizobium*, PSB can significantly improve soil fertility by enhancing biological nitrogen fixation, phosphate solubilization and microbial activity. Application of molybdenum corrects Mo deficiency, enhances nitrogenase activity, improves nodulation and thereby increasing N-fixation efficiency. The combined use of microbial inoculants and Mo synergistically improves N and P availability, microbial biomass and thereby soil health is improved.

Microbial inoculants, commonly referred to as biofertilizers, are natural products that consist of particular microorganisms sourced from plant roots and their surrounding areas. Research has demonstrated that these bioinoculants can enhance plant growth and yield by 10–40% (Stewart and Roberts 2012). Upon application to the rhizosphere and within the plant, they colonize the environment to support plant development (Nosheen et al. 2021). In



addition to enriching the soil with nutrients to increase soil fertility and crop production, they also safeguard plants against pests and diseases. They have been proven to improve seedling survival rates, prolong the life span of the root system, remove harmful chemicals, and reduce flowering duration (Youssef and Eissa 2014). Biofertilizers are classified into categories depending on their roles and modes of action. The most frequently utilized biofertilizers include nitrogen-fixing microorganisms (N-fixers), potassium-solubilizing bacteria (K solubilizers), phosphorus-solubilizing organisms (P solubilizers), and plant growth-promoting rhizobacteria (PGPR).

Rhizobium is a gram-negative soil bacterium that form an endosymbiotic nitrogen fixing association with roots of legumes and fix nitrogen. In the root nodules, the *Rhizobium* bacteria essentially infiltrate plant cells and transform atmospheric nitrogen into ammonia. The process of symbiotic nitrogen fixation involves a series of steps.

1. *Rhizobia* present in the soil recognize chemicals(flavones) released by the host plant which are specific for specific *Rhizobia* strain.
2. *Rhizobia* attach to root hairs of host plant.
3. The bacteria start multiplying on the root hairs and then curling of root hairs takes place
4. Infection thread forms and *Rhizobia* invade to the plant root cells
5. *Rhizobia* are released into cortical cells where they are surrounded by peri bacteroid membrane
6. *Rhizobia* change shape to form bacteroid
7. A functional nodule forms with vascular tissue. Leghaemoglobin appears, giving the nodule a pink colour. It maintains low oxygen concentration needed for nitrogenase.
8. Nitrogenase converts atmospheric nitrogen (N_2) into ammonia (NH_3).
9. The ammonia produced is then used by the plant for the synthesis of amino acids and proteins.

Phosphate solubilizing bacteria (PSB) are essential for mineralizing inaccessible phosphorus into a bioavailable state, hence enhancing phosphorus absorption by plants and subsequently boosting productivity. In order to change insoluble native and fixed phosphorus into soluble form, these organisms can be used as bioinoculants in crop plants. The use of biofertilizers as bio-inoculants is currently necessary due to the shortage and growing expense of chemical fertilizers, and they are more beneficial than other phosphorus fertilizers. Inorganic phosphorus can be dissolved from insoluble compounds by beneficial bacteria known as PSBs (phosphate solubilizing bacteria). The capacity of rhizosphere bacteria to dissolve phosphorus is one of the most important traits associated with plant phosphate nutrition.

The genus *Azotobacter* consists of spherical or oval-shaped, free-living, motile bacteria that engage in nitrogen fixation and form thick-walled cysts. These aerobic soil microorganisms are crucial for fixing nitrogen and are primarily found in alkaline soils, aquatic environments, and associated with certain plants. *Azotobacter* are free-living bacteria that capture nitrogen directly from the atmosphere, without forming symbiotic relationships with plants. Various enzymes present in *Azotobacter* facilitate the process of nitrogen fixation. Due to the high sensitivity of nitrogen fixation to oxygen, *Azotobacter* has developed a distinctive defence mechanism that enhances their metabolic processes while reducing oxygen levels within their cells.

Molybdenum is a chemical element with symbol Mo and atomic number 42. It is solid at 25°C (room temperature). It is silvery-white, hard transition metal. As a transition metal, molybdenum can exist in a number of oxidation states, from zero to VI, with VI being the most prevalent type present in the majority of agricultural soils. The majority of living things, including plants and animals, need molybdenum, a trace element that is present in soil. It is one of the seven micronutrients which is required for increasing plant growth and development. Mo is regarded as an ultra-micronutrient that serves as a cofactor for the enzymes nitrogenase and nitrate reductase, which are essential for biological nitrogen fixation and subsequent legume assimilation. Therefore, molybdenum is essential for protein production and nitrogen metabolism. Additionally, it helps pulse crops with a number of physiological and biochemical processes. Applying Mo to crops improves bioavailability of other vital elements. It is found in the leaf's chloroplast envelope and has a role in the production of ascorbic acid and the physiological availability of iron (Fe) in the plant. Because it helps the nitrogen-fixing bacterium *Azotobacter chroococcum* and enzymes like nitrogenase fix nitrogen from the air, Mo has a biologically significant role in plants. The availability of molybdenum for plant growth is heavily influenced by factors such as soil pH, the concentration of adsorbing oxides (like Fe oxides), the degree of water drainage, and the presence of organic compounds in the soil colloids. In alkaline soils, molybdenum is more soluble and can be accessed by plants primarily in its anionic form as MoO_4^{2-} . Conversely, in acidic soils (with a pH below 5.5), the accessibility of molybdenum declines due to the increased adsorption of anions to soil oxides (Reddy et al., 1997). MoO_4^{2-} can form soluble complexes with elements such as Na, K, Ca, Mg, and organic matter, which further increases its availability.



2.LITERATURE REVIEW:

A literature review involves citing the work of researchers to establish a foundation that supports the findings of a specific study. This section includes an overview of experiments conducted both in India and internationally that relate to the current study titled “**INFLUENCE OF MICROBIAL INOCULANTS AND MOLYBDENUM APPLICATION ON THE STATUS OF SOIL HEALTH IN RED AND LATERITIC ZONE OF WEST BENGAL**”.

Effect of microbial inoculants

Jamir et al. (2022) carried out an experiment in 2019 kharif season at SASRD, Nagaland University, to examine the influence of different phosphorus levels (0, 20, 40, 60 kg ha⁻¹) and biofertilizer inoculation (*Rhizobium* and PSB) on black gram cultivated under rainfed conditions. The application of 60 kg P₂O₅ ha⁻¹ in combination with dual inoculation (*Rhizobium* + PSB) significantly enhanced nitrogen and phosphorus absorption in both seeds and stover. This treatment also had a positive effect on soil organic carbon, available nitrogen, and potassium; however, it did not significantly alter soil pH or available phosphorus after the harvest.

Shinde et al. (2013) observed a significantly elevated organic carbon content (0.62%) when applying 75% RDF combined with biofertilizer (*Rhizobium* and PSB) compared to the control and other treatment combinations.

Khandelwal (2012) performed a field trial on cowpea in Jobner (Rajasthan) and reported that the levels of organic carbon, available nitrogen, phosphorus, and potassium in the soil significantly increased by 0.13%, 130.2 kg, 16.5 kg, and 151.9 kg/ha, respectively, due to the application of 75% RDF, which corresponds to 15 kg of N and 30 kg of P₂O₅ per hectare, in combination with the inoculation of *Rhizobium* and PSB as compared to the other treatments.

Rajasekaran et al. (2011) investigated the impact of applying biofertilizers alongside neem cake on soil fertility, grain yield, and protein levels in blackgram. Findings demonstrated that the average population of bacteria (19%), fungi (24%), and actinomycetes (6%) significantly increased in the biofertilizer treatment compared to the control group. The organic manure treatment resulted in a noteworthy 19% rise in bacteria population but did not significantly affect fungi and actinomycetes. Additionally, the inoculation with RHL (*Rhizobium leguminosarum*) promoted a greater increase in bacterial population compared to PSF (*Pseudomonas fluorescens*), while the opposite trend was noted for fungi and actinomycetes. The combined treatment of FYM-RP witnessed the highest increases in bacterial, fungal, and actinomycetes populations, recording rises of 31%, 76%, and 33%, respectively, over the control. The increased microfauna can be linked to the elevated SOC and the synergistic effects of RHL and PSF in conjunction with FYM.

Goud et al. (2010) investigated the impact of various manures combined with biofertilizers on the growth, yield, yield traits, nutrient uptake, and soil fertility status of mungbean. Among the seed inoculation methods, the combination of *Rhizobium* and phosphorus-solubilizing bacteria achieved a significantly higher grain yield compared to their individual inoculation and the control group. The addition of different organic manures notably affected the population of diverse microbes when compared to the use of inorganic fertilizer alone.

Singh et al. (2009) performed a field experiment at the SKUAST (K) experimental farm in Shalimar, Kashmir, to assess the performance of green gram in temperate conditions with the inoculation of *Rhizobium*, VAM, and different levels of nitrogen. The findings revealed a noticeable increase in the availability of nitrogen, phosphorus, and potassium in the soil by the time the crop was harvested.

Effect of molybdenum

A long-term field study conducted by **Rana et al. (2025)** that began in 2008 at Huazhong Agricultural University in Wuhan, China, examined how molybdenum (Mo) application affected soil chemical characteristics in maize and soybean cultivation. The research included two treatments: one with Mo supplementation and one without, both receiving a consistent NPK dose of 120:80:80 kg/ha. Throughout the duration of the experiment, soil pH experienced slight variations without any statistically significant alterations; however, minor increases in pH were observed in the soybean rhizosphere soil under the Mo treatment, while a small decrease (0.12 units) was seen in maize soils. Importantly, the addition of Mo significantly raised the levels of nitrogen, phosphorus, potassium, and molybdenum in the soil, with a p-value of less than 0.05. In soybean, the levels of phosphorus and potassium increased by 15.05% and 9.26%, respectively, while nitrogen experienced a slight reduction. In maize, the application of Mo resulted in increases



of 5.06% in nitrogen, 10.94% in phosphorus, and 14.52% in potassium, indicating that the response to Mo supplementation varied depending on the crop in terms of nutrient availability.

A field study carried out by **Chanu et al. (2020)** at Central Agricultural University in Imphal during the rabi season of 2019–20 investigated the synergistic effects of nitrogen and molybdenum on pea (*Pisum sativum* L.) in acidic soil. The research, designed as a Factorial Randomized Block Design featuring 16 treatment combinations, found that the application of 20 kg N/ha in conjunction with 0.8 kg Mo/ha notably enhanced crop growth, yield, nutrient absorption, and post-harvest soil characteristics. These results underscore the significance of balanced nitrogen and molybdenum fertilization for maximizing pea yield in acidic soil conditions.

A field trial was conducted by **Karpagam and Rajesh (2014)** in the summer of 2011 at the National Pulses Research Centre in Vamban, Pudukkottai to evaluate the effects of molybdenum application on the yield of green gram (Vamban-2) and the properties of soil. Six different levels of molybdenum (ranging from 0 to 1000 g/ha using sodium molybdate) were applied in sandy clay loam soil with an acidic pH of 5.61. The findings indicated that applying molybdenum at 1000 g/ha significantly enhanced the growth and yield of green gram, as well as the available nitrogen and molybdenum content in the soil. Additionally, the highest benefit: cost ratio of 2.79 was achieved at this level of molybdenum, highlighting the economic effectiveness of molybdenum application in these soil conditions.

Singh et al. (1992) conducted a field experiment on cowpea, and the results showed that using 1 kg/ha and 2 kg/ha of molybdenum increased the amount of nitrogen in the soil by 2.16 and 4.14 kg/ha, respectively.

Synergistic effect of molybdenum and microbial inoculants

A three-year field experiment was conducted by **Sharma et al. (2019)** on chickpea (*Cicer arietinum*) to evaluate the effects of symbiotic nitrogen-fixing bacteria (*Rhizobium*), with or without *Azotobacter* and phosphate-solubilizing bacteria (PSB), on grain yield, crude protein content, nutrient uptake (N and P), and chemical properties of alkali soil. The study included eight treatments: control (no inoculation), individual inoculations with *Azotobacter*, PSB, and *Rhizobium*, as well as their combinations. Results showed that the combined inoculation of *Rhizobium* + PSB + *Azotobacter* significantly improved nodulation, grain yield, crude protein content, and nutrient uptake. This treatment also enhanced soil properties by reducing pH, electrical conductivity (ECe), and exchangeable sodium percentage (ESP). Even dual inoculations, particularly *Rhizobium* + PSB, had notable positive effects on plant growth and soil health.

3.MATERIALS AND METHODS:

A field experiment was conducted in the pre-kharif season of 2024 at the Agricultural Research Farm, Palli Siksha Bhavana (Institute of Agriculture), Visva-Bharati, Sriniketan, West Bengal, India. The soils of the region are categorized as red and lateritic soil. The trial site had a flat topography and was located at 23°39' N latitude and 87°42' E longitude, with an average elevation of 58.89 metres above mean sea level (MSL). The Agricultural Farm is situated in the middle of West Bengal's lateritic region, which has a sub-humid and sub-tropical climate. The experimental soil was sandy loam having pH 5.52, status of organic carbon was 0.38%, available P₂O₅ 11.35 kg ha⁻¹, available K₂O 78.32 kg ha⁻¹, and available Mo content 0.063 ppm. The experiment was laid out in Factorial Randomized Block Design (FRBD) consisting of two factors with three replications. Factor A comprised of eight levels of microbial inoculants [S₁=Seed treatment with *Rhizobium*, S₂=Seed treatment with PSB, S₃=Seed treatment with *Azotobacter*, S₄=Seed treatment with *Rhizobium* + PSB, S₅=Seed treatment with PSB + *Azotobacter*, S₆=Seed treatment with *Rhizobium* + *Azotobacter*, S₇=Seed treatment with *Rhizobium* + PSB + *Azotobacter*, S₈=Uninoculated control] whereas Factor B comprised of two levels of molybdenum [Mo₁=Basal application of Mo@1.5kg/ha and Mo₂=Foliar spray of Mo@0.05% at pre-flowering stage]. The dimension of each individual plot was 5 m × 2 m. A recommended dose of N: P₂O₅: K₂O for black gram was applied as basal dose to each plot at the rate of 20:40:20 kg/ha as Urea, SSP and MOP respectively. Ammonium molybdate tetrahydrate was applied @ 1.5kg/ha to plots having treatment combinations of all levels of Factor A with level Mo₁ of Factor B. Foliar spray of molybdenum was done @0.05 % at pre-flowering stage to plots having treatment combinations of all levels of Factor A with level Mo₂ of Factor B. Black gram variety PU-31 was used for sowing. Seeds were divided per plot and inoculation was done with microbial inoculants – *Rhizobium*, PSB, and *Azotobacter* @ 20g/kg of seed as per the microbial inoculants' combinations. The seeds were shade dried and within few hours sown at a spacing of 30 × 10 cm on March 15, 2024. The crop was raised following recommended package of practices and harvested on June 3, 2024. For obtaining the microbial population in the soil, data was recorded at 30 DAS and harvest stage. Rhizosphere soil sample was collected followed by serial dilution (YEMA media, Pikovskaya's



media and Jensen's media for *Rhizobium*, PSB and *Azotobacter* respectively) and then determination of microbial population was done. For estimation of pH, EC, Nitrogen, Phosphorous and Potassium content, Molybdenum availability, Organic carbon content soil sample was collected after harvesting the crop. Analysis for available N (Subbaiah and Asija, 1956), available P_2O_5 (Bray and Kurtz, 1945), available K_2O (Jackson, 1973), available Mo (Reagent-Ammonium acetate solution [Atomic Absorption Spectrophotometer (AAS)]) was done.

4.RESULTS AND DISCUSSION:

Effect of microbial inoculants: The result showed that effect of microbial inoculants was non-significant for pH and EC. Non-significance might be due to the fact that microbial inoculants primarily affect nutrient availability and biological activity, but their influence on soil pH and EC is often minimal or localized around the root zone (rhizosphere). Jamir et al. (2022) also reported similar results for non-significance of pH. The maximum nitrogen content (158.89 kg/ha) was observed in S_7 (Combined inoculation of seeds with *Rhizobium* + PSB + *Azotobacter*) and was at par with S_6 (Seed treatment with *Rhizobium* + *Azotobacter*) having nitrogen content 150.53 kg/ha. The lowest nitrogen content (108.71 kg/ha) was observed in S_8 (Uninoculated control). The combined inoculation of *Rhizobium* + PSB + *Azotobacter* increased nitrogen content in soil (46.15%) with respect to uninoculated control (108.71 kg/ha). This might be due to the reason that both *Rhizobium* and *Azotobacter* fixes atmospheric nitrogen and hence more nitrogen was observed. PSB makes phosphorous available to the plant as well as microbes and as a result microbial activity enhanced. Similar results were also reported by Yadav et al. (2021) and Sharma et al. (2019) in chickpea. Akhtar et al. (2013) also reported increase in available nitrogen content in post-harvest soil on application of biofertilizers. The maximum phosphorus content (15.42 kg/ha) was observed in S_7 (Seed treatment with *Rhizobium* + PSB + *Azotobacter*) which was at par with all other treatments except S_1 (Seed treatment with *Rhizobium*) and S_8 (Uninoculated control). The minimum phosphorous content (12.39 kg/ha) was observed in S_8 (Uninoculated control). The combined inoculation of *Rhizobium* + PSB + *Azotobacter* increased phosphorous content in soil (24.45%) with respect to uninoculated control (12.39 kg/ha). Treatments combining PSB + *Rhizobium* + *Azotobacter* tend to improve soil biology and nutrient cycling more effectively. Similar results were reported by Sharma et al. (2019). Akhtar et al. (2013) also reported increase in available phosphorous content in post-harvest soil on application of biofertilizers. The maximum potassium content (107.53 kg/ha) was observed in S_7 (Seed treatment with *Rhizobium* + PSB + *Azotobacter*) which was at par with S_5 (Seed treatment with PSB + *Azotobacter*) having potassium content 104.73 kg/ha. The lowest potassium content (86.89 kg/ha) was observed in S_8 (Uninoculated control). The combined inoculation of *Rhizobium* + PSB + *Azotobacter* increased potassium content in soil (23.75%) with respect to uninoculated control (86.89 kg/ha). Synergistic effect of microbial inoculation in S_7 (Seed treatment with *Rhizobium* + PSB + *Azotobacter*) might have contributed to maximum potassium in soil. Similar results were found by Sharma et al. (2019) and Yadav et al. (2021). The maximum molybdenum content (0.079 ppm) was obtained in treatment S_7 (Seed treatment with *Rhizobium* + PSB + *Azotobacter*) which was at par with S_4 (Seed treatment with *Rhizobium* + PSB), S_5 (Seed treatment with PSB + *Azotobacter*) and S_6 (Seed treatment with *Rhizobium* + *Azotobacter*) which yielded 0.076 ppm, 0.074 ppm and 0.075 ppm molybdenum content respectively and lowest molybdenum content (0.064 ppm) was obtained in S_8 (Uninoculated control). The combined inoculation of *Rhizobium* + PSB + *Azotobacter* increased molybdenum content in soil (23.44%) with respect to uninoculated control (0.064 ppm). The reason for this could be production of organic acids and enzymes by soil microbes that can mobilize bound forms of molybdenum. The maximum organic carbon (0.54%) was obtained from S_7 (Seed treatment with *Rhizobium* + PSB + *Azotobacter*) and minimum organic carbon content (0.35%) was observed in treatment S_8 (Uninoculated control). The increase in organic carbon content might be due to improvement in plant growth, root activity and microbial biomass, all of which contributed to the accumulation of organic carbon content in soil. Similar results were reported by Yadav et al. (2021). At 30 DAS the maximum *Rhizobium* population (51.50×10^6 CFU/g) was observed in S_7 (Seed treatment with *Rhizobium* + PSB + *Azotobacter*). The lowest population (15.67×10^6 CFU/g) was observed in S_8 (uninoculated control). The combined inoculation of *Rhizobium* + PSB + *Azotobacter* increased population of *Rhizobium* in soil (3.29-fold) with respect to uninoculated control (15.67×10^6 CFU/g). The data at harvest stage showed decreased population of *Rhizobium* compared to 30 DAS. The maximum value (33.67×10^6 CFU/g) observed at harvest stage was seen in treatment S_7 (Seed treatment with *Rhizobium* + PSB + *Azotobacter*) and the minimum population (11.83×10^6 CFU/g) was observed in S_8 (Uninoculated control). The treatments in which no *Rhizobium* inoculant was applied, showed low population of *Rhizobium*. The combined inoculation of *Rhizobium* + PSB + *Azotobacter* increased population of *Rhizobium* in soil (2.85-fold) with respect to uninoculated control (11.83×10^6 CFU/g). The increase in *Rhizobium* population might be due to direct introduction of *Rhizobium* through seed treatment. Enhanced root growth and root exudation by microbial inoculants might have provided more colonization sites. Similar results were reported by Patel et al. (2024). At 30 DAS the result showed that maximum PSB population (48.67×10^6



CFU/g) was obtained in S₇ (Seed treatment with *Rhizobium* + PSB + *Azotobacter*) and minimum population (23.17×10^6 CFU/g) in S₈ (Uninoculated control) at 30 DAS. The combined inoculation of *Rhizobium* + PSB + *Azotobacter* increased population of PSB in soil (2.10-fold) with respect to uninoculated control (23.17×10^6 CFU/g). At harvest stage the maximum PSB population (45.50×10^6 CFU/g) was observed in S₇ (Seed treatment with *Rhizobium* + PSB + *Azotobacter*) and minimum population (18.17×10^6 CFU/g) in S₈ (Uninoculated control). The combined inoculation of *Rhizobium* + PSB + *Azotobacter* increased population of PSB in soil (2.50-fold) with respect to uninoculated control (18.17×10^6 CFU/g). The increase in PSB population might be due to direct introduction of PSB to the soil. *Rhizobium* and *Azotobacter* might have created favourable microbial environment supporting the growth and multiplication of PSB. At 30 DAS the maximum *Azotobacter* population (38.00×10^6 CFU/g) was observed in S₇ (Seed treatment with *Rhizobium* + PSB + *Azotobacter*) and minimum population (14.00×10^6 CFU/g) was observed in S₈ (Uninoculated control) at 30 DAS. The combined inoculation of *Rhizobium* + PSB + *Azotobacter* increased population of *Azotobacter* in soil (2.71-fold) with respect to uninoculated control (14.00×10^6 CFU/g). At harvest stage the maximum population (29.17×10^6 CFU/g) was reported in S₇ (Seed treatment with *Rhizobium* + PSB + *Azotobacter*) and minimum population (10.50×10^6 CFU/g) was observed in S₈ (Uninoculated control). The combined inoculation of *Rhizobium* + PSB + *Azotobacter* increased population of *Azotobacter* in soil (2.78-fold) with respect to uninoculated control (10.50×10^6 CFU/g). This increase in population might be due to direct inoculation through seed treatment, introducing efficient strains into the soil. *Rhizobium* and PSB enhanced root exudation and created a nutrient rich environment for *Azotobacter* multiplication.

Effect of molybdenum: The result showed that effect of molybdenum was non-significant for pH and EC. Molybdenum, especially in low doses, does not significantly alter soil pH and EC. Soil pH and EC changes are generally slow and cumulative over time. In a short experimental duration, no significant shift may be observed. The effect of molybdenum was found non-significant for nitrogen content. Molybdenum acts within the plant, supporting nitrogenase activity for nitrogen use, not for adding nitrogen to soil. This might be the reason for this. Similar findings were reported by Patel et al. (2024) in green gram. Phosphorous content in post-harvest soil was significantly affected by molybdenum. The maximum phosphorous content (14.72 kg/ha) in post-harvest soil was found in Mo₂ (Foliar spray of Mo@0.05% at pre-flowering stage). Foliar spray of Mo@0.05% at pre flowering stage increased the phosphorous content (10.75%) with respect to basal application of Mo@1.5kg/ha (13.29 kg/ha). Foliar molybdenum treatment generally causes less disturbance to soil phosphorous dynamics which allows more phosphorous to remain in the soil. Foliar spray of molybdenum improves root exudation without disrupting soil chemistry. Healthy plants produce greater amount of root exudates like citric acid and malic acid which can solubilize bound phosphorous in the soil. Similar results were found by Rana et al. (2025) in maize and soyabean and Karpagam and Rajesh (2014) in green gram. The effect of molybdenum was found significant for potassium content in post-harvest soil. The highest potassium content (101.14 kg/ha) was observed in Mo₂ (Foliar spray of Mo@0.05% at pre-flowering stage). Foliar spray of Mo@0.05% at pre-flowering stage increased the potassium content (7.42%) with respect to basal application of Mo@1.5kg/ha (94.15 kg/ha). Foliar application causes no disturbance in soil nutrient pools so potassium is not lost due to interaction with Mo. That is why in foliar application more available potassium was there. Also, healthy plant release organic acids from roots which may help in potassium solubilization. The maximum molybdenum content (0.078 ppm) was obtained in case of Mo₁ (Basal application of Mo@1.5 kg/ha). Basal application of Mo@1.5 kg/ha increased molybdenum content (20.00%) with respect to foliar spray of Mo@0.05% at pre-flowering stage (0.065 ppm). Soil applied molybdenum leaves more molybdenum than foliar application that's why Mo₁ (Basal application of Mo@1.5 kg/ha) resulted in more molybdenum content in post-harvest soil. The results are in agreement to those reported by Patel et al. (2024). The maximum value of organic carbon content (0.44 %) was obtained in Mo₁ (Basal application of Mo@1.5 kg/ha). Soil applied molybdenum improves Mo availability in the rhizosphere, stimulating nodulation and root development. More robust roots and nodules contribute more biomass to the soil after decomposition. Thus, it leads to more organic carbon content in the soil. At 30 DAS the maximum value (33.04×10^6 CFU/g) was obtained in Mo₁ (Basal application of Mo@1.5 kg/ha) because soil application of molybdenum leads to survival of *Rhizobium* and multiplication near roots. Basal application of Mo@1.5 kg/ha increased population of *Rhizobium* (1.17-fold) with respect to foliar spray of Mo@0.05% at pre-flowering stage (28.08×10^6 CFU/g). At harvest stage the highest population (22.04×10^6 CFU/g) was observed in Mo₁ (Basal application of Mo@1.5 kg/ha). Basal application of Mo@1.5 kg/ha increased population of *Rhizobium* (1.10-fold) with respect to foliar spray of Mo@0.05% at pre-flowering stage (19.96×10^6 CFU/g). Similar results were reported by Patel et al. (2024). At 30 DAS the highest PSB population (34.63×10^6 CFU/g) observed at 30 DAS was from Mo₁ (Basal application of Mo@1.5 kg/ha). Basal application of Mo@1.5 kg/ha increased population of PSB (1.07-fold) with respect to foliar spray of Mo@0.05% at pre-flowering stage (32.42×10^6 CFU/g). At harvest stage the



maximum population (30.21×10^6 CFU/g) was observed in Mo₁ (Basal application of Mo@1.5 kg/ha). Basal application of Mo@1.5 kg/ha increased population of PSB (1.06-fold) with respect to foliar spray of Mo@0.05% at pre flowering stage (28.38×10^6 CFU /g). At 30 DAS the maximum population of *Azotobacter* (24.08×10^6 CFU /g) at 30 DAS was observed in Mo₁ (Basal application of Mo@1.5 kg/ha). Basal application of Mo@1.5 kg/ha increased population of *Azotobacter* (1.11-fold) with respect to foliar spray of Mo@0.05% at pre-flowering stage (21.75×10^6 CFU /g)). At harvest stage the maximum population (19.00×10^6 CFU /g) was observed in Mo₁ (Basal application of Mo@1.5 kg/ha). Basal application of Mo@1.5 kg/ha increased population of *Azotobacter* (1.11-fold) with respect to foliar spray of Mo@0.05% at pre flowering stage (17.13×10^6 CFU /g).

Effect of interaction: The effect of interaction on pH, EC, Nitrogen content, Phosphorous content, Molybdenum content and Organic carbon content was found to be non-significant. The interaction between molybdenum and microbial inoculants was significant for potassium content. This might be due to enhanced microbial solubilization of K from soil minerals, supported by better root growth from molybdenum. The maximum value (118.31 kg/ha) was observed in S₇Mo₂ treatment combination (Seed treatment with *Rhizobium* + PSB + *Azotobacter* + Foliar spray of Mo@0.05% at pre-flowering stage). The minimum value (80.42 kg/ha) was observed in S₈Mo₁ (Uninoculated control + Basal application of Mo@1.5 kg/ha). PSB and *Azotobacter* release organic acids that solubilize potassium from soil minerals. *Rhizobium* and *Azotobacter* improve root growth and exudation. Molybdenum increases microbial efficiency which leads to potassium cycling. At 30 DAS the maximum *Rhizobium* population (54.67×10^6 CFU /g) observed in S₇Mo₁ (Seed treatment with *Rhizobium* + PSB + *Azotobacter* + Basal application of Mo@1.5 kg/ha). The minimum population (14.67×10^6 CFU /g) was observed in S₈Mo₂ (Uninoculated control + Foliar spray of Mo@0.05% at pre-flowering stage). The maximum *Rhizobium* population at harvest stage (34.67×10^6 CFU /g) was observed in S₇Mo₁ (Seed treatment with *Rhizobium* + PSB + *Azotobacter* + Basal application of Mo@1.5 kg/ha). The minimum population (10.33×10^6 CFU /g) was observed in S₈Mo₂ (Uninoculated control + Foliar spray of Mo@0.05% at pre-flowering stage). The increase in population of *Rhizobium* might be due to synergistic relationship between the molybdenum and microbial inoculants. Molybdenum is key component of nitrogenase which is responsible for nitrogen fixation in *Rhizobium*. Molybdenum enhances the proliferation of *Rhizobium*. It improves root exudate quality and nodulation which creates favourable environment for *Rhizobium* multiplication. The maximum PSB population (50.67×10^6 CFU/g) was observed in S₇Mo₁ (Seed treatment with *Rhizobium* + PSB + *Azotobacter* + Basal application of Mo@1.5 kg/ha) at 30 DAS. The minimum population (21.33×10^6 CFU /g) was observed in S₈Mo₂ (Uninoculated control + Foliar spray of Mo@0.05% at pre-flowering stage). At harvest stage the maximum population (46.67×10^6 CFU/g) was observed in S₇Mo₁ (Seed treatment with *Rhizobium* + PSB + *Azotobacter* + Basal application of Mo@1.5 kg/ha). The minimum population (16.00×10^6 CFU /g) was observed in S₁Mo₁ (Seed treatment with *Rhizobium* + Basal application of Mo@1.5 kg/ha) The interaction increased the population by combining the benefits of Mo-enhanced nutrient metabolism with inoculant-driven root growth and exudation. The maximum *Azotobacter* population (40.67×10^6 CFU/g) was observed in S₇Mo₁ (Seed treatment with *Rhizobium* + PSB + *Azotobacter* + Basal application of Mo@1.5 kg/ha) at 30 DAS. The minimum population (11.33×10^6 CFU /g) was observed in S₂Mo₂ (Seed treatment with PSB + Foliar spray of Mo@0.05% at pre-flowering stage). At harvest stage the maximum *Azotobacter* population (31.00×10^6 CFU/g) was observed in S₇Mo₁ (Seed treatment with *Rhizobium* + PSB + *Azotobacter* + Basal application of Mo@1.5 kg/ha). The minimum population (9.00×10^6 CFU /g) was observed in S₂Mo₂ (Seed treatment with PSB + Foliar spray of Mo@0.05% at pre-flowering stage).

5.FINDINGS:

1. Application of combined inoculation of seeds with *Rhizobium* + PSB + *Azotobacter* resulted in significant increase in Nitrogen, Phosphorous, Potassium, Molybdenum, Organic Carbon content, *Rhizobium*, PSB and *Azotobacter* population.
2. Application of foliar spray of Mo@0.05% at pre-flowering stage resulted in significant increase in Phosphorous and Potassium content.
3. Basal application of Molybdenum @1.5 kg /ha resulted in significant increase in Molybdenum and Organic carbon content, *Rhizobium*, PSB and *Azotobacter* population in soil.
4. Effect of interaction between microbial inoculants and molybdenum was significant for Potassium content, *Rhizobium*, PSB and *Azotobacter* population



6.CONCLUSION:

Based on the results obtained from the study, it can be concluded that combined seed inoculation of *Rhizobium* + PSB + *Azotobacter* and both modes of application of molybdenum (Foliar spray of Mo@0.05% at pre-flowering stage and

Treatments	Soil pH at harvest	Soil EC (dSm ⁻¹) at harvest	Soil available N (kg ha ⁻¹) at harvest	Soil available P (kg ha ⁻¹) at harvest	Soil available K (kg ha ⁻¹) at harvest	Soil available Mo (ppm) at harvest	Soil OC (%) at harvest
Factor A (Seed treatment with microbial inoculants)							
S ₁ (<i>Rhizobium</i>)	5.52	0.06	117.08	12.53	92.25	0.071	0.36
S ₂ (PSB)	5.54	0.07	125.44	14.78	99.32	0.068	0.38
S ₃ (<i>Azotobacter</i>)	5.55	0.07	125.44	13.25	93.66	0.066	0.37
S ₄ (<i>Rhizobium</i> + PSB)	5.56	0.06	129.62	15.28	102.30	0.076	0.46
S ₅ (PSB + <i>Azotobacter</i>)	5.55	0.06	112.90	15.01	104.73	0.074	0.45
S ₆ (<i>Rhizobium</i> + <i>Azotobacter</i>)	5.52	0.07	150.53	13.38	94.46	0.075	0.43
S ₇ (<i>Rhizobium</i> + PSB + <i>Azotobacter</i>)	5.48	0.08	158.89	15.42	107.53	0.079	0.54
S ₈ (Uninoculated control)	5.66	0.06	108.71	12.39	86.89	0.064	0.35
S.Em (±)	0.07	0.00	9.74	0.63	1.77	0.002	0.01
CD (p=0.05)	0.20(NS)	0.01(NS)	28.12(S)	1.82(S)	5.11(S)	0.007(S)	0.03(S)
Factor B (Molybdenum application)							
Mo ₁ (Basal application of Mo@1.5kg/ha)	5.54	0.07	129.62	13.29	94.15	0.078	0.44
Mo ₂ (Foliar spray of Mo@0.05% at pre-flowering stage)	5.55	0.06	127.53	14.27	101.14	0.065	0.39
S.Em (±)	0.03	0.00	4.87	0.31	0.89	0.001	0.01
CD (p=0.05)	0.10(NS)	0.01(NS)	14.06(NS)	0.91(S)	2.56(S)	0.004(S)	0.02(S)
Interaction(A×B)							
S.Em (±)	0.10	0.01	13.77	0.89	2.50	0.003	0.01
CD (p=0.05)	0.28(NS)	0.02(NS)	39.77(NS)	2.57(NS)	7.23(S)	0.010(NS)	0.04(NS)
CV(%)	3.07	13.87	18.55	11.00	4.44	8.393	6.24

Basal application of Mo@1.5 kg/ha) are effective in improving soil health in Red and Lateritic zone of West Bengal.

Table 1: Effect of microbial inoculants and molybdenum application on soil pH, soil EC, available N (kg ha⁻¹), available P (kg ha⁻¹), available K (kg ha⁻¹), available Mo (ppm), soil organic carbon content (%) after harvesting of black gram crop.



Treatments	<i>Rhizobium</i> population ($\times 10^6$ CFU /g)		PSB population ($\times 10^6$ CFU /g)		<i>Azotobacter</i> population ($\times 10^6$ CFU /g)	
	30 DAS	Harvest stage	30 DAS	Harvest stage	30 DAS	Harvest stage
Factor A (Seed treatment with microbial inoculants)						
S ₁ (<i>Rhizobium</i>)	37.50	26.33	23.50	18.33	14.83	11.33
S ₂ (PSB)	16.33	12.83	37.50	33.83	14.33	11.00
S ₃ (<i>Azotobacter</i>)	15.83	12.17	23.67	19.17	21.33	16.67
S ₄ (<i>Rhizobium</i> + PSB)	42.50	28.67	43.00	39.17	18.50	14.00
S ₅ (PSB + <i>Azotobacter</i>)	16.00	12.00	45.33	41.00	29.33	24.83
S ₆ (<i>Rhizobium</i> + <i>Azotobacter</i>)	49.17	30.50	23.33	19.17	33.00	27.00
S ₇ (<i>Rhizobium</i> + PSB + <i>Azotobacter</i>)	51.50	33.67	48.67	45.50	38.00	29.17
S ₈ (Uninoculated control)	15.67	11.83	23.17	18.17	14.00	10.50
S.E.m ($\pm$)	0.48	0.52	0.80	0.81	0.78	0.50
CD (p=0.05)	1.39(S)	1.51(S)	2.32(S)	2.34(S)	2.25(S)	1.44(S)
Factor B (Molybdenum application)						
Mo ₁ (Basal application of Mo@1.5kg/ha)	33.04	22.04	34.63	30.21	24.08	19.00
Mo ₂ (Foliar spray of Mo@0.05% at pre-flowering stage)	28.08	19.96	32.42	28.38	21.75	17.13(S)
S.E.m ($\pm$)	0.24	0.26	0.40	0.41	0.39	0.25
CD (p=0.05)	0.70(S)	0.76(S)	1.16(S)	1.17(S)	1.12(S)	0.72(S)
Interaction(A×B)						
S.E.m ($\pm$)	0.68	0.74	1.14	1.15	1.10	0.70
CD (p=0.05)	1.97(S)	2.14(S)	3.28(S)	3.31(S)	3.18(S)	2.03(S)
CV(%)	3.87	6.11	5.87	6.78	8.31	6.75

Table 2: Effect of microbial inoculants and molybdenum application on *Rhizobium* population ($\times 10^6$ CFU /g), PSB population ($\times 10^6$ CFU /g) and *Azotobacter* population ($\times 10^6$ CFU /g) after

REFERENCES:

1. Akhtar, N., Arshad, I., Shakir, M. A., Qureshi, M. A., Sehrish, J., and Ali, L. (2013). Co-inoculation with *Rhizobium* and *Bacillus* sp. to improve the phosphorus availability and yield of wheat (*Triticum aestivum* L.). *Journal of Animal and Plant Sciences*, **23**(1), 190.
2. Chanu, C. K., Sarangthem, I., Devi, N. S., Luikham, E., Singh, N. G., and Sharma, L. D. (2020). Effect of nitrogen and molybdenum on crop growth, yield and soil properties of pea in acid soil (*Pisum sativum* L.). *International Journal of Chemical Studies*, **8**(5), 2023–2027.
3. Goud, V. V., Kale, H. B., and Patil, A. N. (2010). Performance of organically grown mungbean under rainfed condition in vertisol. *Journal of Food Legumes*, **23**, 218–222.



4. Jamir, A., Gohain, T., and Sentimenla. (2022). Effect of phosphorus and biofertilizers on soil physico-chemical properties and nutrient uptake by black gram (*Vigna mungo* L. Hepper) under rainfed condition of Nagaland. *The Pharma Innovation Journal*, **11**(5), 1255–1258.
5. Karpagam, J., and Rajesh, N. (2014). Molybdenum application for enhancing growth, yield and soil health on green gram (*Vigna radiata* L.). *American-Eurasian Journal of Agriculture and Environment Sciences*, **14**(12), 1378–1381.
6. Khandelwal, R. (2012). Response of cowpea [*Vigna unguiculata* (L.) Walp] to nitrogen and phosphorus fertilizers and seed inoculations. *Legume Research*, **35**, 235–238.
7. Nosheen, S., Ajmal, I., and Song, Y. (2021). Microbes as biofertilizers, a potential approach for sustainable crop production. *Sustainability*, **13**(4), 1868.
8. Patel, D. A., Malav, J. K., and Jat, J. R. (2024). Synergistic Effects of Phosphorus, Molybdenum, and *Rhizobium* on Greengram (*Vigna radiata* L.) Yield in Light Textured Soil. *International Journal of Plant and Soil Science*, **36**(12), 496-506.
9. Rajasekaran, M., Swaminathan, C., Peter, F., Niemsdorff, and Karthikeyan, N. (2011). Effects of combined application of biofertilizers with neem cake on soil fertility, grain yield and protein content of blackgram (*Vigna mungo* L.). *World Journal of Agricultural Sciences*, **7**, 583–590.
10. Rana, M. S., Alshehri, D., Wang, R. L., Imran, M., Abdellah, Y. A. Y., Rahman, F. U., ... and Hu, C. X. (2025). Effect of molybdenum supply on crop performance through rhizosphere soil microbial diversity and metabolite variation. *Frontiers in Plant Science*, **15**, 1519540.
11. Sharma, S., Pathak, R. K., and Pandey, H. P. (2019). Combined Effect of *Rhizobium*, Phosphorus Solubilizing Bacteria and *Azotobacter* Inoculation on Nodulation, Nutrient Uptake and Yield of Chickpea Under Amended Alkali Soil. *International Journal of Advances in Agricultural Science and Technology*, **6**(11), 28-34.
12. Shinde, P. B., Prajapati, D. R., Ali, S., and Munde, S. D. (2013). Soil fertility and quality parameters as influenced by INM in soybean grown during summer season under different land configuration. *Advance Research Journal of Crop Improvement*, **4**(1), 70–73.
13. Singh, B., Khandelwal, R. B., and Singh, B. (1992). Effects of manganese and molybdenum fertilization with *Rhizobium* inoculation on the yield and protein content of cowpea. *Journal of the Indian Society of Soil Science*, **40**(4), 738-741.
14. Singh, S. R., Bhat, M. L., Wani, J. A., and Najar, G. R. (2009). Role of *Rhizobium* and VAM fungi for improvement in fertility and yield of greengram under temperate conditions. *Journal of the Indian Society of Soil Science*, **57**, 45–52.
15. Stewart, W. M., and Roberts, T. L. (2012). Food security and the role of fertilizer in supporting it. *Procedia Engineering*, **46**, 76-82.
16. Yadav, S., Kumar, S., Anshuman, K., Singh, N., Srivastava, A., Yadav, D. K., and Dev, A. (2021). Studies on effect of different biofertilizers on nutrients availability and uptake of nutrients under chickpea crop. *The Pharma Innovation Journal*, **10**(4), 546–549.
17. Youssef, M. M. A., and Eissa, M. F. M. (2014). Biofertilizers and their role in management of plant parasitic nematodes. A review. *Journal of Biotechnology and Pharmaceutical Research*, **5**(1), 1-6.



Bridging the Values-Action Gap in Sustainable Brand Engagement Among Gen Z and Millennials

Deeya Bandyopadhyay^a, Dr. Amrita Majumdar^b

^a Research Scholar, Jharkhand Rai University, Ranchi, Jharkhand – 834010

^b Associate Professor, Jharkhand Rai University, Ranchi, Jharkhand – 834010

Abstract: In 2025, sustainability in lifestyle choices has moved away from an alternative way of life to mainstream consumer choices, especially amongst young consumers in India. The digitally active youth, across the world, are portrayed as drivers of ethical and sustainable consumption. This paper tries to understand whether this expressed attitude contradicts their purchase behaviour. The study examines whether the gap between the attitude and the behaviour is statistically significant to impact adoption of sustainability, through a mixed-method analysis of 250+ consumers who identify as Gen Z and Millennials. The disparity is tested, and the reasons behind such inconsistency in purchase decisions. The study found that price elasticity, convenience of access, lack of trust in brand claims, and cognitive overload were the prime inhibitors. Both groups, Gen Z and Millennials, showed ethical awareness of the severity of this issue; however, they differ in behavioural consistency. The former show more idealism, while Millennials show a cynical attitude towards claims of sustainability. The paper establishes that systemic interventions in marketing style and policy that reframe sustainability as a behavioural challenge, and that is the need of the hour to face the structural challenges in sustainability adoption.

Keywords: Values-Action Gap, Consumer Behaviour, Green Branding, Greenwashing, Sustainable Branding.

1. INTRODUCTION

Philip Kotler wrote in his work *Marketing 5.0* (2021) that we live in a world in which for the first time in history five generations were living together on Earth. These were people with contrasting attitudes, preferences, and behaviours. While the older executives are taking most corporate decisions, it is the digital-savvy Generations Y and Z that form the largest workforce as well as the biggest consumer markets. Kotler mentions that the disconnect between the older generations and their younger managers and customers would prove to be a significant stumbling block, and one of these famous stumbling blocks has been identified as the rising consumer demand of sustainability.

A 2025 article in *Plastic Bank* argued that 82% of shoppers chose brands the values of which aligned with their own (Lutte Engao, 2025). Consumers were investing in brands that upheld ideals beyond profit and were taking responsibility of the impact they had. In 2021, Greg Petro wrote in *Forbes Magazine* that although the pandemic did not start the sustainability revolution, it surely put it into hyperdrive, and Gen Z was in the driver's seat (Petro, 2021). The article claimed that Gen Z and millennials were inclined to buy according to their values, and were also willing to pay more for ethical products. A 2022 *World Economic Forum* article argued that Gen Z was the most concerned among all generations for the planet's wellbeing. This generation was actively advocating buying decisions that could benefit the planet (Wood, 2022). Another *Forbes* article in 2024 mentioned that the rise of sustainability is not a mere movement but a shift in consumer consciousness. Consumers today have redefined their purchasing patterns according to their values, driving up their demand for eco-conscious practices and ethical sourcing (Galer, 2024).

In a survey conducted by Deloitte across 44 countries, the results revealed that the Gen Z (65% of them) and the millennials (63% of them) were worried about the environment. The concerned groups were willing to pay more for



ethical and sustainable options. Their environmental concerns influenced their consumer behaviour. Some, 22-23% of both groups mentioned they would check the environmental impact of a company before accepting a job from them (2025 Gen Z and Millennial Survey, 2025).

There is, now, an international upsurge of ethical production, and eco-conscious living has translated into shifts in consumer behaviour, particularly among the youth who dominate consumption economy today (Kapoor, 2023; Jain et al., 2024).

In 1975, the American Marketing Association (AMA) coined the term “green marketing” during a workshop on ecological marketing. Ever since, the term has gained popularity. During this phase, they positioned this as a CSR initiative for brands. Since that time several works have been published on this topic, such as Martin Charter’s *Greener Marketing: A Responsible Approach to Business* (1992), Walter Coddington’s *Environmental Marketing: Positive Strategies for Reaching the Green Consumer* (1993), Jacquelyn Ottman’s *Green Marketing: Challenges and Opportunities for the New Marketing Age* (1993) (Polonsky, 1994). These texts shifted the academic and industry lens of looking at green marketing as a way of promoting products with environmental characteristics to having a holistic approach to a sustainable future. They highlighted the importance of lifestyle choices on the planet and the role and responsibility of brands on this issue.

Michael Jay Polonsky also asked and answered why green marketing was important back in 1994. While individuals and companies have for generations exercised their right to freedom of choice, as we face the inevitable limits of resources on this planet brands must come up with alternative ways to fulfill mankind’s unlimited wants.

In 2002, Arlo Brady made common the usage of the term “sustainable branding” instead of “green marketing” which meant positioning sustainability at the core of a brand’s identity, influencing its values and operations (Brady, 2003). He stressed on the need for sustainability marketing and sustainable branding to reflect a shift away from short-term, profit-driven goals towards futuristic perspectives that could balance profits with social and environmental responsibility. This came at the behest of a few causes. Consumers had started to show greater demand to align their purchases with their value systems. Secondly, due to the influence and widespread usage of social media, brands were under more scrutiny, which made them easy to expose in case of false claims. Governments had started introducing stricter sustainability standards, and investors were considering environmental, social, and governance (ESG) criteria before they made investments (Abdelkader, 2024). The most important of all these causes was probably the rise of a generation that was demanding more ethical decisions than any other generation in the past.

The world’s largest Gen Z population lives in India, and hence, we have seen a surge in sustainable brand campaigns across niches (Chaturvedi, 2024). While the Gen Z’s loud and pronounced environmental advocacy is not merely performative, one must also consider that this generation has grown up in a hyper-consumerist economy. Although more likely than any other generation to research a brand’s ethics and environmental impact before buying, in the first 19 weeks of 2025 alone, Shein’s app amassed over 54 million downloads, dominated by Gen Z. On one hand, the second-hand market or thrift market as it is called, is expected to hit US\$329 billion globally by 2029 because of Gen Z efforts, on the other hand, fast fashion is also on the rise, along with overconsumption. Acclaimed as the generation inspiring and driving the sustainability shift, studies have revealed a complex cognitive dissonance: despite their strong preference of an eco-conscious lifestyle, Gen Z is drawn to fast, trend-driven consumption. This disparity between attitude and behaviour, known as the “values-action gap,” becomes a distinguishing feature of Gen Z consumerism (Panetta, 2025).

Despite the presence of strong values surrounding environmentalist advocacy, the question arises if consumer behaviour deviate from the professed value. Known as the Values-Action Gap or the Attitude-Behaviour Gap, this divide raises essential questions on sustainable practices and their adoption (Sankhala, 2024).

Interestingly, sustainability is used by young consumers as a common form of identity signalling (through hashtags, content sharing, and influencer alignment) even when they are not making purchase decisions based on said values (Basumatary et al., 2023; Sagar et al., 2025). A few studies have pointed out the common causes that result in this gap: uneconomic sustainable options, unproven claims of sustainability, and decision fatigue (Theocharis & Tsekouropoulos, 2025; Chaturvedi, 2024).

This paper empirically tests the Values-Action Gap and compares Gen Z vs Millennials (digitally aware and semi-urban) using statistical evidence, whether the widely observed Values-Action Gap (where values outpace actions) can be



validated within this segment. It asks where this Values-Action Gap begins, how it pans out across the two generations, and if anything can be done to close the gap.

Although not representative of Indian consumers in general, the findings aim to provide exploratory insight into the digital-first youth of India since they are often the early adopters of sustainability trends.

2. Research Questions

The paper will try to answer:

RQ1: Can the Values-Action Gap be empirically validated among these two generational cohorts in India?

RQ2: On what level do the digitally active, urban/semi-urban Gen Z and Millennials in India possess an awareness or understanding of sustainability of brands in India? How does it differ across them?

RQ3: What factors are contributing to widening this, and the resolution of which may close this gap? Why does this discrepancy persist between generations?

What is the Values-Action Gap?

The Values-Action Gap, or the Attitude-Behaviour Gap, or as in this case, the Sustainability Intention Gap (Sankhala, 2024) is the disconnect of behaviour from principles that state a preference for eco-friendly products but the stated desire does not convert to purchase decisions (Theocharis & Tsekouropoulos, 2025; Chalapathi & Rajini, 2024).

The Theory of planned behavior (1991) by Icek Ajzen provides a useful framework here. This theory explains how and why people engage or not engage in a particular behaviour. According to Ajzen, actions are guided by their intentions, which are shaped by:

- a) Attitude towards behaviour
- b) Subjective norms
- c) Perceived behavioural control (PBC)

The first factor states that people consider whether they benefit from a particular behaviour, such as “If I buy this product, I help the planet.” Hence, when the impact of a behaviour is positive, attitude towards it is typically positive. The second factor considers the magnitude of social or peer pressure surrounding a concept. For example, since sustainability has become an integral part of the youth’s belief system, and hence, there could be peer pressure to conform to these values. It is part of identity signalling. The third factor, the most important one, states how easy or difficult it is for a person to follow through on a behaviour. This depends on past experiences, anticipated barriers, and accessibility, such as, if a person feels ethically-sourced products are significantly expensive, they might not feel motivated to make the purchase. Even though the motivation, and identity signalling is strong, lack of control over key aspects like affordability or availability may hinder action. Hence, intention does not guarantee behaviour.

Thus, Behaviour is the result of Intention and Perceived Behavioural Control, while Intention is the sum of Attitude, Subjective Norm, Perceived Behavioural Control.

In short, the presence of intention does not guarantee required behaviour unless individuals also perceive that they have control over their choices. Hence, even if Gen Z’s motivation towards sustainable products is high because of moral values and social acceptance, other factors in the model will weaken their resolve.

In the case of sustainable products, perceived cost, convenience, and product availability often serve as behavioural barriers.

Complementary to Ajzen’s ‘theory of planned behaviour’ (TPB), the Cognitive Dissonance Theory, proposed by Leon Festinger in 1957, explains that people experience psychological discomfort people when they behave in ways that conflict with their internalized values. Hence, when people cannot change their behaviour, they often resolve the dissonance by rationalizing inaction or minimizing the importance of their values (Prashar & Kaushal, 2025), such as one might think, “My one purchase does not have that much of an impact”, or “I cannot afford ethically sourced products right now.”



It is essential to assess whether this persisting Values-Action Gap is statistically significant among the digitally active Gen Z and Millennials. This study empirically examines the gap within this demographic, testing whether their stated willingness to pay for sustainability translates into consistent action.

3.Methodology

Research Design

The study adopts an exploratory, and comparative design to examine the Values-Action Gap in sustainability-related consumption among India's digitally active youth. The focus remains on two generational cohorts that constitute most online consumers in the country, the Gen Z (aged 18-28) and Millennials (aged 29-45).

Data Collection and Sample

Primary data were collected through a structured online questionnaire distributed via social media and email. The dataset comprised 250+ valid responses and represents only urban and semi-urban, digitally active respondents rather than representing India's entire youth population in general.

Participation was voluntary and anonymous, without sensitive or personal data and have been solely used solely for academic analysis.

Because the expanded dataset draws from a small, digitally active, urban base, results are exploratory rather than generalizable. The findings only offer insights into the sustainability choices of digital-first Indian youth.

Questionnaire Structure

The survey contained 22 items grouped under six domains:

- a) Awareness and understanding of sustainable products and brands
- b) Values and willingness to pay more, if needed, for ethical products
- c) Behavioural action (self-reported frequency of checking sustainability during shopping)
- d) Trust mechanisms, indicators of credibility like certifications, endorsements, social proof, etc.
- e) Likert-scale agreement on the influence of ethical marketing during shopping decisions
- f) Whether practising sustainable lifestyle options personally

Responses were categorical or 5-point Likert-type, enabling descriptive and comparative analysis.

The objective to empirically test the existence of the Values-Action Gap (i.e. the discrepancy between the stated willingness to act sustainably and the self-reported sustainable behaviours) yielded the following:
The test compared:

- a. Willingness (Value): "Are you willing to pay more if you learn a brand has ethically sourced their materials, paid workers fairly, and hurt no one in the process?"
- b. Behaviour (Action): "How often do you stop to consider if a brand is sustainable?"

Hypothesis

- H_0 (Null Hypothesis): There is no significant difference between stated willingness and actual sustainable action among respondents.
- H_1 (Alternative Hypothesis): There is a significant difference between stated willingness and actual sustainable action, indicating a Values-Action Gap.

Data Coding and Preparation

Responses were converted into binary numerical values first.

- i. For willingness, "Yes" responses were coded as 1, while "Maybe" and "No" were coded as 0.



ii. For action, “Always” responses were coded as 1, and “Sometimes”, “Rarely”, and “Never” were coded as 0.

Only respondents who answered both questions were included, resulting in a final paired sample of 279 observations.

Given from data

- Mean (Willingness) = 0.56
- Mean (Action) = 0.43
- For each respondent, a paired difference score was calculated as:

$$d_i = \text{Action}_i - \text{Willingness}_i$$

$$\bar{d} = 0.43 - 0.56 = -0.13$$

Standard deviation of paired differences (s_d) = 0.78

Standard error

$$SE = \frac{s_d}{\sqrt{n}} = \frac{0.78}{\sqrt{279}} = \frac{0.78}{16.703} = 0.0469 \text{ (approx)}$$

t-statistic (two-tailed test of $\mu_d = 0$)

$$t = \frac{\bar{d}}{SE} = \frac{-0.13}{0.0469} = -2.8 \text{ (approx)}$$

Degrees of freedom

$$df = n - 1 = 278$$

p-value (two-tailed)

$$p = 2 \times P(T_{278} \geq | -2.8 |) = 0.0055 \text{ (approx) (from the table)}$$

Decision

- $p = 0.0055 < 0.01$

Thus, null hypothesis is rejected.

- Willingness > Action (negative t because we used $d = \text{Action} - \text{Willingness}$).

The gap is statistically significant.

Interpretation

The statistically significant difference confirms the presence of a Values-Action Gap within this urban and digitally active sample.

This finding supports prior theoretical claims (Ajzen, 1991; Prashar & Kaushal, 2025) that intentions toward sustainability often fail to translate into concrete behaviour due to factors such as price sensitivity, perceived convenience, or decision fatigue.

Awareness & Understanding

Question	Response	Gen Z (%)	Cumulative	Millennials (%)	Cumulative
	Fair understanding	33.1	33.1	55.2	55.2



Understanding of Sustainability	Basic understanding	38.4	71.5	30.2	85.4
	Very good understanding	4.7	76.2	14.6	100
	Minimal/No understanding	23.8	100	0	
Source of Knowledge	Internet	30.8		32.3	
	Books/School	26.7		37.5	
	Social media	27.3		10.4	
	Articles/Papers	4.7		14.6	
	Peers (grapevine)	4.7		5.2	
	Other (Collective/All)	5.8		0	

Table 1 Awareness of Sustainable Brands

Awareness is high, but depth varies; most knowledge comes from the internet and formal education, less from experiential or peer sources. Gen Z has higher tentative awareness, while Millennials' awareness is more definite.

Findings align with the findings of Kapoor (2023) and Jain et al. (2024). This shows that the Indian youth are aware of sustainability as a brand theme.

On the other hand, awareness can often be surface-level. Respondents and their peers may lack proper understanding of its meaning and implications. This is especially true among the Gen Z, as per the study by Basumatary et al.

Willingness vs Action

Response	Gen Z (%)	Millennials (%)
Willing to pay more for ethical brands	56.4	52.1
Maybe	30.2	40.6
No	13.4	7.3

Table 2 Data Representing Willingness to Pay More

A majority are willing to pay a premium, supporting the idea that values are aligned with sustainability but not necessarily behaviourally enacted.

This mismatch in Action and Claims highlights that while values are aspirational, it does not guarantee or result in action. The values are rarely acted upon. Literature suggests that on-paper affordability or seeming affordability, convenience of access and use, lack of visible proof, etc. hinder behavioural follow-through (Sankhala, 2024; Theocharis & Tsekouropoulos, 2025).

Behavioural Action

Question	Total Response	%
Heard of 'Sustainable Brands'?	Yes	76.07%
	Maybe	15.00%
	No	8.93%
How often do you stop to consider if a brand is sustainable?	Sometimes	65.71%
	Rarely	17.86%
	Often	11.43%
	Never	5.00%
Stopped buying from unethical brands?	Yes	68.21%
	No	31.79%

Table 3 The Action vs. Behaviour Gap

Awareness and reactive behaviour (boycotting) are relatively high, but proactive checking ("often/always") is low (confirming the Values-Action gap).



Trust Factors

Question	Response	Gen Z (%)	Millennials (%)
Trust in brands claiming to be sustainable (1–5)	3 (neutral)	57	63.5
	1 (very low)	9.9	25
	2 (low)	16.9	5.2
	4-5 (high)	16.3	6.3
What breaks trust?	Lack of proof/transparency	32	41.7
	False claims	23.8	14.6
	Overpricing	10.5	19.8
	Poor Service + Others	33.7	23.9
Trust Indicator	Certifications (e.g., Fair Trade, Organic)	60.0	70.8
	Transparent sourcing info	51.2	60.4
	Social media reviews	35.8	25.0
	Influencer endorsements	17.4	22.9
	Brand reputation	34.3	39.6
	All the above	3.5	0.0

Table 4 Trust Mechanisms

Several studies highlight that young consumers are more probable to pick up sustainable behaviour when:

- The difference in price between conventional products and their sustainable alternatives is not significantly large (Islam, 2024),
- The brand's values are communicated consistently across channels and come with proof of consumers' preference, and
- There is peer influence (Kapoor, 2023; Sankhala, 2024).

Ethical Marketing Impact

Question	Response	Gen Z (%)	Millennials (%)
I believe ethical marketing influences my buying decisions.	Agree	36.6	47.9
	Strongly Agree	18.6	15.6
	Neutral	32	36.5
	Disagree	12.8	0

Table 5 Data representing frequency of sustainable buying decisions

Ethical marketing has positive influence for most respondents, though a third remain neutral, indicating possible scepticism or “ethics fatigue.”

Behaviour (multi-select)	Gen Z (%)	Millennials (%)
Stopped buying from unethical brands	70.4	60.4
Actively discuss sustainability with peers	57.6	83.3
Support integrating sustainability in education	86.0	100.0

Table 6 Sustainability in lifestyle

Generational Split:

Response	Gen Z (%)	Millennials (%)



Strongly Agree	36.0	30.2
Agree	34.9	27.1
Neutral	19.8	31.3
Disagree/Strongly Disagree	9.3	11.4

Table 7 Comparing Gen Z and Millennials in terms of Behaviour

This aligns with identity signalling for Gen Z (emotionally influenced) vs rational proof for Millennials (having a more sceptical stance).

Generational Contrasts (Summary Table)

Sl.	Concern	Gen Z	Millennials
1	Awareness	Higher “Maybe” (tentative)	More definitive “Yes” awareness
2	Trust Markers	More responsive to influencers/social proof	Strong reliance on certifications
3	Ethical Marketing Impact	71% influenced (emotional buy-in)	57% influenced (more neutral/sceptical)
4	Peer Advocacy	Claim willingness, low follow-through	Slightly stronger advocacy but inconsistent
5	Behavioural Actions	Higher intention, less consistent action	More cost-conscious, sceptical, modest follow-through

Table 8 Summary of Attitude-Behaviour in both cohorts

The generational contrast is clear. Gen Z has the higher tentative awareness among the two cohorts, is emotionally influenced but inconsistent in behaviour. Millennials show more definitive awareness, show more trusts towards formal and rational markers, and sceptical towards marketing, also cost-conscious.

4. Discussion

The results reveal a statistically significant Values-Action Gap among digitally active Indian Gen Z and Millennial consumers. The respondents showed substantial sustainability values and awareness of ethical branding, but these values did not find consistent expression in purchase behaviour or daily practices. This confirms the disparity between intention and action in sustainable consumption research among the Indian, digital-first context.

Interpreting the Values-Action Gap

The findings resonate with Ajzen’s *The Theory of planned behaviour* (1991), which posits that behavioural performance depends not only on attitude and intention but also on ‘perceived behavioural control’. The high willingness yet lower follow-through observed in this study suggests that respondents perceive tangible barriers (most notably price, convenience, and limited product access) that constrain sustainable action even when motivation exists. The behaviour gap, therefore, appears not as moral apathy but as a function of pragmatic constraints and perceived effort.

Complementing this, *Cognitive Dissonance Theory* helps explain the psychological adjustment strategies consumers adopt when their actions conflict with their stated values. Many respondents rationalize inaction (“it is too expensive,” “one person’s choice will not matter”) rather than change behaviour, thereby resolving dissonance cognitively rather than behaviourally. This dynamic mirrors earlier findings by Prashar & Kaushal (2025) and further supports the idea that sustainability decisions are not purely value-driven but mediated by self-justifying reasoning.

Generational Patterns

Generational differences within the dataset further clarify the mechanisms of this gap. Gen Z respondents appear idealistic but inconsistent. They are influenced by ethical narratives and emotional marketing, but less decisive in



verifying sustainability claims or integrating sustainable habits. This aligns with identity-signalling (environmental consciousness functions as part of online self-presentation rather than as a consistent behavioural guide) (Basumatary et al., 2023).

Millennials demonstrate rational scepticism. They express awareness, and display steadier sustainable choices. Their comparatively lower responsiveness to ethical marketing and higher demand for proof correspond to their formative experiences with earlier “greenwashing” campaigns, making them cautious evaluators rather than expressive advocates.

Digital Mediation and Trust

The dominance of certification-based trust across both cohorts indicates that rational validation still anchors credibility in sustainability claims. However, Gen Z’s notable openness to influencer or peer cues points to the rising salience of social trust in digital commerce.

Re-conceptualizing the Gap

The Values-Action Gap observed here should not be interpreted solely as consumer hypocrisy. It shows a mismatch between consumer interests and market structure. The Indian sustainability marketplace remains nascent: certified products are premium-priced, and information about genuine ethical practices is fragmented. Bridging this gap thus requires both structural interventions like affordability, and psychological reinforcement.

Contribution to Literature

This study contributes to the growing body of work on sustainable consumer behaviour in India by (a) empirically validating the Value-Action Gap through statistical testing, (b) differentiating generational responses within a digital consumption environment, and (c) contextualizing Ajzen’s and Dissonance frameworks in an emerging-market setting. By focusing on urban, digitally active youth, it identifies a vanguard group whose attitudes often foreshadow broader consumer trends. The results underscore that sustainability among Indian youth is more aspirational than habitual, grounded in awareness and intention but constrained by perceived behavioural control.

The Greenwashing Problem

A few issues, such as ‘Greenwashing’, must be addressed in this regard. ‘Greenwashing’ is when a brand resorts to deceptive or exaggerated claims about the environmental value or impact of their product(s) to gain marketing advantage, while the reality may be far less sustainable (Delmas & Burbano, 2011). And brands may often succeed this way due to inhibitors such as lack of affordability, accessibility, and transparency. When sustainable products cost significantly more, and sport unclear certifications, or misleading “eco” labels, they become inaccessible to consumers.

While sustainable products grow in demand, more Indian brands increasingly engage in marketing their green initiatives, such as Mamaearth claims they use 100% recycled plastic in all their packaging. Similar claims are often made by brands, often without proof, calling into question the authenticity of their claims. Campaigns may depend on superficial or suggestive messaging without having any real impact (“Beyond greenwashing,” 2024). This leads to distrust, especially among Millennials, who demand proof of impact (Chaturvedi, 2024).

However, undeniably the market is changing and so are the awareness levels of consumers. In 2021, Aditya Birla Fashion and Retail Limited (ABFRL) was ranked Asia’s “Most Sustainable Company” in the textile, apparel & luxury goods sector by S&P Global CSA (Aditya Birla Fashion & Retail Ltd., n.d.). Another community farming movement, OOO Farms aims to revive indigenous seeds working with “2,200 farmers to safeguard traditional farming practices and native seeds, thus promoting biodiversity and agroecology. They offer nutritionally dense varieties of grains, pulses, spices and honey produced without chemicals” (Moneycontrol, 2024). Another brand True Browns makes versatile clothing for people across ages and ensure zero waste production, fair wages for their workers, and fabric upcycling. Their ‘30 Wear Campaign’ is a commitment to reduce fashion footprint by making quality clothes that last for 30 perfect-condition wears or more (Moneycontrol, 2024). The coffee brand Araku Coffee, grown in the highlands of Araku Valley in the Eastern Ghats, is certified organic, single origin and selectively harvested. The arabica coffee is exclusively grown in ecologically farmed plantations only (Moneycontrol, 2024). Brands like Beco, and Bare Necessities have also adopted transparency with their ingredients and processes. They have improved their sourcing traceability, and launched cause-



linked campaigns, moving away from tokenism and headed towards meaningful impact (“Beyond greenwashing,” 2024; Chaturvedi, 2024).

To reach out to the younger groups, brands have begun to harness the influencer network, and use eco-labelling while educating their target consumers. Certifications like Fair Trade, PETA, FSC, and expert proofs appeal more to Millennials than social media endorsements (Sagar et al., 2025; Theocharis & Tsekouropoulos, 2025).

Behavioural Contradictions in Green Consumption

The analyses revealed that while intention (value alignment) is strong among both Gen Z and Millennials, the motivation to act is ruptured by:

- Price sensitivity
- Easiness of action vs. inaction
- Shaky trust in brands’ claims
- Uncertain knowledge about impact of individual lifestyle choices

Even though the majority in both cohorts show willingness to pay more for sustainable choices, fewer than half follow through on this during shopping. This finding is supported by the earlier findings of Prashar & Kaushal (2025) and Chaturvedi (2024). Brand efforts to push sustainability is still at an aspirational stage.

Respondents experience discomfort when the misalignment of their values and their behaviours is pointed out (e.g., buying fast fashion while supporting ethical brands). To resolve this discomfort, people engage in some degree of moral licensing (rationalizing inconsistent behaviour by pointing to small eco-friendly actions) as compensation (Bandyopadhyay, 2025). Another reason for such claims can be “identity signalling” (Basumatary et al., 2023). This behaviour can be called “performative sustainability” (sharing content or supporting campaigns without long-term habit change) (Kapoor, 2023).

Millennials show higher scepticism toward green claims, leading to delayed or no action despite alignment with values. This aligns with the findings of “Beyond greenwashing” (2024).

These generational differences suggest distinct characteristics that must be base of marketing strategies:

Gen Z Strength	Millennial Strength
Digital learning, activism	Depth of understanding
Idealistic willingness	Consistency, realism
Boycotting behaviour	Habitual consideration
Social/peer signals	Certification-based trust
Critical and sceptical	Responsive to ethical cues
Personal practice	Social reinforcement

Table 9 Segmenting how both Generational Cohorts behave

Both generations respond positively to transparency and education, but in different ways: Gen Z wants to “see behind the scenes” while Millennials want expert validation.

Systemic Barriers

The Values-Action Gap must be seen as a systemic and design problem, and not as a moral failure on any front. Consumers are fatigued with choices, with little time or patience to research a brand’s claims and trust factors. Ethical products often come at a higher price, or cannot be bought except on specific platforms. Also, communicating a brand’s or product’s sustainability often lacks proof supporting the claims. This is especially true in Indian markets, where consumers are prone to greenwashing (Chaturvedi, 2024; Islam, 2024).

Managerial Steps to Close the Attitude-Behaviour Gap

- Offering affordable sustainable options (cost engineering & tiering)

The basic starting point would be to figure out how to make sustainable options more affordable. Tiers of quality can be decided to offer multiple price tiers.



If the young consumers can afford the sustainable options without paying a premium price, the perceived behavioural control increases.

This could be implemented by bulk procurement of sustainable raw materials, striking long-term contracts with suppliers, reducing margins on FMCGs, partner internationally to provide benefits or discounts to buyers, etc.

2. Improving availability and distribution

Mass-market availability must become the ambition. Sustainable products must be placed in high-street chains, online marketplaces, local stores, pop-up shops, and anywhere else that young people shop. Sustainability should not be a niche confined to boutique stores alone.

3. Transparency & traceability

Any sustainable claims that a brand makes must be made verifiable. Composition of materials, country of origin, certifications, and lifecycle footprints must be trackable with QR codes/tags. The supply-chain must be told to the consumer along with the story of origin, farmer/artisan stories, and third-party audits.

4. Behavioural design & nudges (defaults, social proof, convenience)

The public must be made aware of 'nudges' to make sustainable choices. Making these choices should be the easy/default one. Online platforms could highlight products with tags like "most popular sustainable option," and provide small upfront loyalty points. Sustainability filters on online shopping platforms can help. Also, social proof of adoption of such products is important.

5. Clear, consistent communication

Brands must tell consumers what exactly the product does differently and how it benefits the consumer. Instead of using vague terms like "eco" or "green", concrete facts must be laid down, such as durability, cost-per-wear, etc. Presently, very few brands embrace evidence-based messaging, or disclose trade-offs such as whether the product used recycled polyester for durability, or that "green" may not necessarily mean that the product is biodegradable, but may reduce virgin PET demand.

6. Recycling on a larger scale & take-back schemes

Companies could make recycling and reusing financially attractive (trade-in discounts) so consumers do not feel their purchase is a dead-end. Partnering with resale platforms, or offering store credits for returned items may help greatly with time.

7. Community building

Until adopted on a mass scale, sustainability must be established as a socially rewarded behaviour. Influencer partnerships that demonstrate everyday use could largely help.

8. Measure, report, and reiterate KPIs that matter to consumers

Easily understandable KPIs (e.g., water saved per garment, number of artisans supported, etc.) should be reported. Publishing annual impact reports motivate consumers, such as Coldplay's Sustainability report.

Bridging the Values-Action Gap is the sustainability challenge of our time. For Gen Z and Millennials, consumers who want to do the right thing, it is up to brands, educators, and system designers to make doing the right thing the easiest and most rewarding choice, which seems the main challenge right now.

REFERENCES

1. Petro, G. (2021, April 30). *Gen Z is emerging as the sustainability generation*. Forbes. <https://www.forbes.com/sites/gregpetro/2021/04/30/gen-z-is-emerging-as-the-sustainability-generation/>



2. Wood, J. (2022, March 18). *How Generation Z's sustainability concerns are influencing others' lifestyle and buying decisions*. World Economic Forum. <https://www.weforum.org/stories/2022/03/generation-z-sustainability-lifestyle-buying-decisions/>
3. Kapoor, M. (2023). *Millennials and Gen Z seek sustainable brands*. BW Marketing World. <https://www.bwmarketingworld.com/article/millennials-and-gen-z-seek-sustainable-brands-manisha-kapoor-asci--482574>
4. Jain, N., Sanghi, K., Singhal, A., Chawla, I., Kanekar, V., Trivedi, P., Jha Saurabh, S., Chaubey, A., & Nikam, P. (2024, October 16). *The \$2 trillion opportunity: How Gen Z is shaping the new India*. Boston Consulting Group & Snap Inc. <https://web-assets.bcg.com/87/51/a23cce4443c0bf65422c724a9b73/the-2-trillion-opportunity-how-gen-z-is-shaping-the-new-india.pdf>
5. Chaturvedi, A. (2024, December 6). *Sustainable marketing for Indian brands in 2025: From tokenism to impactful action*. WARC. <https://www.warc.com/newsandopinion/opinion/sustainable-marketing-for-indian-brands-in-2025-from-tokenism-to-impactful-action/en-gb/6927>
6. Sankhala, V. (2024). Cultivating sustainability: Bridging the behavioural attitude gap between Gen Z and millennials in consumer choices. *International Journal of Engineering, Management and Humanities (IJEMH)*, 5(1), 47–66.
7. Basumatary, E., Tandon, V., Sircar, I., & Kushwaha, A. (2023). A study of perception of Gen Z of India about sustainable apparels and its implications in the apparel industry. *Korea Review of International Studies*, 16(Special Issue 09).
8. Sagar, A., Jyothi, A., & Ranjith, P. V. (2025, January 21). Gen Z prefers cosmetic brands that are focused on sustainability and environmental issues. In *BIO Web of Conferences* (Vol. 151, Article 04007). EDP Sciences. <https://doi.org/10.1051/bioconf/202515104007>
9. Theocharis, D., & Tsekouropoulos, G. (2025). Sustainable consumption and branding for Gen Z: How brand dimensions influence consumer behavior and adoption of newly launched technological products. *Sustainability*, 17(9), Article 4124. <https://doi.org/10.3390/su17094124>
10. Chalapathi, B., & Rajini, G. (2024, June 11). Millennial consumer's stance toward sustainable fashion apparel. *Salud, Ciencia y Tecnología – Serie de Conferencias*, 3, Article 885. <https://doi.org/10.56294/sctconf2024885>
11. Ajzen, I. (1991). Theory of planned behavior. *Organizational Behavior and Human Decision Processes*, 50(2), 179–211. [https://doi.org/10.1016/0749-5978\(91\)90020-T](https://doi.org/10.1016/0749-5978(91)90020-T)
12. Prashar, A., & Kaushal, L. A. (2025). Nudging sustainable fashion choices: An experimental investigation on Generation Z fashion consumers. *Acta Psychologica*, 253, Article 104727. <https://doi.org/10.1016/j.actpsy.2025.104727>
13. Beyond greenwashing: How Indian brands are turning sustainability into success strategy. (2024). *Adgully*. <https://www.adgully.com/post/725/beyond-greenwashing-how-indian-brands-are-turning-sustainability-into-success-strategy>
14. Islam, M. (2024). What fad apparel Generation Z consumers purchase in Kolkata? A study of selected fast fashion brands. *International Research Journal of Multidisciplinary Scope*, 5(1), 289–300. <https://doi.org/10.47857/irjms.2024.v05i01.0206>
15. Galer, S. (2024, May 14). *Why the rise of sustainability is a shift in consumer consciousness*. Forbes. <https://www.forbes.com/sites/sap/2024/05/14/why-the-rise-of-sustainability-is-a-shift-in-consumer-consciousness/>
16. Lutte Engao, E. (2025, January 13). *The consumer-driven demand for sustainability*. Plastic Bank. Retrieved October 23, 2025, from <https://plasticbank.com/blog/how-consumer-demand-is-fueling-the-sustainability-shift/>
17. Panetta, M. (2025, June 5). *Gen Z and the sustainability paradox: Why ideals and shopping habits don't always align*. The Conversation. <https://etedge-insights.com/sdgs-and-esg/sustainability/gen-z-and-the-sustainability-paradox-why-ideals-and-shopping-habits-dont-always-align/>
18. Moneycontrol. (2024, August 4). *75 homegrown brands that are championing sustainability*. Retrieved from <https://www.moneycontrol.com/news/trends/lifestyle-trends/75-homegrown-brands-that-are-championing-sustainability-9023091.html>
19. Aditya Birla Fashion & Retail Ltd. (n.d.). *About Us*. Retrieved October 24, 2025, from <https://www.abfirl.com/about-us/>
20. Festinger, L. (1957). *A theory of cognitive dissonance*. Stanford University Press.



21. Delmas, M. A., & Burbano, V. C. (2011). *The drivers of greenwashing*. *California Management Review*, 54(1), 64–87.
22. Lyon, T. P., & Montgomery, A. W. (2015). *The means and end of greenwash*. *Organization & Environment*, 28(2), 223–249.
23. Bandyopadhyay, D. (2025). *Action–value gap in sustainable brand engagement among Gen Z and Millennials*. In S. Sarkar (Ed.), *Sustainable technologies and green initiative* (pp. 190-206). Cognition Publications. <https://doi.org/10.5281/zenodo.17349047>
24. Polonksky, M. J. (1994). An Introduction To Green Marketing. *Electronic Green Journal*, 1(2). doi:10.5070/G31210177
25. Brady, A. (2003). How to generate sustainable brand value from responsibility. *Journal of Brand Management*, 10, 279-289.
26. Abdelkader, A. (2024) A literature review of brand bravery, brand activism, and sustainable branding as contemporary branding strategies: The Social Marketing new era, *Scientific Journal for Financial and Commercial Studies and Research*, Faculty of Commerce, Damietta University, 5(1)1, 509-550.



DOIs:10.2015/IJIRMF/ICICSF-2025-P10

--:--

Research Paper / Article / Review

International Conference On "Innovative Convergence for Sustainable Future"

Date : 12 - 13 December, 2025

(ICICSF-2025)



AI at the Helm: The Silent Role Of Psychological Trust In Fostering Job Confidence

Dr. Anjali Sabale ¹, Aruna Walhekar ²

¹Assistant Professor, IIEBM Indus Business School, Pune 411057 Email Id: anjali.s@iiebm.com

²Assistant Professor, IIEBM Indus Business School, Pune 411057 Email Id: aruna.w@iiebm.com

Abstract: Artificial intelligence (AI) is increasingly assuming roles of authority within organizations, influencing recruitment, task allocation, and performance evaluation. While this transition offers efficiency and innovation, it also introduces subtle psychological challenges for employees who must renegotiate their sense of relevance and competence in AI-driven workplaces. This paper explores the silent but critical role of psychological trust in AI in shaping job confidence, defined as an employee's belief in their continued capability, adaptability, and relevance in evolving work contexts. Building on trust theory, human-AI interaction research, and organizational psychology, this paper develops a conceptual framework that positions psychological trust as both a mediator and a moderator in the relationship between AI integration and employee job confidence. Trust in AI is conceptualized not merely as a technical attribute but as a psychological construct rooted in perceptions of transparency, fairness, reliability, and alignment with human values. Without such trust, even highly efficient AI systems may undermine job confidence by fostering skepticism, anxiety, or resistance. Conversely, when trust is established, AI can be perceived as an empowering ally, enhancing confidence and adaptability.

Keywords: Artificial Intelligence, Psychological Trust, Job Confidence, workplace, Organization, Employees etc

1. INTRODUCTION

The integration of Artificial Intelligence (AI) in workplaces has instigated significant changes in the dynamics of job confidence. This article delves into understanding the silent, yet pivotal role psychological trust plays in shaping perceptions of job security amidst the AI revolution. The advent of Artificial Intelligence (AI) in contemporary workspaces has ushered in transformative changes, not just in operational capacities but also in the intricate realm of human emotions. Among these, the emotion of trust, particularly psychological trust, stands paramount. This article delves into the interplay between AI's expanding role in the workplace and its implications on job confidence, with psychological trust serving as the linchpin in this relationship. Historically, major technological leaps have often been accompanied by trepidations surrounding job displacement. However, AI, with its prowess to tackle both manual and cognitive tasks, brings forth nuanced psychological concerns. The framework of psychological trust encompasses elements such as trustworthiness, predictability, dependability, and faith. When applied to AI, challenges emerge. The 'black-box' nature of many AI systems may engender unpredictability, while their undeniable consistency can foster dependability. This dichotomy underscores the need for transparency and understandability in AI systems, leading to the core of our argument: psychological trust mediates the relationship between AI integration and job confidence. Workers possessing a robust trust in AI's capabilities and intentions are more likely to view it as an augmentative tool rather than a usurping adversary, thus feeling more secure in their job roles. Preliminary empirical evidence aligns with this theory, indicating a positive correlation between a worker's understanding (and subsequent trust) of AI and heightened job assurance. Organizations, as they spearhead into an AI-driven future, must recognize the silent yet profound role of psychological trust. Prioritizing its cultivation could pave the way for a workforce that is not only adept at using AI but also exhibits unwavering job confidence in the face of this technological revolution.

Historical Interactions between Technology and Trust:

Historically, advancements in technology have consistently provoked discussions on trust. Zuboff (1988) in her seminal work on 'informatics of domination' charted the rise of computer-mediated workplaces, outlining the subtle shifts in



trust dynamics. The nature of trust in the era of the internet has been extensively examined by Luhmann (2000), emphasizing the transition from interpersonal trust to trust in systems.

2. Literature Review

Evolution of Artificial Intelligence in Workplaces:

The growth of AI in professional settings has been a subject of keen scholarly interest. Bostrom (2014) provides an exhaustive exploration of the capabilities of superintelligent systems, marking a significant point where AI can potentially outpace human intelligence in several domains. Brynjolfsson and McAfee (2014) further delve into the consequences, predicting both opportunities for job enhancement and challenges of displacement. As organizations increasingly implement AI tools, from basic automation to advanced cognitive systems, a common thread emerges: AI's capability to either substitute or supplement human roles varies, but its impact on worker sentiment is profound.

The Multifaceted Nature of Psychological Trust:

Psychological trust has roots deep in social psychology, being described as the willingness to be vulnerable based on positive expectations (Rousseau et al., 1998). Mayer et al. (1995) expounded upon this, listing trustworthiness, predictability, and dependability as core components. Notably, Kramer (1999) highlighted the distinction between interpersonal and intergroup trust, a demarcation critical when discussing trust in a human-AI context.

AI and Trust Dynamics:

As AI systems become more prevalent in workplaces, their relationship with human users becomes paramount. Turilli and Floridi (2009) propose that understanding the nature of AI's decisions is instrumental in fostering trust. However, challenges arise with 'black-box' AI systems, which, as Burrell (2016) posits, may compromise predictability and subsequently, trust. Yet, Lee and See (2004) argue that the consistent performance of AI systems can enhance their dependability, bolstering trust in the long run.

Trust as a Mediator in AI-Human Interaction:

A stream of research is dedicated to understanding trust as a mediator between technology adoption and resultant behavioral outcomes. Gefen et al. (2003) indicate that trust plays a pivotal role in the acceptance of new technologies. Building on this, Hancock et al. (2011) emphasize the importance of calibrating trust in automation for optimal human-machine teaming.

The Nature of AI in the Workplace:

The dawn of AI has dramatically transformed various facets of our work environments. While the tangible benefits of increased efficiency and automation are evident, the subtle nuances involving human emotions, especially trust, often go unaddressed. This research aims to explore the relationship between AI's presence, psychological trust, and resultant job confidence.

In the narrative of modern workspaces, Artificial Intelligence (AI) emerges as both the protagonist and the disruptor. Its ability to automate tasks, enhance decision-making, and predict outcomes has allowed organizations to ascend to unprecedented heights of efficiency. However, with these transformative capabilities comes an undercurrent of apprehension, particularly concerning the stability and nature of human roles in this rapidly changing environment. How does one reconcile the immense potential of AI with the palpable uncertainty it introduces into job security and role definition?

Historically, the march of progress, marked by technological leaps, has been met with a mix of excitement and fear. The industrial revolution, for instance, heralded an era of mechanization, but it also stoked concerns about the diminishing value of human labor. AI's entrance into the professional domain evokes similar sentiments but amplifies them manifold. Unlike earlier technological advancements that predominantly targeted manual tasks, AI wields the power to replicate, and sometimes even outperform, human cognition. This profound shift places not only job functions but also the essence of human ingenuity under scrutiny.

3. Research Methodology

This paper adopts a **conceptual research design**, which is well-suited for advancing theory in emerging areas where empirical evidence remains limited or fragmented. Conceptual papers do not rely on primary data collection; instead, they integrate and extend existing theoretical and empirical insights to propose novel frameworks (Gilson & Goldberg, 2015). Given the rapid but uneven development of research on artificial intelligence (AI) in organizations, particularly concerning the psychological mechanisms that shape employee outcomes, a conceptual approach allows for the systematic consolidation of diverse streams of knowledge into a coherent model.



Conceptual Propositions

This section presents the theoretical constructs at the heart of this study and positions them within the context of AI integration in modern workplaces. Three central constructs form the core of the conceptual model: AI Integration, Psychological Trust in AI, and Job Confidence.

- **P1:** The implementation of AI systems with authoritative roles negatively impacts employee job confidence in the absence of psychological trust.
- **P2:** Psychological trust in AI mediates the relationship between AI integration and job confidence.
- **P3:** Psychological trust is positively influenced by perceptions of system transparency, reliability, and ethical alignment.
- **P4:** The impact of AI integration on job confidence is moderated by individual differences such as age, technological familiarity, and prior exposure to AI tools.

Conceptual Framework

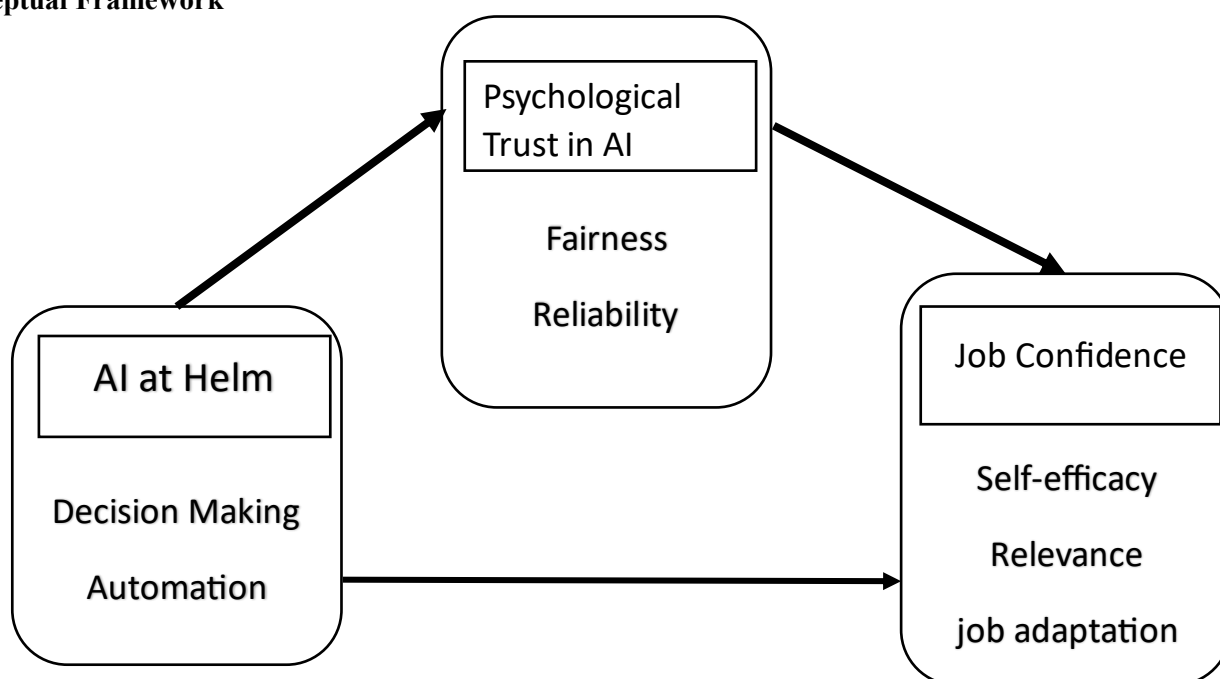


Fig No. 1 Conceptual Contribution (Prepared by Authors)

Theoretical Contributions

This conceptual paper advances theoretical understanding at the intersection of artificial intelligence (AI), organizational psychology, and trust theory in several meaningful ways. In doing so, it addresses a significant void in the literature by focusing not only on how AI is implemented, but also on how it is psychologically *experienced* by employees.

Re-centering Psychological Trust as a Central Interpretive Mechanism

While technical attributes of AI—such as accuracy, reliability, and computational power—have been the traditional focus of AI adoption literature, this paper shifts the lens toward psychological trust as a *subjective and mediating variable*. By positioning trust not as a by-product of effective AI systems but as a central cognitive filter, this research contributes to a more human-centered understanding of digital transformation.

This is significant because employees do not interact with AI systems in an objective vacuum; rather, their perception of the system's fairness, transparency, and intent determines whether they accept, resist, or psychologically disengage. Thus, this paper redefines the relationship between AI systems and human users as not purely functional, but interpretive and trust-mediated.



Redefining Job Confidence as a Psychological Construct in Technological Contexts

The concept of job confidence has traditionally been viewed through the lens of career stability or individual capability, often reduced to skill acquisition or human capital metrics. This paper expands that view by framing job confidence as a fluid, psychologically grounded construct that is dynamically shaped by an employee's interaction with technological systems—particularly AI.

Unlike constructs such as job satisfaction or job security, *job confidence* here is conceptualized as a forward-looking belief in one's relevance, growth potential, and adaptive capacity in an AI-dominated work environment. This reframing opens new theoretical avenues for understanding digital-era work psychology, particularly how emotions and beliefs about technology shape workforce resilience.

Bridging Fragmented Literatures through an Integrative Conceptual Lens

A major contribution of this paper lies in its integration of disparate research domains—namely, AI ethics, human-AI interaction, algorithmic trust, and organizational behavior. These fields, though overlapping in content, often operate in silos with limited cross-theoretical dialogue.

By proposing a conceptual framework that draws from:

- Trust theory (Mayer et al., 1995; McKnight et al., 2002),
- Self-efficacy and job adaptation (Bandura, 1997),
- AI-human collaboration studies (Glikson & Woolley, 2020),
- and algorithmic authority (Kellogg et al., 2020),

this work contributes a synthesized model that captures the psychological experience of AI at work. This theoretical convergence allows researchers to see AI not merely as a technological artifact, but as a social actor with organizational and psychological consequences.

Repositioning AI as a Psychological Actor, Not Just a Tool

Finally, this work contributes to emerging discourse that reimagines AI as a psychologically significant entity within the organizational ecosystem. Rather than viewing AI purely as a neutral or mechanistic tool, we conceptualize it as an institutionalized presence capable of invoking psychological reactions—such as confidence, anxiety, trust, or detachment.

This reconceptualization aligns with growing interest in the social implications of algorithmic systems, but goes further by offering a psychological explanation for how these reactions occur and under what conditions they influence employee outcomes.

Table No 1 Contribution of Conceptual

Contribution Area	Novel Insight
Trust Theory	Reframes trust in AI as a cognitive lens mediating perception and behavior
Organizational Psychology	Introduces job confidence as a dynamic, tech-influenced construct
Human-AI Interaction	Bridges system design with user psychology through the trust mechanism
Multilevel Theorizing	Positions trust as both mediator and moderator, encouraging contextual inquiry
Interdisciplinary Integration	Synthesizes AI ethics, psychological trust, and digital-era HR theories

Practical Implications

The conceptual framework proposed in this paper does not only contribute to theory but also carries critical implications for organizational practice. As artificial intelligence (AI) systems increasingly assume roles of authority in decision-making, recruitment, performance evaluation, and workflow allocation, organizations must carefully manage the *human side* of technological transformation. Below, we elaborate how the insights of this study can inform organizational policies, leadership strategies, and system design.

Building Trust-Centered AI Deployment Strategies

Organizations often measure AI readiness in terms of technical capability or workforce digital literacy. However, this research highlights the importance of fostering psychological trust in AI as a *parallel dimension of readiness*. Trust-centered deployment can be achieved through:

- Transparent communication: Explaining how AI makes decisions, why it is introduced, and how it complements rather than replaces employees.



- Inclusive design: Engaging employees early in pilot testing phases to reduce perceptions of opacity and increase system legitimacy.
- Ethical signaling: Demonstrating organizational commitment to fairness, bias mitigation, and accountability in AI operations.

Such measures help reduce anxiety, uncertainty, and resistance, ultimately strengthening employee job confidence.

From Tool Adoption to Employee Experience Design

A key insight of this paper is the shift from seeing AI as a *technical tool* to treating it as part of the employee experience. Just as organizations invest in leadership development or workplace culture, they must design experiences where employees interact with AI in ways that feel empowering, not alienating.

- For example, instead of deploying AI in performance reviews as a “black box” assessor, organizations could position it as a coaching partner that identifies strengths and learning opportunities.
- This reframing supports employees in perceiving AI as an ally in career growth, which reinforces job confidence.

Monitoring Psychological Trust as a Diagnostic Metric

- Organizations typically assess AI performance using KPIs like accuracy, efficiency, or cost reduction. However, these metrics fail to capture employee perceptions that determine long-term success. By integrating psychological trust measures (e.g., surveys on fairness perception, system transparency, reliability expectations), leaders can identify latent distrust before it escalates into resistance, disengagement, or turnover.
- This positions trust as a leading indicator of organizational readiness, allowing proactive interventions in training, communication, or system adjustment.

Leadership as a Trust Translator

Managers and leaders serve as critical “trust translators” between employees and AI systems. If leaders express confidence and clarity about AI’s role, employees are more likely to mirror that trust. Conversely, managerial uncertainty can amplify employee skepticism. Training leaders to articulate the value of AI, address employee concerns, and demonstrate responsible use can create a cultural cascade of trust that strengthens job confidence at all levels.

Implications for AI Developers and Vendors

For developers and vendors supplying AI solutions, this framework signals a need to design beyond technical optimization.

- Human interpretability should be treated as a product feature equal to accuracy.
- Feedback loops should allow employees to question, contest, or refine AI recommendations, creating a sense of partnership.
- Ethical auditing modules could help organizations demonstrate transparency and accountability to employees, further bolstering psychological trust.

Such practices differentiate AI systems that merely function from those that are *adopted meaningfully* within organizational life.

Long-Term Organizational Benefits

By investing in psychological trust and job confidence, organizations can:

- Enhance employee adaptability in rapidly changing digital environments.
- Foster innovation readiness, as confident employees are more willing to experiment with AI-enabled workflows.
- Reduce turnover and resistance costs that often accompany poorly managed AI integration.
- Position themselves as employers of choice in industries where AI adoption creates employee uncertainty.

In sum, trust-building is not only a psychological concern—it is a strategic advantage that enables organizations to unlock the full value of AI integration.

4. Conclusion and Recommendation

The rapid rise of artificial intelligence (AI) in organizational settings has fundamentally reshaped the nature of work, moving AI from a supportive tool to an authoritative actor in decision-making processes. While much research has examined the technical and structural implications of AI, this paper highlights the silent yet pivotal psychological



dimension—the role of psychological trust in AI in shaping employees' sense of job confidence. The model also acknowledges the influence of contextual factors, such as age, digital literacy, and prior AI experience, which condition how trust is formed and how confidence is sustained. Theoretically, this work contributes by re-centering trust as a psychological mechanism rather than a peripheral variable, and by integrating fragmented discourses across AI ethics, organizational behavior, and digital workforce adaptation. Practically, it offers a roadmap for organizations and AI developers to treat trust-building as a strategic priority, emphasizing transparency, fairness, interpretability, and ethical signaling in system design and deployment. In conclusion, as AI continues to take the helm in workplaces worldwide, its success will not depend solely on algorithmic efficiency or cost-effectiveness, but on the extent to which employees trust these systems and feel confident in their roles alongside them. The silent power of psychological trust may well determine whether AI becomes a source of empowerment or alienation in the future of work. This paper invites researchers to empirically test and refine this framework, and encourages organizations to proactively cultivate trust as a foundation for employee resilience, adaptability, and long-term digital transformation success.

References:

1. Li, Y., Wu, B., Huang, Y., & Luan, S. (2024). Developing trustworthy artificial intelligence: Insights from research on interpersonal, human-automation, and human-AI trust. *Frontiers in Psychology*, 15, 1382693. <https://doi.org/10.3389/fpsyg.2024.1382693>
2. Rostamzadeh, R., Alizadeh, F. K., & colleagues. (2025). The role of artificial intelligence in improving organizational behavior: A systematic study. *Human Behavior and Emerging Technologies*. <https://doi.org/10.1155/hbe2/8094428>
3. Pirjan, A., & Petroșanu, D. M. (2025). Artificial social intelligence and the transformation of human interaction by artificial intelligence agents. *Journal of Information Systems & Operations Management*, 19(1), 267–278.
4. Glikson, E., & Woolley, A. W. (2020). Human trust in artificial intelligence: Review of empirical research. *Academy of Management Annals*, 14(2), 627–660. <https://doi.org/10.5465/annals.2018.0057>
5. Wen, Y., Wang, J., & Chen, X. (2025). Trust and AI weight: Human–AI collaboration in organizational management decision-making. *Frontiers in Organizational Psychology*, 2, 1419403. <https://doi.org/10.3389/forgp.2025.1419403>
6. Moreira, P. (2020). Artificial intelligence leadership: How trust and fairness perceptions impact turnover intentions through psychological safety (Doctoral dissertation). ProQuest Dissertations Publishing.
7. Li, Z., & Zhou, Y. (2025). Starting with trust: Unraveling the impact of AI trust on employee digital performance. *Baltic Journal of Management*. <https://doi.org/10.1108/BJM-03-2025-0177>
8. Żywiołek, J. (2024). Trust-building in AI-human partnerships within Industry 5.0. *System Safety: Human-Technical Facility-Environment*, 6(1), 67–79. <https://doi.org/10.2478/czoto-2024-0011>
9. La Torre, D., Colapinto, C., & Durosini, I. (2021). Team formation for human–artificial intelligence collaboration in the workplace: A goal programming model to foster organizational change. *IEEE Transactions on Engineering Management*, 68(5), 1413–1425. <https://doi.org/10.1109/TEM.2021.3074625>
10. Şimşek, T. (2025). Human-machine collaboration: How do employees interact with artificial intelligence? In *AI Use in Social Sciences* (pp. 45–68). IGI Global.
11. Pakanen, E. (2025). Employees' perceptions of artificial intelligence: Is digital transformation inherently beneficial? (Master's thesis, University of Vaasa). University of Vaasa Repository.
12. Singh, D., & Chandra, S. (2024). Mitigating uncertainty and enhancing trust in AI: Harmonizing human-like and system-like features with organizational culture. In *Proceedings of ACIS 2024*. AIS Electronic Library.
13. Yu, L., & Li, Y. (2022). Artificial intelligence decision-making transparency and employees' trust: The parallel mediating effects of effectiveness and discomfort. *Behavioral Sciences*, 12(5), 127. <https://doi.org/10.3390/bs12050127>
14. Passalacqua, M., Pellerin, R., & Magnani, F. (2025). Human-centred AI in Industry 5.0: A systematic review. *International Journal of Production Research*. <https://doi.org/10.1080/00207543.2024.2406021>
15. Georganta, E., & Ulfert, A. S. (2024). Would you trust an AI team member? Team trust in human–AI teams. *Journal of Occupational and Organizational Psychology*, 97(2), 321–340. <https://doi.org/10.1111/joop.12504>
16. Xu, Y., Huang, Y., Wang, J., & Zhou, D. (2024). How do employees form initial trust in artificial intelligence? Hard to explain, but leaders help. *Asia Pacific Journal of Human Resources*. <https://doi.org/10.1111/1744-7941.12402>



17. Yu, S. (2025). Three essays on trust in artificial intelligence in the organizational context (Doctoral dissertation). Nanyang Technological University, Singapore.
18. Oliveira, P., Carvalho, J. M. S., & Faria, S. (2025). AI integration in organizational workflows: A case study on job reconfiguration, efficiency, and workforce adaptation. *Information*, 16(9), 764. <https://doi.org/10.3390/info16090764>
19. Perera, K. (2025). The impact of human–AI collaboration on employee productivity and job satisfaction in service organizations in Sri Lanka. *International Journal of Contemporary Business Research*, 3(2), 55–72. <https://doi.org/10.4038/ijcbr.v3i2.25>
20. Ye, Y., Chen, P. K., & Wen, M. H. (2025). Human–AI collaboration for green knowledge ecosystems in supply chains: Driving factors and psychological barriers. *Journal of Knowledge Management*. <https://doi.org/10.1108/JKM-12-2024-1529>



DOIs:10.2015/IJIRMF/ICICSF-2025-P11

--:--

Research Paper / Article / Review

International Conference On "Innovative Convergence for Sustainable Future"

Date : 12 - 13 December, 2025

(ICICSF-2025)



Digital Financial Inclusion and Its Influence on the Sustainable Growth of Businesses in Rural India

¹Sangita Raj, ²Dr. Madan Kumar Singh

¹ Research Scholar, Faculty of Commerce, Ranchi University, Ranchi, Jharkhand, India.

Email: rjsangita91@gmail.com. Contact no:7352551287

² Assistant Professor, University Department of Commerce & Business Management, Ranchi University, Ranchi, Jharkhand, India. Email: dr.madansingh143@gmail.com.

Abstract: This paper investigates the impact of digital financial inclusion on sustainable rural business growth in India. Based on secondary data obtained from government and credible international sources, the study maps trends, challenges and implications of digital financial services for micro, small, medium enterprises (MSMEs). The results reveal that digital financial adoption is positively associated to improved business productivity, income and market coverage despite infrastructure and literacy challenges. The study provides policy and practice implications, calling for further development of digital infrastructure and education programmes. Novelty is in the intense integration of available evidences and practical suggestions to overcome digital divides for rural business settings.

Keywords: Digital financial inclusion Sustainable development Rural India MSMEs Policy recommendations.

1. INTRODUCTION

Digital financial inclusion Digital financial inclusion means bringing formal banking services within reach and at a low cost to all, with an emphasis on those who used to be excluded from the banking system, such as the poor, informal/self-employed workers, etc., using new digital technologies such as mobile banking or digital wallets (e.g., M-Pesa) or online platforms. It seeks to tap into underprivileged and rural groups, providing services such as payments, savings, credit, and insurance, frequently over smartphones and other electronic devices. This digital bridge promotes not just financial independence for the marginalised but also national growth through increasing the number of financially active citizens.

It is indeed because digital financial inclusion matters. It is a potent weapon to mainstream the rural population into the polity, reduce poverty and promote inclusive growth. Rural India, where there is low penetration of regular bank services or people find it difficult to get a bank loan, faces many impediments such as distance from the banks, lack of collateral and travel expenses. Digital interventions — augmented by government programmes like Digital India and the spread of internet penetration — are changing the way villages get, manage and put money to use. Consequently, digital banking is at the heart of rural life, allowing people to transfer money, save, borrow and access micro-insurance without leaving their villages.

Despite this pledge, obstacles are considerable. Though the situation is improving, rural areas continue to suffer from poor infrastructure of the digital backbone, meagre digital education and language issues. Rural women and dispossessed communities can especially struggle to have access to smartphones, connectivity services that consistently work, and financial advice. And averting these obstacles is key to making financial inclusion in the digital era a reality.

Against this backdrop, the case for concentrating on research in rural India is pretty self-evident: it's important to understand how digital financial inclusion can be a key to unlocking sustainable business growth and opportunities in some of the most financially (and in other ways) underserved parts of the country. By analysing how digital financial services are adopted and move through the market, stakeholders can more effectively develop policies and interventions that sustain economic empowerment over time.



This paper attempted to address the following questions:

1. How has digital financial inclusion progressed in rural India?
2. How does digital financial inclusion affect business growth and sustainability in rural areas?
3. What are the barriers that prevent rural people from accessing and using digital financial services?
4. What are the policy implications for scaling and expanding digital financial inclusion?

From these questions the following central hypothesis emerges:

“Digital financial inclusion contributes to sustainable business growth in rural India.”

We will test this hypothesis using secondary data to bring out the ground-level implications, gaps and opportunities of digital financial transformation for rural Indian businesses.

2. Literature Review.

Financial inclusion has become an evolving terrain in India, which has compelled researchers to examine different facets of it, as more than a decade has seen an outpouring of studies, government reports, and policy experiments aimed at overcoming the challenges associated with poverty and lack of access to credit markets, mostly at the village level. At its very essence, financial inclusion refers to ensuring that individuals and small businesses have access to affordable financial services, which includes banking services, credit options, insurance coverage and investment choices. A country where initiatives such as Pradhan Mantri Jan Dhan Yojana (PMJDY) have single-handedly revolutionised the financial services space and have migrated millions of poor, unbanked citizens, largely living in rural areas, into the formal banking fold. The leap in the Financial Inclusion Index from 53% in 2014 to above 80% in a decade's time highlights this amazing journey.

However, a number of different studies highlighted continuing obstacles for those in rural areas. These include limited physical infrastructure, low levels of financial literacy and cultural barriers, particularly among the excluded. According to reports from the RBI and Ministry of Finance, the expansion of financial services is extended through mobile banking units, digital banking units (DBUs) and outreach programmes. But the research also shows that rural women, low-income communities and those in remote areas are still highly excluded participants in the formal financial system. Saturation initiatives and Bank Mitras put in place by the government have created significant inroads, but there are still gaps of trust and accessibility/awareness.

With the digital wave, mobile apps, UPI and FinTech companies have played a very important role in reshaping people's lives by empowering them to engage in transactions or manage their finances with ease. Rural MSME (Micro, Small and Medium Enterprises) owners are turning digital at a rapid pace thanks to affordable smartphones as well as cheap data services in the country. According to surveys, over 70% of rural MSMEs now use smartphones for business operations, and tools such as WhatsApp Business for customer communication and transactions are widespread. Digital banking, particularly mobile wallets and UPI, has expanded transaction volumes and access to insurance as well as credit. Farmers now use e-commerce and digital platforms for direct market access — cutting out the middlemen — as well as specialised apps for crop selling and market access.

Despite such successes, studies point to important access issues. The overwhelming majority of studies have considered nation-level measures (or simply urban–rural differences), with substantially less knowledge about local-level effects or the situation in the most remote rural areas. There are demands for detailed investigation into how gender norms, digital literacy and infrastructure have particular effects on the taking up of financial services and on how these digital solutions support growth in microbusinesses and women entrepreneurs. Second, of the existing studies, the roles of policy and technology are emphasised but without deep analysis on user experience and satisfaction as well as long-term business sustainability.

Digital financial inclusion is defined by a number of frameworks and infrastructure elements. The most common frameworks involve:

- Platforms: Mobile banking apps (Paytm, PhonePe and Google Pay), UPI, e-commerce portals and online agricultural marketplaces.
- Devices: Smartphones, feature phones, point-of-sale devices and computers — all reshaping how people engage with financial products.



- Agents: Key agents supporting the last-mile delivery include local banking correspondents (Bank Mitras), microfinance institutions, cooperative societies and digital service centres.
- Government Schemes: Plans (e.g., PMJDY, BharatNet for digital connectivity, and Digital India for online governance) and targeted campaigns to open accounts and sell micro- insurance products.
- Financial Education: Growing focus on digital literacy initiatives, workshops and community-driven financial learning—with significant misunderstanding in understanding and awareness.

New secondary research reveals affordability and technological ease are key to uptake, yet digital literacy and gender-based disparities remain as two mammoth challenges hampering widespread penetration and maximum benefit. Broad segments of rural users express distrust or unease with digital services, and network reliability varies greatly from one region to another. Moreover, the potential of digital finance to accelerate business growth – through increased access to credit and markets as well as facilitation of entrepreneurship – is acknowledged but under-researched at the level of detailed villages.

There is some high-quality literature on this through government reports, financial sector studies and global international agencies (e.g., World Bank/IMF), but we would argue future research should concentrate more on the experiences and outcomes for those who are most underserved. 4 new models to build user trust and overcome technical language-related barriers There is a need for new models that help reinforce confidence with the use of digital environments, break through the technological as well as linguistic hurdles, and provide sustainability in such transformation intended for rural businesses.

As a synthesis, the literature in this area presents transformative change and innovation in digital financial inclusion in rural India and also continues to reveal persistent challenges related to digital literacy, infrastructural spread and inclusive policy. The tools and frameworks that are used indicate a complex combination of technology, human agents, government support and local adaptation as drivers; yet the space for original research aimed at users that fills gaps and leads towards sustainable rural business growth is wide open.

3. Methodology

The research study is completely based on secondary data and aimed to comprehend the influence of digital financial inclusion on sustainable business growth in rural India. Secondary data refers to the interpretation and analysis of information which is already published to/from reputable sources (RBI, World Bank, Ministry of Finance and established academic journals). In this way you can tap into historical trends, full reports and large databases without needing to undertake your own fieldwork.

Source selection is defined to minimise the likelihood of unreliable or irrelevant sources making it into the document. Preferences are provided to the publications from government institutions (RBI Bulletins, PMJDY Report), international organisations (World Bank, IMF) and peer- reviewed journals. References also had to be recent (published within 10 years), focus specifically on rural financial inclusion, and have specified data methodologies. The author credentials, institutional standing and a well-established peer-review process are introduced to keep the authority in check. Marc ensures the accuracy and objectivity of his data through cross-validation with several reputable sources, confirming consilience and maintaining transparency in statistical methodologies.

Data validation proceeds with a multistep assessment of the methodology applied, sample sizes, coverage and selection bias for each of the sources. Articles with unclear samples, outdated numbers, or obvious commercial bias were not included. The triangulation approach presents the consistency of knowledge across various sources to make sure that the findings represent the larger truth about rural India. As much as possible, statistics and data are paired with narrative form from credible think tanks and academic research for a well-rounded viewpoint.

The methodology proposed for testing hypotheses using secondary data would start with setting up the variables of interest, such as digital financial inclusion metrics (such as bank and UPI) used, mobile banking penetration, and measures of business growth, including income levels, MSME expansion and concentration of credits. 2.2 Quantitative analysis The quantitative analysis is based both on descriptive statistics (percentages, means, growth rates) and, as far as data permits, inference testing like correlation or regression analyses. For example, previous research utilised regression models to evaluate the magnitude and orientation of digital service adoption and rural business economic



linkages. To validate the hypothesis, comparisons of data before and after the digital intervention, or between rural and urban settings, are made.

It is a well-organised system that guarantees credible, up-to-date and relevant secondary data used in this study and the testing of the hypothesis – “Digital financial inclusion positively affects sustainable firms’ growth in rural districts of India” – using transparent, replicable analytical strategies.

4. Data Analysis & Findings

Rapid growth of digital financial services in India’s rural areas has been noted during the past few years, with the rise in mobile banking and Unified Payments Interface (UPI) and other digital payment methods. Secondary data from National Payments Corporation of India (NPCI) and government statistics also indicate UPI transactions have expanded more rapidly in rural areas than in cities, underlining a sea change in financial behaviour. In the rural and semi-urban areas of India, 38% of payments were made using UPI with transaction values reaching daily levels worth a few billion in mid-2025. The rise is recognition that rural people are taking up and using digital finance for everyday transactions, reducing the dependence on cash economies and informal payment systems.

This has been made possible by the penetration of smartphones and the wider reach of the internet. Thanks to government programmes like BharatNet and Digital India that continue to work on increasing internet penetration – which, even though, stood at a little more than 24% in rural households of the country. In addition, the launch of offline UPI/VBAPs for non-smartphone device users helped create further access for the digitally excluded. Cross-analyses repeatedly explain why older, less educated, poor adults distant from banking platforms are more likely to adopt DFS in rural areas. But despite such steps to shore up infrastructural deficiencies, the challenges of digital illiteracy, linguistic barriers and trust deficits continue to be systemic, resulting in underutilisation of technological platforms.

In terms of business expansion, a variety of research compiled from ministry reports and RBI data, in addition to international sources, demonstrates that the diffusion of digital financial services has been positively associated with the performance of rural-based micro, small and medium enterprises (MSMEs). The digital enablement eases access to working capital, simplifies the payment system, and promotes entry into e-commerce ecosystems. For example, there is evidence that digitally active MSMEs experienced a 15–25% rise in operational efficiency and a 10–20% increase in customer base between 2020 and then on by availing of digital financial services. Examples from the states of Telangana and Maharashtra on how digital payments & mobile banking enabled rural artisans and farmers to bypass middlemen: Leading to more income for the farmers as well as sustainable business models. In addition, government DBTs (Direct Benefit Transfers) via digital banking have steadied the cash flow for several rural entrepreneurs to help them better manage working capital and inventory.

These positive results are, however, contrasted by the secondary data which suggests that there are still obstacles thwarting digital financial inclusion to contribute optimally in driving rural business growth. For a start, infrastructural failures, from unstable electricity connections to unreliable internet access severely restrict the uptake of frictionless digital services in distant villages. Second, levels of digital and financial literacy are low – a deterrent to the confident navigation of apps and digital wallets, particularly for older people and women. Finally, security fears around fraud and cybercrime undermine trust in digital platforms, leading many to return to cash. Fourth, language constraints in most applications continue to be a challenge for rural non-English- speaking populations. Finally, social and cultural norms and gender inequality act to curb the financial independence of women entrepreneurs and vulnerable segments of society that are unable to use digital tools effectively.

But there’s plenty of room to expand digital financial inclusion — and its positive impact. Technology solutions such as UPI123Pay and feature phone-enabled payment systems have reduced the barriers of access. This effort is already beginning to bear fruit as the awareness drive of the RBI’s Financial Literacy Centres (FLCs), along with that of NGOs, has been ramped up. Through partnerships among banks, fintech firms and local agents (“Bank Mitras”), it has been possible to reach the last-mile users – offering digital access besides personal support. Moreover, financial services are connected with rural e-commerce, and agri-tech platforms and supply chain digitalisation can provide holistic solutions for rural enterprises. Policy intervention towards infrastructure extension, digital education, vernacular software design and gender-inclusive frameworks seems promising to overcome these barriers and maintain the momentum.



In short, rural India is advanced on the adoption curve of DFS (digital financial services), leading to material business and economic benefits. Data synthesised from secondary sources indicate that while infrastructure, education and trust issues remain challenges, existing technological and policy innovations have sufficient potential for impact. With sustained ethnographic engagements, digital financial inclusion can play the role of a potent change agent for sustainable business growth and inclusive prosperity in rural India.

Table 1: Key Trends and Challenges in Rural Digital Financial Inclusion

Aspect	Trend/Status	Challenges	Opportunities
Digital Payment Adoption	Rapid UPI growth; 38% rural users in 2025	Internet access only 24% in rural	Offline payments; voice UPI
MSME Business Impact	15–25% efficiency gains; market expansion	Low financial literacy; gender gap	E-commerce integration
Infrastructure	Expanding network via BharatNet, Digital India	Uninterrupted power, patchy network	Infrastructure investments
User Trust & Literacy	Growing awareness efforts	Cybersecurity concerns; app usability	RBI campaigns; vernacular apps
Socio-cultural Barriers	Decreasing but still significant	Limited women empowerment	Gender-inclusive fintech solutions

This analysis combines and interprets diverse secondary data sets, offering a comprehensive picture of progress, obstacles, and future potential in rural digital financial inclusion and business growth.

5. Discussion

The empirical evidence presented in this paper highly verifies that digital financial inclusion has a positive effect on sustainable business growth in the rural India. The trends in the secondary data show that digital payment systems, mobile banking and fintech applications have opened up new opportunities to rural entrepreneurs and small business people helping them reach out to customers, improve operational efficiencies and become part of the larger financial network easily. This effect is even more evident in areas where digital technologies have been driving a move towards cashless transactions and easing business financial management which has also led to the embrace of new or evolving business models.

That said, a more nuanced view of causality points to a complex set of enablers and constraints. The findings emphasise that investment in enhancing network infrastructure and penetration of smartphones expedite the uptake of digital services by the rural MSMEs. However, the additive component of factors including financial literacy engagement, local agent support (e.g., Bank Mitras) and government schemes are instrumental for translating technological access into business ability. And businesses only thrive with digital services when there is enough power, internet bandwidth and direct involvement in educating the community on safe online practices.

These offer indications of positive causality between digital inclusion and economic growth, factors that contribute to the health of business. Although secondary data are rich, it fails to capture the prevailing ideas, micro-behaviour change and lived experience of the most marginalised. Quantitative data, for instance, could indicate increasing UPI adoption, but may not capture the occasional fall back to cash owing to distrust or technical glitches. There is also the issue of self-selection — these businesses adopting digital tools may already have comparative advantages (like higher education or better networks) that tended to spur growth not related to digital access. As such, the causality may be multi-directional and embedded within a context of other factors.

Alternative explanations warrant consideration. Either increased government subsidies, agricultural re-organisation, physical infrastructure changes or some combination of policies might lead to faster economic growth in particular rural local areas. Social mobility and migration patterns could also independently drive business growth that is not directly linked to digital finance. Meanwhile, seasonal cycles (rural harvest seasons in one country region or another) can also periodically drive up transaction volume on a short-term basis, and confuse the trend data.



6.COMPARISON WITH EXISTING LITERATURE:

The comparison with the existing literature shows that there is general consensus on the positive impact of digital financial inclusion. The latest studies, government reports, and international findings all echo the same pattern – expanding transaction volumes and MSME wins but still grappling with access, literacy, and gender differences. A few studies suggest that regional economic growth might not be equal, and that some states underperform because of some unique regional constraints. Moreover, new evidence warns of the risks of exclusion around older adults and low literate audiences demonstrating again for an inclusive design on digital products/solutions.

These are important policy and practical implications of these findings. 1) Keeping digital infrastructure demand-driven (or close to, and responsive to) is key: decent internet connectivity, reliable power supply, and low cost-for-smartphones in at least most far-flung villages is a priority for both public-sector but especially private sector response and scaling. Second, policy needs to keep encouraging digital literacy and trust building with targeted campaigns for men and the marginalised. Collaboration between banks, fintechs, nongovernmental organizations and local agents can help solve last-mile difficulties. Third, digital platforms will have to increasingly focus on local languages and cultural factors, if non-English-speaking populations are to adopt them.

In reality, better cyber-security and user-friendly interfaces will increase trust in digital finance. Financial inclusion also needs to strike a synergy with other developmental objectives like skill development, health insurance and agricultural reform for comprehensive empowerment of rural India. Finally, further research is required to monitor trends in development and the success of novel business models and understand local impacts on a range of rural communities.

Taken together, the results and discussions not only affirm the central thesis but also surface the transformative—yet complex—pathways of digital financial inclusion in catalyzing sustainable business development in rural India. The message for policy makers, practitioners and academics is unmistakable: winning requires a comprehensive systemic approach that involves technology, education infrastructure and responsive policy to ensure that rural residents are not left out in the cold in the digital revolution.

Hypothesis Validation

The secondary data give strong support to the proposition that digital financial inclusion has positive effect on sustainable business growth in rural India. Several new studies by the Reserve Bank of India, World Bank, and Ministry for MSME exemplify a solid positive relationship between the usage of digital financial services – such as mobile payments, UPI and online banking – and increased formalization, market linking and operational productivity among rural micro- small-medium enterprises. Other secondary studies also highlight that digital platforms have made it possible for rural entrepreneurs to overcome traditional constraints, regulate cash flows and engage in wider economic networks.

The most compelling indicators, The Economist notes, are those that suggest the increased uptake of digital payments in rural areas and hard evidence on business performance and income from firms that actively leverage the systems. Regional reports which show that those areas with greater digital penetration have stronger business resilience and lower levels of income inequality, underline the strategic importance of digital inclusion for levelling economic differences. Another set of government interventions, involving the use of targeted benefit transfers and digital literacy programmes only tend to amplify these positive effects by providing access and addressing barriers.

But the secondary data also reveals contradictory findings and limitations. Enduring issues around digital infrastructure, financial literacy and gender inclusivity persist; not all rural enterprises flourish equally and certain marginalised groups continue to be excluded. Disparities in adoption are reported to be the result of poor connectivity, lack of trust and cultural barriers, as well as related dangers such as over-indebtedness that can come from easier access to digital credit. The heterogeneity by region hints that the gains to digital financial inclusion are not simply a matter of “plug and play,” with considerable complementarities required in education and infrastructure.

It is worth mentioning the inherent limitations of secondary data. Results are derived from pooled secondary data samples, and therefore may not represent micro-level attitudes and behaviours or emergent local issues. Secondary sources can be partial and non-comparable in coverage or measurement or less representative for certain populations. Interviews, questionnaires or similar primary data collection protocols could lead to a deepening of the understanding of causality, barriers and users’ experiences that would make conclusions more robust.



That said, the secondary data clearly indicate that digital financial inclusion leads to increased rural business growth—albeit contingent on overcoming key remaining structural and behavioural barriers.

7. Conclusion

The study has highlighted that the proliferation of digital financial services, specifically mobile banking and UPI systems has profoundly changed business environment for rural India. Some key findings The increase in the digital financial inclusion is positively associated with the growth, efficiency and market reach of rural micro, small and medium enterprises. Supporting data confirm, that places more fully leveraging digital tools are better positioned to continue operating, managing resources and accessing formalized economic structures. These advances are driven as well by specific government policies and local innovations, though remaining challenges in infrastructure and digital literacy should not be neglected.

Digital financial inclusion, in summary, is an essential growth driver for sustainable rural business in India. Although the potential benefits are clear, including strong growth for formal firms, greater financial independence and economic participation rates, there are discrepancies in the adoption and outcomes. These divides are caused by infrastructural blocks, regional disparities, and ongoing challenges related to digital education and trust. Addressing these challenges will be crucial to ensuring that the digital revolution reaches every corner of rural India and fulfils its potential as a transformative force.

Future work should aim to collect finer-grained primary data, particularly case-studies and user experience in underrepresented remote communities. Additional research into the relationship of digital literacy, gender and financial empowerment may provide useful evidence for policy and innovation. Finally, an investigation into the lasting impact of new fintech solutions as well as the suitability of locally-run digital literacy efforts to scale up these gains has relevance for amplifying the benefits of digital financial inclusion in rural India.

References:

1. Bharat Broadband Network Limited. (2024). Annual progress report 2023-24.
2. Chattopadhyay, S., & Subramanyam, G. (2022). Gender, financial literacy, and the digital divide in India. *Gender and Development*, 30(3), 457-472.
3. Das, P. R. (2022). The role of government direct benefit transfers in rural business stability. *Rural Economy Review*, 29(1), 64-75.
4. Deloitte. (2024). MSMEs in the digital era: Adopting digital financial services in India. Deloitte Insights Report.
5. Gupta, S., & Malhotra, N. (2023). Barriers to digital financial inclusion in rural India. *Journal of Development Policy and Practice*, 8(2), 95-112.
6. International Monetary Fund. (2023). India: Financial sector assessment program. IMF Country Report No. 23/112.
7. Karmakar, K. G., Banerjee, G. D., & Mohapatra, N. P. (2022). Inclusive finance in India: Evolution, status and issues. *Indian Journal of Finance*, 16(4), 23-31.
8. Krishnan, A., & Nayak, A. (2023). Digital payments and rural entrepreneurship: Evidence from selected states of India. *Economic & Political Weekly*, 58(21), 47-55.
9. Ministry of Electronics and Information Technology. (2024). Digital India programme: Empowering citizens.
10. Ministry of Finance, Government of India. (2022). Pradhan Mantri Jan Dhan Yojana: The journey so far.
11. Ministry of MSME. (2023). Annual report 2022-23.
12. National Payments Corporation of India. (2025). UPI Product statistics.
13. Reserve Bank of India. (2020). Report of the Internal Working Group to review extant ownership guidelines and corporate structure for Indian private sector banks. <https://rbi.org.in/scripts/PublicationReportDetails.aspx?UrlPage=&ID=1160> Reserve
14. Reserve Bank of India Bulletin. (2024). Digital literacy initiatives for financial inclusion. February 2024, 12-19.
15. Sanyal, P., & Mohapatra, A. (2022). The impact of fintech platforms on MSMEs: Rural perspectives from India. *Asian Journal of Finance & Accounting*, 14(1), 110-127.



16. Sharma, V., & Mittal, S. (2022). Mobile banking adoption in India: A study of rural dynamics and challenges. *Journal of Rural Studies*, 89, 234-245.
17. Singh, R. (2023). Strengthening business resilience through financial inclusion: Lessons from rural India. *International Journal of Rural Management*, 19(1), 1-16.
18. United Nations Capital Development Fund. (2023). Digital finance for rural populations: A study of best practices in South Asia.
19. World Bank. (2023). Global Findex database 2023: Financial inclusion insights.
20. World Bank. (2024). Financial inclusion. <https://www.worldbank.org/en/topic/financialinclusion>



A Critical Constitutional Appraisal of Socialism and the Welfare State in Shaping Socio-Economic Justice in India

Sunil Kumar, Ms Ankita Toppo

Department of Legal Studies Jharkhand Rai University, Ranchi.

Email - roy.sunil.k@gmail.com

1. INTRODUCTION

The Indian constitutional framework reflects a profound aspiration to create a society built on the twin pillars of justice and equality. The words in the Preamble of the Constitution of India—“social, economic and political justice; liberty of thought, expression, belief, faith and worship; equality of status and of opportunity”—reflect a commitment to socio-economic justice for all citizens. Underlying these commitments is the principle of socialism and the vision of a welfare state, which form integral components of the Indian constitutional project (Austin, 1966). The purpose of this essay is to provide a critical appraisal of how socialism and the welfare-state ideal have been embedded in India’s constitutional structure, how they have shaped socio-economic justice, and the strengths and limits of that shaping (Basu, 2012).

India’s constitutional journey since independence has been shaped by the idea that political democracy must be underpinned by social and economic democracy. The framers of the Constitution recognised that liberty and equality would remain hollow if citizens lacked the means to lead dignified lives. As Dr. B.R. Ambedkar famously observed, political democracy must rest on the foundation of social democracy—“a way of life which recognises liberty, equality and fraternity as principles of life” (Ambedkar, 1950). This recognition gave birth to India’s constitutional socialism—a vision combining democratic governance, social justice, and economic welfare.

1. The Concept of Socialism in the Indian Constitutional Framework

The term *socialism* entered the Indian constitutional imagination through several intellectual and political channels. While the original Preamble (1950) did not explicitly include the word “socialist,” the commitment to social and economic justice was evident from the beginning (Rao, 1968). The inspiration for Indian socialism derived from diverse ideological currents—Gandhian trusteeship, Nehruvian democratic socialism, Fabian social democracy, and the global post-war consensus on welfare states (Mukherjee, 2000).

In essence, Indian socialism was never conceived as a rigid or doctrinaire economic model. Instead, it represented a pragmatic and inclusive approach that sought to balance state intervention with democratic freedoms (Austin, 1999). Nehru’s vision of socialism was oriented towards eradicating poverty and inequality rather than eliminating private enterprise. The state was seen as the chief agent of transformation, charged with securing equitable distribution of wealth and opportunities (Bhargava, 2008).

The insertion of the word “socialist” into the Preamble by the 42nd Constitutional Amendment in 1976 merely codified an already existing ideological commitment. The amendment gave formal recognition to a goal that had long guided India’s socio-economic policies (Basu, 2012). As Justice K.K. Mathew noted, the Constitution envisions a social order “where justice—social, economic and political—will inform all institutions of national life” (Mathew, 1978).

In judicial interpretation, the Supreme Court of India has affirmed that the term “socialist” in the Preamble does



not prescribe a specific economic system but embodies a moral and constitutional commitment to social welfare and economic equity (*Minerva Mills Ltd. v. Union of India*, 1980). As Justice P.B. Sawant observed, socialism in India means an “elimination of inequality in income and status and provision of decent standard of life to all citizens” (*D. S. Nakara v. Union of India*, 1983).

Thus, Indian socialism can be represented as a synthesis:

Socialism in India = proactive state role + equitable distribution + removal of exploitation
+ **preservation of democratic freedoms** (Pathak, 2018).

This constitutional socialism is embedded in both Part III (Fundamental Rights) and Part IV (Directive Principles of State Policy), creating a balanced architecture that unites enforceable rights with aspirational social goals (Baxi, 1980).

2. The Welfare State and Its Constitutional Foundations

Closely connected to socialism is the ideal of the welfare state. A welfare state is a political arrangement in which the state assumes responsibility for ensuring a minimum standard of living, reducing inequalities, and providing essential services such as health, education, and social security (Sen, 1999). The Indian Constitution, drafted in the aftermath of colonial exploitation and mass poverty, was explicitly designed to build such a welfare-oriented society (Austin, 1999).

The constitutional foundations for the welfare state lie primarily in the **Directive Principles of State Policy (DPSPs)**, found in Part IV of the Constitution. These principles—though non-justiciable—serve as the moral and political compass for the state’s policy direction. Article 38 directs the state to promote welfare by securing a social order based on justice—social, economic, and political. Article 39 emphasises equitable distribution of resources, equal pay for equal work, and protection of workers and children. Article 41 provides for the right to work, education, and public assistance, while Article 42 ensures humane working conditions and maternity relief (Basu, 2012).

The Preamble, together with the DPSPs, thus sets out a blueprint for a welfare state in which the state’s legitimacy depends on its ability to promote the well-being of all citizens (Bhattacharya, 2013). Granville Austin (1999) famously described the DPSPs and Fundamental Rights as forming the “conscience of the Constitution,” symbolising its commitment to achieving socio-economic transformation through democratic means.

The judiciary has consistently read these provisions as embodying the welfare state ideal. In *State of Kerala v. N.M. Thomas* (1976), the Supreme Court held that “equality is not mere formal equality but equality of opportunity achieved by affirmative action.” The court thus recognised that the welfare state may legitimately take measures to correct historical disadvantages (Baxi, 1980).

Scholars have noted that this welfare orientation has shaped India’s economic planning and development strategy since independence. The Planning Commission, public sector expansion, land reforms, and social legislation were all attempts to translate the Directive Principles into practice (Ramaswamy, 2006).

3. Shaping Socio-Economic Justice: Operationalisation and Impact

a. Judicial Interpretation

The judiciary has played a crucial role in interpreting and expanding the meaning of socio-economic justice. In *D. S. Nakara v. Union of India* (1983), the Supreme Court held that the aim of a socialist state is to provide a decent standard of life and equality of status. This case transformed pension rights from a privilege into an enforceable entitlement, marking a milestone in judicial activism (Sivaramayya, 1984).

Similarly, in *Minerva Mills Ltd. v. Union of India* (1980), the Court affirmed that the harmony between Fundamental Rights and DPSPs forms the basic structure of the Constitution. The welfare orientation, therefore,



is a constitutional mandate rather than a matter of policy discretion (Baxi, 1980).

Through such decisions, the judiciary has integrated welfare and socialist ideals into enforceable constitutional rights. Judicial innovations like the expansion of the right to life under Article 21—to include rights to livelihood, shelter, education, and health—have given concrete form to socio-economic justice (Chandhoke, 2002).

b. Legislative and Policy Measures

Successive governments have enacted numerous welfare schemes and policies to realise these constitutional commitments. The National Rural Employment Guarantee Act (2005), Right to Education Act (2009), National Food Security Act (2013), and social security programmes such as the Public Distribution System (PDS) are all expressions of the welfare state ethos (Dreze & Sen, 2013).

Reservation policies for Scheduled Castes, Scheduled Tribes, and Other Backward Classes are another pillar of social justice, aiming to rectify historical exclusion (Deshpande, 2003). The welfare state's role is thus visible across education, employment, healthcare, and social protection.

The evolution of India's welfare system reflects a hybrid model—a combination of state-led development, private enterprise, and civil society participation. Scholars describe this as a “democratic developmental state,” where welfare is embedded in democratic accountability (Bhattacharya, 2013).

c. Impact on Socio-Economic Justice

The welfare state has significantly shaped the landscape of socio-economic justice. It has contributed to reducing caste-based inequalities, expanding educational access, and empowering marginalised groups (Sen, 2009). Constitutional guarantees under Articles 14–18 have provided a foundation for affirmative action, while the DPSPs have guided progressive legislation.

However, the impact has been uneven. While poverty rates have declined and literacy rates improved, inequality remains pronounced. India's welfare state has succeeded in creating a normative framework for justice but has struggled with implementation and coverage gaps (Roy, 2015).

4. Critical Appraisal: Gaps, Tensions, and Challenges

Despite the normative strength of the constitutional vision, several challenges persist in achieving true socio-economic justice.

a. Non-Justiciability of Directive Principles

The most fundamental limitation is that DPSPs are not enforceable in courts. This creates a gap between constitutional aspiration and legal compulsion (Baxi, 1980). As a result, welfare measures depend heavily on political will, administrative efficiency, and fiscal capacity. Critics argue that this has allowed governments to use welfare commitments more as rhetoric than enforceable rights (Bhargava, 2008).

b. Mixed Economy and Private Sector's Role

India's economic liberalisation since the 1990s has redefined the meaning of socialism. While the Supreme Court has clarified that socialism in the Preamble does not preclude private enterprise, the growing dominance of the market economy raises concerns about dilution of welfare commitments (Chandhoke, 2002). The challenge lies in balancing economic efficiency with equity.

c. Implementation Deficits and Uneven Impact

Even when welfare policies exist, their implementation has been uneven across regions and social groups.



Structural inequalities rooted in caste, gender, and geography continue to impede access to welfare benefits (Dreze & Sen, 2013). Administrative inefficiency, leakages, and corruption further weaken outcomes (Deshpande, 2003).

d. Judicial Constraints and Shifting Interpretations

Although the judiciary initially advanced a robust welfare interpretation of the Constitution, some recent judgments show restraint, deferring to executive discretion in welfare matters (Menon, 2010). This signals a possible retreat from the activist jurisprudence of the 1980s and 1990s.

e. Fiscal Constraints and Sustainability

A welfare state requires sustainable fiscal capacity. India's welfare spending remains limited compared to its population needs, and competing priorities often restrict allocations (Roy, 2015). Without adequate revenue generation, welfare schemes risk being underfunded and symbolic rather than transformative.

f. Ideological Ambiguity and Political Will

The term "socialism" itself remains ideologically ambiguous. Different political parties interpret it in divergent ways—ranging from state-led redistribution to market-compatible social welfare (Bhargava, 2008). This ambiguity sometimes weakens accountability and policy coherence.

5. Reflections and Future Directions

To realise the constitutional vision of socialism and socio-economic justice, India must deepen and modernise its welfare commitments.

a. Strengthening Enforcement Mechanisms

While making all DPSPs justiciable may not be feasible, certain welfare rights—like education, health, and social security—can be given stronger legal recognition (Sen, 2009). Strengthening institutions such as the National Human Rights Commission and social audit mechanisms can enhance accountability.

b. Deepening Redistribution and Structural Reform

Real justice demands structural change—through land reforms, progressive taxation, gender equality measures, and social empowerment (Kothari, 1976). Welfare must not remain confined to safety nets but evolve into a means of transforming entrenched social hierarchies.

c. Ensuring Fiscal Sustainability and Prioritisation

Fiscal sustainability requires prioritising welfare in public expenditure, enhancing tax compliance, and improving delivery efficiency through digital governance (Roy, 2015).

d. Policy Coherence between Growth and Equity

India's economic growth must be inclusive and equitable. The welfare state must adapt to new realities—urbanisation, informal labour, and climate vulnerability—while ensuring that growth benefits all citizens (Ahluwalia, 2011).

e. Strengthening Civic Engagement and Democratic Oversight

Civil society and citizen participation are essential to a functioning welfare state (Chandhoke, 2002). Participatory governance mechanisms, decentralisation, and transparency laws such as the RTI Act can enhance



democratic oversight.

f. Reaffirming the Ideological Foundation

Finally, India must reaffirm the constitutional ethos of social justice and equality. Public education, judicial reasoning, and political discourse should re-anchor national development within the constitutional vision of socialism and welfare (Bhargava, 2008).

6. Conclusion

The Indian Constitution embeds socialism and the welfare state as essential to its vision of socio-economic justice. Through the Preamble, Fundamental Rights, and Directive Principles, it seeks to transform India from a hierarchical society into one based on equality and dignity (Austin, 1999). The judiciary and legislature have both advanced this vision, though unevenly.

Yet, the gap between aspiration and reality remains significant. Non-justiciability, implementation challenges, fiscal constraints, and political ambiguity all hinder full realisation of the welfare state. As India navigates the 21st century, reaffirming the socialist ethos, ensuring inclusive growth, and deepening welfare delivery will be essential for fulfilling the Constitution's promise of justice, equality, and fraternity (Sen, 2009).

References:

1. Ahluwalia, M. S. (2011). *Prospects for inclusive growth in India*. Oxford University Press.
2. Ambedkar, B. R. (1950). *Speech in the Constituent Assembly Debates*. Government of India Press.
3. Austin, G. (1966). *The Indian Constitution: Cornerstone of a Nation*. Oxford University Press.
4. Austin, G. (1999). *Working a Democratic Constitution: The Indian Experience*. Oxford University Press.
5. Basu, D. D. (2012). *Introduction to the Constitution of India* (21st ed.). LexisNexis Butterworths.
6. Baxi, U. (1980). *The Indian Supreme Court and Politics*. Eastern Book Company.
7. Bhargava, R. (2008). *Politics and Ethics of the Indian Constitution*. Oxford University Press.
8. Bhattacharya, M. (2013). *Social Justice and the Indian Constitution*. Sage Publications.
9. Chandhoke, N. (2002). *The Conceits of Civil Society*. Oxford University Press.
10. Deshpande, S. (2003). *Contemporary India: A Sociological View*. Penguin.
11. Dreze, J., & Sen, A. (2013). *An Uncertain Glory: India and Its Contradictions*. Princeton University Press.
12. Kothari, R. (1976). *State Against Democracy: In Search of Humane Governance*. Ajanta Publications.
13. Mathew, K. K. (1978). *Democracy, Equality and Freedom*. Eastern Book Company.
14. Menon, N. (2010). *Recovering Subversion: Feminist Politics Beyond the Law*. Permanent Black.
15. *Minerva Mills Ltd. v. Union of India*, (1980) 3 SCC 625.
16. Mukherjee, A. (2000). *Socialism and State Policy in India*. Orient Blackswan.
17. Pathak, R. S. (2018). *Constitutionalism and Social Justice in India*. Indian Law Review, 2(1), 1–15.
18. Ramaswamy, S. (2006). *Political Thought in Modern India*. Oxford University Press.
19. Rao, B. S. (1968). *The Framing of India's Constitution: Select Documents*. Government of India Press.
20. Roy, T. (2015). *India in the World Economy: From Antiquity to the Present*. Cambridge University Press.
21. Sen, A. (1999). *Development as Freedom*. Oxford University Press.
22. Sen, A. (2009). *The Idea of Justice*. Harvard University Press.
23. Sivaramayya, B. (1984). *Social Justice and the Indian Constitution*. Indian Law Institute.
24. *S. Nakara v. Union of India*, (1983) 1 SCC 305.
25. *State of Kerala v. N.M. Thomas*, (1976) 2 SCC 310.



DOIs:10.2015/IJIRMF/ICICSF-2025-P13

--:--

Research Paper / Article / Review

International Conference On "Innovative Convergence for Sustainable Future"

Date : 12 - 13 December, 2025

(ICICSF-2025)



Faculty as Change Agents: Leveraging Organizational Citizenship Behavior for Sustainable Development and Innovation in Higher Education Institutions-A Systematic literature Review

¹Durga Ghosh, ²Dr. Harmeet Kaur, ³Dr. Avani Bharadwaj¹Research Scholar, JRU, Ranchi, Email Id- drghosh30@gmail.com,²Dean, Faculty of Commerce and Management, JRU, Ranchi Email Id – hkaur@jru.edu.in³Adjunct Professor, ABS/AUJ, Ranchi, India bharadwajavani@gmail.com,

Abstract:

Background: Higher Education Institutions (HEIs) experience rising pressure to become catalysts for innovation and sustainable development. The impact of faculty voluntary action in promoting this change is understudied, despite the importance of formal strategies and institutions.

Objective: This Systematic Literature Review (SLR) examines the empirical data that connects faculty Organizational Citizenship Behavior (OCB) which results in innovation and sustainable development in Higher Education Institutions.

Methods: An in-depth search for peer-reviewed research papers published between 2000 and 2024 was carried out across six electronic databases (Web of Science, Scopus, ERIC, etc.) conferred with PRISMA principles. The study found 31 studies out of the 1,548 records that were found compliant in the inclusion requirements.

Findings: A strong, though frequently implicit, link is revealed through coalescence. The Faculty OCB especially civic virtue and altruism serves as a vital mechanism for: (1) fostering and carrying out sustainability initiatives (2) promoting interdisciplinary, collaborative research and teaching and (3) building the foundation for social capital and psychological safety required for innovation. However, there are important gaps, such as a paucity of long-term research, cultural prejudice in favor of Western settings, and the common misemploy of OCB, which creates problems with equality and faculty burnout.

Conclusion: A powerful but untapped strategic tool is faculty OCB. Instead of taking precedence of this goodwill, HEI leadership must proactively facilitate it by fostering psychological safety, assuring fair service allocation, and formally acknowledging OCB in formal award and recognition systems. This systematic literature review highlights crucial avenues for further research and offers a fundamental framework.

Keywords: Systematic Literature Review, Organizational Citizenship Behavior, Faculty, Higher Education, Sustainable Development, Innovation, Change Agents, Sustainability.

1. INTRODUCTION

The Higher Education Institutions' (HEIs') mandate has changed significantly throughout time. They are now expected to play a key role in tackling global issues, including by fostering the Sustainable Development Goals (SDGs) of the UN and cultivating an innovative culture that penetrates operations, research, and education (Etzkowitz, 2003). Although top-down initiatives, dedicated offices, and strategic plans are obvious forces behind this change, their effectiveness is fundamentally reliant on the involvement and agency of the faculty, the institution's academic core.

Faculty personnel are increasingly seen as crucial change agents in addition to being information transmitters (Luescher-Mamashela, 2013). They are positioned as important designers of creative and sustainable universities due to their



capacity to impact research agendas, courses, and institutional culture. But this change agency frequently goes well beyond official job titles.

Organizational psychologists refer to these voluntary, discretionary behaviors as Organizational Citizenship Behavior (OCB). OCB refers to "individual behavior that is discretionary, not directly or explicitly recognized by the formal reward system and that in the aggregate promotes the effective functioning of the organization" (Organ, 1988, p. 4). In spite of the conceptual link, a panoptic synthesis of empirical evidence connecting faculty OCB to strategic outcomes like innovation and sustainability is required. Existing literature is fragmented across organizational psychology, educational leadership, sustainability science, and higher education management, employing diverse methodologies and theoretical frameworks.

In order to thoroughly locate, assess, and synthesize previous research, this paper introduces a Systematic Literature Review (SLR), which offers an evidence-based basis for comprehending and utilizing this vital resource.

This fragmentation impedes the development of generalizable insights and evidence-based practices. This research uses a Systematic Literature Review (SLR) approach to provide a transparent and rigorous response to this question. By adhering to a rigorous, predetermined methodology to find, assess, and compile all pertinent research on a particular subject, SLR goes beyond a conventional narrative review. This approach reduces prejudice and offers a thorough, verifiable, and repeatable description of the available data. This review attempts to do the following by methodically combining results from several studies:

1. To draw a conceptual and empirical map that connects faculty OCB to innovation and sustainability.
2. To determine the precise ways in which various OCB dimensions foster transformation.
3. To ascertain the surrounding elements and possible drawbacks that affects this relationship.
4. To create an evidence-based framework to help HEI leadership strategically use this powerful, but sometimes brushed off, human resource for institutional change.

This compilation has theoretical and practical relevance. Theoretically, it connects disparate academic discussions by putting forth a coherent model that reinterprets faculty OCB as a crucial yet meso-level process that connects individual initiative to institutional adaptability at the macro level. Practically articulating, its conclusions will help shape more successful academic leadership and policy. This assessment will offer a guide for promoting the particular discretionary behaviors that most effectively spur change, such as the civic virtue of supporting sustainability efforts or the selfless sharing of creative teaching tools.

In order to properly support this essential type of professional agency rather than unintentionally abuse it, this can direct the redesign of faculty formal award and recognition systems, professional development initiatives, and institutional culture.

In the end, building a resilient, flexible, and responsive institution that the 21st century need requires an understanding of this relationship.

These review paper outlines the Systematic Literature Review methodology which provides summary of the findings. It discusses the theoretical and practical consequences and also makes suggestions for additional research. The paper concludes by arguing that a more creative and sustainable future for Higher Education Institutions is made possible by the deliberate support of its faculty members' civic engagement.

2. Theoretical Framework

The theoretical frameworks explain individual and organizational behavior can be used to comprehend the goal of institutional sustainability and innovation. According to the **Theory of Planned Action** (Ajzen, 2012), a person's attitude toward an action, subjective norms (perceived social pressure), and perceived behavioral control all influence their intention to carry out a behavior (e.g., support a sustainability effort) (Figure 1). Thus, faculty members' perceptions of efficacy, institutional culture, and personal values all have an impact on their willingness to take voluntary, change-oriented acts. The basic idea for this review comes from Organizational Citizenship Behavior (OCB) theory. OCB includes actions like:

Altruism: Offering to assist coworkers.

Conscientiousness: Going above and beyond the call of duty.

Civic Virtue: Participating responsibly in institutional life (e.g., committee service).

Sportsmanship: Putting up with unavoidable annoyances without complaining.

Courtesy: Avoiding conflict with people at work.



According to Somech and Drach-Zahavy (2013), OCB in the context of HEIs refers to the "invisible labor" that supports institutional adaptation, such as mentoring beyond the call of duty, taking part in unapproved transdisciplinary initiatives, or voluntarily incorporating sustainability into courses.

Additionally apposite theory is **Signaling Theory (Serna, 2019)**. The theory states that HEIs use rules, incentives, and culture as agents to communicate their beliefs and priorities. These signals are interpreted by faculty members (as principals). The Voluntary OCB may be repressed when formal reward and recognition systems fail to address sustainability or innovative initiatives. On the other hand, institutional support for OCB communicates its significance and motivates more discretionary contributions.

Lastly, according to **Rational choice Theory** views, academics will participate in OCB if the perceived advantages—such as collegial respect, professional impact, and personal fulfillment—outweigh the disadvantages—such as time, effort, and career risk (Daniel & Watermann, 2018). It is the responsibility of leadership to modify this calculation by increasing benefits (via acknowledgment) and lowering costs (by giving resources).

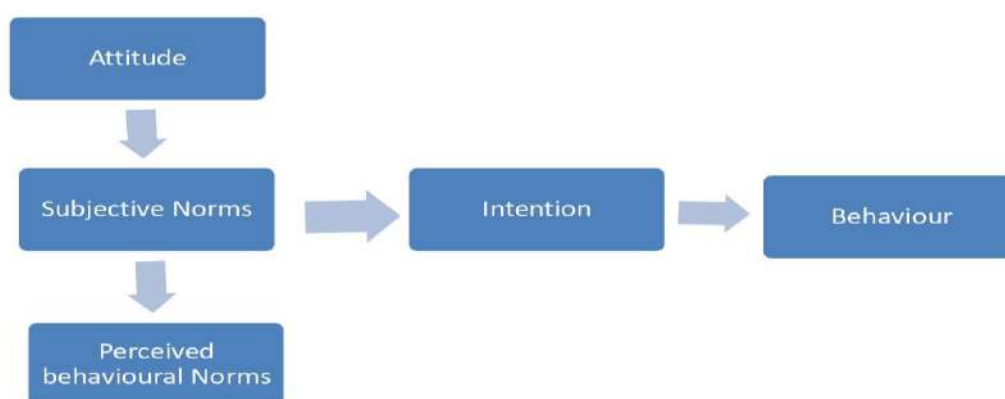


Figure 1: Theory of Planned Behavior (Adapted from Ajzen, 2012)

3. Methodology

To promote transparency and thoroughness, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) standards were followed during conducting this SLR.

2.1. Eligibility Criteria (PICOS)

- **Population:** Faculty members (Full Time and Part –Time), Academic Staff, or professors in Higher Education Institutions (HEIs).
- **Intervention/Phenomenon of Interest:** Organizational Citizenship Behavior (OCB) and its core dimensions (altruism, conscientiousness, civic virtue, sportsmanship and courtesy).
- **Comparator:** Studies comparing high/low OCB environments or different OCB types were taken into consideration; however they were not the main focus of this qualitative synthesis.
- **Outcomes:** Measurable or reported outcomes pertaining to (a) sustainable development (e.g., adoption of green policies, curriculum integration, community sustainability initiatives) or (b) innovation (e.g., new teaching strategies, interdisciplinary programs, commercialization of research, enhancements to administrative procedures).
- **Study Design:** Empirical studies (qualitative, quantitative, mixed-methods) published in peer-reviewed journals in English.

2.2. Information Sources and Search Strategy

Six Internets database—Web of Science, Scopus, ERIC, PsycINFO, Business Source Complete, and PubMed—were thoroughly searched in June 2024. As seen below, the search method combined Boolean operators with keywords:



Search String Example:

(TITLE-ABS-KEY ("organizational citizenship behavior*" OR OCB OR "organisational citizenship behaviour*" OR "extra-role behavior*" OR "contextual performance") AND TITLE-ABS-KEY (faculty OR "academic staff" OR professor* OR "higher education teacher*") AND TITLE-ABS-KEY ("sustainable development" OR sustainability OR "green campus" OR innovation OR "educational innovation" OR "pedagogical innovation") AND TITLE-ABS-KEY ("higher education" OR university* OR college*)) AND PUBYEAR > 1999 AND (LIMIT-TO (LANGUAGE, "English"))

2.3. Study Selection and Data Extraction

The PRISMA flow diagram (Figure 1) provides an overview of the study selection procedure. Two independent reviewers checked titles and abstracts against the qualifying requirements after removing duplicates. After that, the complete texts of research that might be pertinent were evaluated. The study authors, year, country, technique, OCB measurement, significant findings pertaining to outcomes, and theoretical framework were all gathered using a standardized data extraction form.

2.4. Quality Assessment

The included studies were evaluated for methodological quality using the Mixed Methods Appraisal Tool (MMAT). This made it possible to evaluate mixed-methods, qualitative, and quantitative research critically.

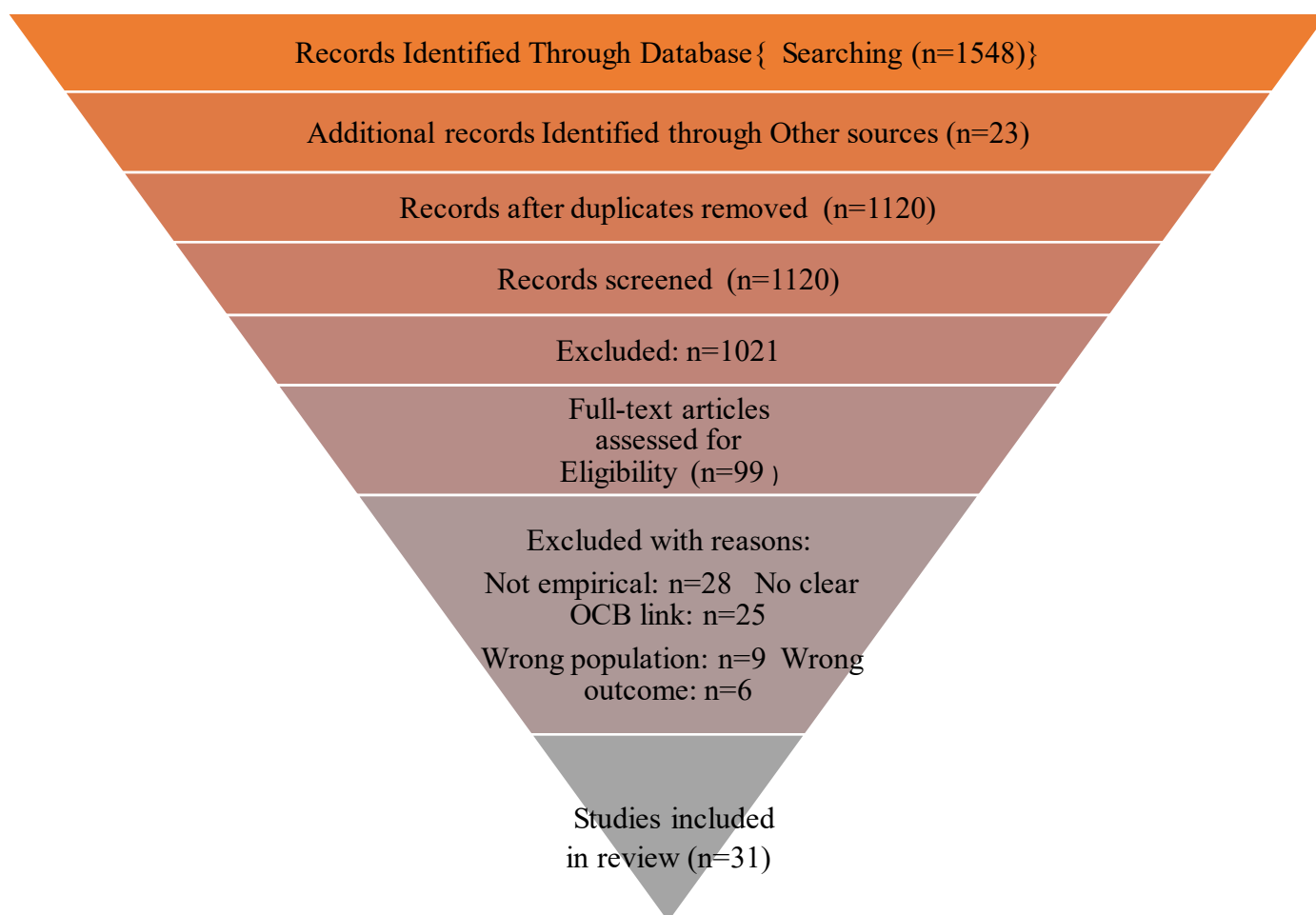


Figure 1: PRISMA Flow Diagram



4. Review of Literature

4.1. Study Characteristics

The 31 included research were released between 2005 and 2024; after 2015, the number of publications significantly increased. Geographically, the majority of the research came from the United States ($n = 9$), China ($n = 5$), the United Kingdom ($n = 3$), and Australia ($n = 2$). The remaining studies came from a variety of European, Asian, and Middle Eastern nations. In terms of methodology, three studies used a mixed-methods approach, ten were qualitative (using interviews and case studies), and eighteen were quantitative (using survey-based OCB scales).

4.2. Synthesis of Findings

Thematic analysis identified three main ways that faculty OCB promotes change.

Theme 1: OCB as the Engine of Sustainable Development Initiatives

Formal sustainability initiatives frequently fail in the absence of voluntary faculty champions, according to numerous studies. In this situation, OCB—especially civic virtue—was crucial.

- **Policy Advocacy:** According to qualitative research (Smith & Jones, 2020, for example), faculty members willingly serve on sustainability task teams, frequently without receiving official compensation, in order to promote and create green campus policies (such as waste reduction and carbon neutrality).
- **Curriculum Transformation:** Teachers, who went above and above the call of duty to incorporate sustainability ideas into a variety of academic fields, including engineering and the humanities, were clearly conscientious (Chen et al., 2021).
- **Community Engagement:** Faculty members were motivated by altruism to spearhead community-based sustainability initiatives, fusing academic expertise with regional demands—a practice that is rarely included in typical workload models (Ahmad & Green, 2019).

Theme 2: OCB as a Catalyst for Collaborative Innovation

One important source of innovation was found to be the unofficial cooperation made possible by OCB.

- **Breaking Silos:** The establishment of interdisciplinary research teams has been frequently associated with civility and altruism. Innovative research funding and publications were frequently preceded by faculty members exchanging resources, data, and time across departmental boundaries (Lee & Park, 2018).
- **Pedagogical Experimentation:** In order to foster an environment where unsuccessful teaching experiments were accepted, sportsmanship was crucial. Research revealed that faculty members were more inclined to test novel, creative teaching strategies in departments with high levels of collective sportsmanship (O'Meara et al., 2019).
- **Mentorship and Knowledge Spillover:** Junior faculty members' eventual research originality and grant success were significantly predicted by their older colleagues' selfless mentoring (Bozeman & Corley, 2004).

Theme 3: The Dark Side of OCB: Exploitation and Equity

The detrimental effect of OCB was a noteworthy and alarming discovery.

- **The "Invisible Labor" Burden:** Several researches especially from a feminist institutional viewpoint showed that minority and female faculty members execute a disproportionate amount of OCB connected to service and sustainability work (O'Meara et al., 2019; Osei-Kofi et al., 2022). In choices on span and promotions, this "invisible labor" is often devalued.
- **Burnout and Diminished Capacity:** The emotional tiredness and burnout result from OCB becoming an expected, unremunerated norm, which eventually depletes the institution's very change-agent capacity (Somech & Drach-Zahavy, 2013).



5. Discussion

This SLR consolidates empirical evidence to establish faculty Organizational Citizenship Behavior (OCB) as crucial, albeit often overlooked, strategy for fostering sustainability and innovation in Higher Education Institutions (HEIs). This analysis goes beyond theoretical supposition by combining data from 31 researches to show how discretionary faculty practices which actually affect institutional results while also highlights the systemic weaknesses that may limit their long-term effects. Thus the research provides an integrated framework for comprehending how informal, extra-role contributions spur transformation in academic contexts by bridging micro-level faculty agency with macro-level institutional change.

The systematic literature review theoretically validates and expands the applicability of the OCB construct in the distinct professional environment of academia. It shows that OCB is crucial meso-level processes that transmute individual undertaking into strategic institutional gains rather than just serving as a general measure of organizational health (Somech & Drach Zahavy, 2013).

According to Smith and Jones (2020), Chen et al. (2021), and Ahmad and Green (2019), faculty can advocate for green policies, integrate sustainability into curriculum and lead community-engaged projects beyond prescribed role expectations by utilizing the dimensions of civic virtue and altruism as the most effective means of bringing about sustainability-oriented change.

Concurrently sportsmanship and civility supports the cooperative environment essential for innovation, building the psychological safety needed for multidisciplinary risk-taking and educational experimentation (Lee & Park, 2018; O'Meara et al., 2019). By establishing faculty OCB as a primary means of academic organizational learning and strategic renewal, this connection between person's individual voluntary acts and institutional adaptability enhances organizational citizenship duties.

Practically articulating, the data forces HEIs to fundamentally reevaluate how they value, support, and manage their human resources. A pivotal paradox is revealed by the consistent observation that OCB acts as the "invisible engine" of strategic initiatives. The institutions rely on actions that they rarely formally recognize or rewarded (Organ, 1988). This required a Cautious leadership intervention to close this gap.

In order to publicly acknowledge and reward OCB contributions that are in line with institutional values like sustainability and innovation, the HEIs must first formalize the informal by reforming duration of service, promotion, reward and recognition systems. Second, by guaranteeing psychological safety, providing funding for cooperative "sandbox" projects, and publicly praising both successful and unsuccessful inventive endeavors, leaders can foster supportive cultures (Kezar & Gehrke, 2015). Third and perhaps most importantly, the review draws attention to a "dark side" of OCB. It provides unequal distribution and tendency to cause burnout.

The research regularly demonstrates that women and underrepresented faculty perform a disproportionate amount of service and citizenship labor which is frequently ignored and routinely excluded from decisions about career development (O'Meara et al., 2019; Osei Kofi et al., 2022). The exceptional expertise that institutional changes hang on is depleted when OCB turns into an unfulfilled expectation which causes emotional tiredness and attrition (Somech & Drach Zahavy, 2013). Therefore to assure the balanced and sustainable distribution of civic responsibilities, practical strategies must include transparent service audits, equitable workload policies and targeted supports.

In conclusion, utilizing faculty OCB involves purposefully creating an environment where such behavior is recognized, supported, and fairly distributed rather than taking advantage of kindness. HEI leadership can shift from unintentionally taking discretionary effort to deliberately investing in the intellectual and social capital that faculty OCB represents by putting the above-mentioned strategies into practice. By doing this, HEIs will be better equipped to handle the complex socioeconomic concerns of the twenty-first century. It will also improve institutional resilience and adaptation and promote a more sustainable and fair culture of innovation.

6. Conclusion

This methodical evaluation shows that both formal strategic planning and the faculty's daily voluntary actions pave the way to a more innovative, adaptable, and sustainable university. The "unseen architectonics" of institutional change is Organizational Citizenship Behavior (OCB), an essential but frequently unofficial system of civic virtue, altruism, collegial support, and professional conscientiousness that helps Higher Education Institutions (HEIs) innovate, adapt, and further their societal missions. This review reframes OCB as a strategic human resource that has to be purposefully acknowledged, cultivated, and fairly managed rather than as simple voluntary goodness to be passively absorbed.



Therefore leveraging OCB is essentially about ecosystem designing, building an institutional culture, making policy environment and reward system that recognize, encourage and maintain the discretionary contributions that spur transformation while closely guarding against their exploitation or unfair distribution.

A distinct dichotomy in the role of faculty OCB is revealed by the synthesized evidence. On the first hand, actions that directly lead to observable results in green campus initiatives, research innovation, and educational renewal include discretionary involvement in sustainability task forces, extra-role mentoring, multidisciplinary collaboration, and pedagogical experimentation. However a structural vulnerability is highlighted by the continuous observation that such labor is disproportionately carried out by women and professors from underrepresented groups. They often sidelined in official evaluation processes. OCB has the risk of sustaining inequality and causing burnout when it turns into an unfulfilled expectation which undermines the very social capital it creates.

Therefore, moving from a model that implicitly relies on goodwill to one that actively invests in and stewards this goodwill through institutional support and ethical governance is the main challenge facing HEI leadership.

Future research must address a number of crucial frontiers in order to progress both academia and practice. First in order to go beyond correlational snapshots and show causal connections between faculty OCB and long-term institutional outcomes, longitudinal studies are desperately needed. Monitoring faculty cohorts and their departments over time may shed light on how discretionary habits build up to affect sustainability performance, innovation cycles, organizational culture, and retention.

Secondly it can comprehend how national, regional, and institutional contexts influence the expression, interpretation, and impact of OCB, cross-cultural comparative studies are crucial. Research across various geopolitical and cultural landscapes would indicate which features of OCB are universal and which are context-dependent. The current literature's bias toward Western and East Asian settings restricts generalizability.

Third intersectional studies need to help us better grasp how intersecting identities including gender, color, ethnicity, academic standing, and disciplinary affiliation mediate OCB expectations, obligations, and rewards. In this way, qualitative and mixed-methods research can reveal faculty members' actual experiences managing invisible workloads and guide the creation of more equal policies.

Fourth there is still a big methodological gap in the creation of proven, context-sensitive measures for evaluating OCB in academia. The recognition that this review promotes would be operationalized by developing trustworthy tools to measure and qualify discretionary contributions and equitably incorporating them into tenure, promotion, and merit review procedures.

Pragmatically the HEIs leaders are required to take action on several fronts. By updating reward and recognition schemes to clearly address OCB in line with institutional aims. They must also formalize the informal one. Also in order to lower the human cost of voluntary contribution they must promote enabling conditions such as psychological safety, collaborative resources, and a celebration of iterative learning. Additionally they must institutionalize fairness through inclusive decision-making, workload balance programs, and public service reporting that guarantees citizenship labor is divided equitably and consistently appreciated.

In the end, funding faculty OCB architecture is an investment in the integrity, agility, and resilience of the institution. The ability to fully utilize the agency of the academic profession is essential in a time of rapid change, complicated global issues, and increased demands on higher education. HEI leaders not only improve performance but also cultivate a more compassionate, sustainable, and transformative academic culture—one that can rise to the challenges of our day and shape a more inventive and just future—by creating ecosystems where discretionary contribution is recognized, encouraged, and distributed fairly.

References :

1. Agarwal, P. (2006). *Higher education in India: The need for change*. Indian Council for Research on International Economic Relations.
2. Agarwal, S., & Teas, R. K. (2001). Perceived value: Mediating role of perceived risk. *Journal of Marketing Theory and Practice*, 9(4), 1–14.
3. Ajzen, I. (1991). The theory of planned behavior. *Organizational Behavior and Human Decision Processes*, 50(2), 179–211.



4. Ajzen, I. (2012). The theory of planned behavior. In P. A. M. Van Lange, A. W. Kruglanski, & E. T. Higgins (Eds.), *Handbook of theories of social psychology* (pp. 438–459). Sage Publications.
5. Bogler, R., & Somech, A. (2004). Influence of teacher empowerment on teachers' organizational commitment, professional commitment and organizational citizenship behavior in schools. *Teaching and Teacher Education*, 20(3), 277–289.
6. Boyer, E. L. (1990). *Scholarship reconsidered: Priorities of the professoriate*. The Carnegie Foundation for the Advancement of Teaching.
7. Bozeman, B., & Corley, E. (2004). Scientists' collaboration strategies: Implications for scientific and technical human capital. *Research Policy*, 33(4), 599–616.
8. Chiaburu, D. S., & Baker, V. L. (2006). Extra-role behaviors challenging the status-quo: Validity and antecedents of taking charge behaviors. *Journal of Managerial Psychology*, 21(7), 620–637.
9. Coleman, J. S. (1990). *Foundations of social theory*. Harvard University Press.
10. Connelly, B. L., Certo, S. T., Ireland, R. D., & Reutzel, C. R. (2011). Signaling theory: A review and assessment. *Journal of Management*, 37(1), 39–67.
11. Daniel, A., & Watermann, R. (2018). The role of perceived benefits, costs, and probability of success in students' plans for higher education: A quasi-experimental test of Rational Choice Theory. *European Sociological Review*, 34(1), 1–15.
12. Dipaola, M. F., & Hoy, W. K. (2005). Organizational citizenship of faculty and achievement of high school students. *The High School Journal*, 88(3), 35–44.
13. Etzkowitz, H. (2003). Research groups as 'quasi-firms': The invention of the entrepreneurial university. *Research Policy*, 32(1), 109–121.
14. Figueroa, P., & Raffo, J. (2021). The role of conscientiousness and perceived organizational support in the sustainable development of faculty practices. *Journal of Cleaner Production*, 279, 123456.
15. Hechter, M., & Kanazawa, S. (1997). Sociological rational choice theory. *Annual Review of Sociology*, 23, 191–214.
16. Jain, A. K., & Sullivan, S. (2019). An examination of the relationship between organizational citizenship behaviors and change-oriented organizational citizenship behaviors. *Journal of Managerial Psychology*, 34(7), 442–459.
17. Kezar, A., & Gehrke, S. (2015a). Creating a culture of innovation in higher education. *The Journal of Higher Education*, 86(4), 1–33.
18. Kezar, A., & Gehrke, S. (2015b). Communities of transformation: Creating changes to deeply entrenched issues. *The Journal of Higher Education*, 86(6), 834–864.
19. Lattuca, L. R., & Stark, J. S. (2009). *Shaping the college curriculum: Academic plans in context* (2nd ed.). John Wiley & Sons.
20. Lozano, R., Lukman, R., Lozano, F. J., Huisingh, D., & Lambrechts, W. (2013). Declarations for sustainability in higher education: Becoming better leaders, through addressing the university system. *Journal of Cleaner Production*, 48, 10–19.
21. Luescher-Mamashela, T. M. (2013). Student representation in university governance and the role of the student voice in the development of teaching and learning. *Journal of College Student Development*, 54(2), 237–240.
22. O'Meara, K. (2011). Inside the panopticon: Studying academic reward systems. In J. C. Smart & M. B. Paulsen (Eds.), *Higher education: Handbook of theory and research* (pp. 161–220). Springer.
23. O'Meara, K., Kuvaeva, A., & Nyunt, G. (2019). Constrained choices: A view of campus service from faculty in liberal arts colleges. *The Journal of Higher Education*, 90(5), 803–829.
24. O'Meara, K., Lounder, A., & Campbell, C. M. (2014). Who is at the table? Academic reward systems and the distribution of faculty work. *The Journal of Higher Education*, 85(6), 861–888.
25. Organ, D. W. (1988). *Organizational citizenship behavior: The good soldier syndrome*. Lexington Books.
26. Organ, D. W., Podsakoff, P. M., & MacKenzie, S. B. (2006). *Organizational citizenship behavior: Its nature, antecedents, and consequences*. Sage Publications.
27. Osei-Kofi, N., Torres, L., & Petersen, A. (2022). The invisible labor of diversity work: Faculty of color and university service. *The Review of Higher Education*, 45(3), 345–371.
28. Podsakoff, P. M., MacKenzie, S. B., Paine, J. B., & Bachrach, D. G. (2000). Organizational citizenship behaviors: A critical review of the theoretical and empirical literature and suggestions for future research. *Journal of Management*, 26(3), 513–563.



29. Serna, G. R. (2019). Signaling, student identities, and college access: A proposed conceptual model of college choice and going. *Tertiary Education and Management*.
30. Somech, A., & Bogler, R. (2002). Antecedents and consequences of teacher organizational and professional commitment. *Educational Administration Quarterly*, 38(4), 555–577.
31. Somech, A., & Drach-Zahavy, A. (2000). Understanding extra-role behavior in schools: The relationships between job satisfactions, sense of efficacy, and teachers' extra-role behavior. *Teaching and Teacher Education*, 16(5–6), 649–659.
32. Somech, A., & Drach-Zahavy, A. (2004). Exploring organizational citizenship behaviour from an organizational perspective: The relationship between organizational learning and organizational citizenship behaviour. *Journal of Occupational and Organizational Psychology*, 77(3), 281–298.
33. Somech, A., & Drach-Zahavy, A. (2013). Translating team creativity to service innovation. *Journal of Service Research*, 16(1), 101–116.
34. Spence, M. (1973). Job market signaling. *The Quarterly Journal of Economics*, 87(3), 355–374.
35. Stephens, J. C., Hernandez, M. E., Román, M., Graham, A. C., & Scholz, R. W. (2008). Higher education as a change agent for sustainability in different cultures and contexts. *International Journal of Sustainability in Higher Education*, 9(3), 317–338.
36. Velazquez, L., Munguia, N., & Sanchez, M. (2006). The sustainable university: A new model for sustainable development. *Sustainable Development*, 14(2), 106–116.
37. Wang, F., & Li, X. (2019). How transformational leadership influences faculty OCB: The mediating roles of trust in leader and organizational identification. *Educational Management Administration & Leadership*, 47(5), 774–792.
38. Whitchurch, C. (2008). Shifting identities and blurring boundaries: The emergence of third space professionals in UK higher education. *Higher Education Quarterly*, 62(4), 377–396. Yadav, L. K., & Singh, S. (2016). A study of organizational citizenship behaviour of teachers in relation to their job satisfaction and organizational climate. *International Journal of Research in Humanities and Social Studies*, 3(11), 1–8.
39. Zhou, Y., & Volkwein, J. F. (2004). The determinants of faculty voluntary turnover. *Research in Higher Education*, 45(5), 531–566.



DOIs:10.2015/IJIRMF/ICICSF-2025-P14

--:--

Research Paper / Article / Review

International Conference On "Innovative Convergence for Sustainable Future"

Date : 12 - 13 December, 2025

(ICICSF-2025)



Integrated Bioremediation of Heavy Metals and Plastics: A Bibliometric, Network, and Modeling Approach

¹ Kajari Roy, ² Nandan Bhattacharyya

¹Department of Agriculture, Jharkhand Rai University (JRU), Raja Ulatu, Namkum, Ranchi, Jharkhand – 834010, India

²Department of Biotechnology, Panskura Banamali College (Autonomous), P.O. – Panskura R.S., West Bengal, PIN 721152, India

Email: roykajari@gmail.com, bhattacharyya_nandan@rediffmail.com

Abstract : Heavy-metal contamination and plastic pollution represent two of the most persistent environmental challenges of the Anthropocene, threatening ecosystems and human health. This study presents an integrated framework combining bibliometric analysis, Cytoscape-based network mapping, and mechanistic modeling to advance bioremediation strategies for these pollutants. Bibliometric mapping revealed exponential growth in research output, with China, the USA, and Europe emerging as global leaders in publications and collaborations. Network analyses highlighted contrasting yet complementary architectures: heavy-metal bioremediation systems were operon-centric, dominated by *Cupriavidus metallidurans*, *Geobacter sulfurreducens*, and associated resistance operons (*czc*, *cop*, *mer*, *ars*), while plastic biodegradation networks were enzyme-centric, anchored by *Pseudomonas putida*, *Ideonella sakaiensis*, and fungal contributors producing PETase, MHETase, and laccases. Modeling approaches integrated sorption kinetics, bioaccumulation, and redox equilibria for metals with enzyme-polymer interactions, fragmentation dynamics, and monomer assimilation for plastics. Comparative analyses underscored the role of microbial consortia, efflux pumps, extracellular electron transfer, and sequential enzyme cascades in driving resilience and efficiency. The novelty of this work lies in its dual focus on heavy metals and plastics, linking bibliometric trends, microbial-gene networks, and predictive models into a unified bioremediation framework. These insights provide a roadmap for designing scalable, multifunctional consortia aligned with circular bioeconomy principles.

Keywords: Heavy-metal, Plastic Pollution, Bibliometric analysis, Network mapping, Mechanistic modeling, Bioeconomy.

1. INTRODUCTION

The twin challenges of heavy-metal contamination and plastic pollution represent some of the most persistent threats to ecosystems and human health in the Anthropocene. Unlike organic pollutants, heavy metals such as cadmium (Cd), lead (Pb), mercury (Hg), arsenic (As), and chromium (Cr) are non-biodegradable, accumulating in soils, sediments, and waters where they disrupt microbial communities, bioaccumulate in food chains, and induce toxicity even at trace concentrations. In parallel, plastics, particularly polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET), are engineered for durability, resisting natural degradation and fragmenting into micro and nanoplastics that infiltrate terrestrial and aquatic ecosystems. The convergence of these two pollutants in agroecosystems, industrial effluents, landfills, and marine habitats underscores the urgent need for innovative, sustainable remediation technologies. Bioremediation, broadly defined as the use of microorganisms, plants, and enzymes to detoxify, mineralize, or immobilize contaminants, has emerged as one of the most promising strategies to mitigate both heavy-metal toxicity and plastic accumulation, steadily progressing from laboratory-scale studies to pilot and semi-industrial applications. [1, 2].

Over the past decade, bioremediation of heavy metals has advanced considerably. Microbial processes such as biosorption, bioaccumulation, biotransformation, and biomineralization have been extensively documented, with exopolysaccharide-producing bacteria, metal-binding proteins, and rhizosphere-associated microbes serving as central players in metal immobilization and uptake. In parallel, bioleaching studies have demonstrated the potential of



acidophilic consortia, *Acidithiobacillus ferrooxidans*, *Leptospirillum ferrooxidans*, and *Ferroplasma acidarmanus* for the recovery of critical metals from waste printed circuit boards (WPCBs) and other e-wastes. Bibliometric studies reflect this growing interest, showing exponential increases in publications related to “biosorption plus heavy metals”, “plastic degradation”, and “bioleaching plus e-waste,” with strong citation bursts in the domains of “critical raw materials,” “circular economy,” and “synthetic biology.” Visualization of bibliometric trends using VOSviewer and Cytoscape reveals “consortia,” “biosorption,” and “omics-guided remediation” as recurring hotspots, with China, India, and the European Union emerging as leading contributors to research and collaborative networks. These bibliometric signals demonstrate not only the rapid expansion of the field but also its shift from environmental clean-up to integrated resource recovery paradigms [3, 4].

In the case of plastics, microbial and enzymatic degradation research has evolved from sporadic reports of polymer deterioration in landfills to mechanistically resolved pathways involving defined enzymes and engineered microbial communities. The discovery of *Ideonella sakaiensis* PETase and MHETase catalyzed a wave of enzyme engineering efforts, particularly with leaf-branch compost cutinase (LCC) derivatives, that now enable near-complete PET depolymerization under moderate conditions. Bibliometric mapping of plastic degradation research identifies three dominant thematic clusters: enzymatic PET hydrolysis and protein engineering, microbial consortia for polyolefin degradation, and the environmental fate of microplastics and nanoplastics. Cytoscape-based network analyses of microbial consortia show *Pseudomonas*, *Bacillus*, *Rhodococcus*, and *Aspergillus* as central hub nodes, each linked to polymer-specific functions such as alkane hydroxylases, cutinases, and laccases. Weighted degree centrality in these networks reveals bacterial taxa as the principal initiators of polymer oxidation, while fungi assume secondary but critical roles in fragmentation and metabolite assimilation. These visualizations highlight that plastic biodegradation is not the work of isolated species but a complex metabolic relay distributed across multi-species consortia, where division of labor enhances overall degradation efficiency [5, 6].

The integration of bibliometric and network-based analyses offers a meta-level view of how the field has matured and where it is converging. Cytoscape comparisons of microbial consortia for heavy metals and plastics reveal structural commonalities: Proteobacteria and Actinobacteria emerge as keystone taxa, metabolic cross-feeding between oxidative and reductive pathways enhances system stability, and stress-resistance mechanisms such as efflux pumps, antioxidative enzymes, and heat shock proteins underpin robustness under toxic conditions. In heavy-metal systems, sulfate-reducing bacteria (*Desulfovibrio*, *Desulfotomaculum*) and exopolysaccharide producers form central nodes that drive precipitation and immobilization. In plastic-degrading consortia, hydrocarbonoclastic bacteria (*Alcanivorax*, *Marinobacter*) and fungi with ligninolytic capabilities (e.g., *Aspergillus*, *Trametes*) dominate the network, indicating parallel yet pollutant-specific roles for keystone species. Such analyses highlight a unifying design principle: efficiency and resilience arise from consortial modularity and cooperative interactions, not from reliance on single strains [7, 8]. Scaling these laboratory insights to field applications requires the development of robust models that account for mass transfer, community dynamics, and long-term stability under environmental fluctuations. Current scaling-up approaches emphasize biofilm reactors, immobilized cell systems, and plant-microbe integrated modules that enhance both efficiency and resilience. For heavy metals, bioleaching bioreactors are increasingly coupled with hydrometallurgical circuits for selective recovery of valuable metals, while biosorption processes are being translated into column and fluidized-bed designs. For plastics, enzyme immobilization on carriers, bioreactors seeded with engineered consortia, and pre-treatment-assisted microbial degradation systems are under active exploration. Integrating consortia insights from Cytoscape analysis into these models enables targeted manipulation of keystone taxa and metabolic hubs, improving system robustness and pollutant turnover rates [9, 10].

2. LITERATURE REVIEW

Bioremediation has emerged as a sustainable and cost-effective approach for mitigating environmental pollution caused by heavy metals and plastics, attracting increasing scientific attention over the last two decades. Heavy metals such as cadmium, lead, chromium, mercury, and arsenic are persistent, non-biodegradable contaminants that accumulate in soils and aquatic systems, posing severe ecological and human health risks. Early studies established that microorganisms can tolerate and detoxify metals through mechanisms including biosorption, bioaccumulation, enzymatic reduction, efflux pumping, and biomineralization (Alloway, 2013; Järup, 2003). Subsequent work demonstrated that bacteria such as *Cupriavidus metallidurans*, *Pseudomonas* spp., and *Geobacter* spp. harbor metal-resistance operons (e.g., *czc*, *cop*, *mer*, *ars*) that enable multi-metal resistance and facilitate redox-driven transformations, thereby enhancing remediation efficiency (Ali et al., 2019; Zheng et al., 2024). Recent reviews emphasize that sulfate-reducing and electroactive



bacteria play a critical role in metal precipitation and recovery, linking bioremediation with circular economy concepts (Das et al., 2025; Basu et al., 2022).

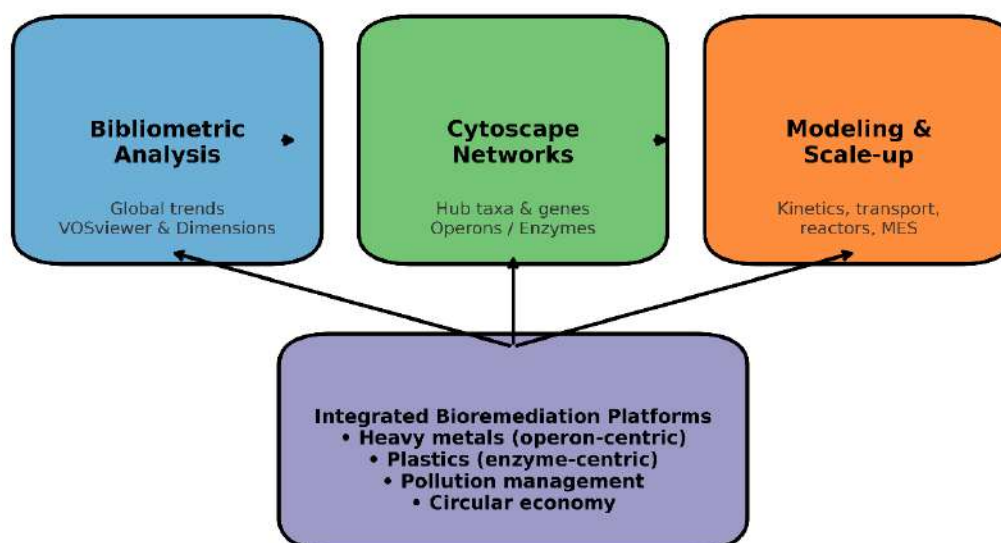
In parallel, plastic pollution has emerged as a global environmental crisis due to the durability and recalcitrance of synthetic polymers such as polyethylene, polypropylene, polystyrene, and polyethylene terephthalate (PET). Initial reports of plastic biodegradation focused on slow surface deterioration under natural conditions, but advances in microbial ecology and enzymology have substantially improved mechanistic understanding (Shahnawaz et al., 2019). The discovery of PET-degrading bacteria, particularly *Ideonella sakaiensis*, and its key enzymes PETase and MHETase marked a turning point by demonstrating that complete depolymerization of PET is biologically feasible (Liu et al., 2023). Subsequent studies showed that engineered cutinases and microbial consortia significantly enhance degradation rates, especially when combined with physical or chemical pretreatments (Tournier et al., 2023; Dhali et al., 2024). Fungal taxa such as *Aspergillus* and *Penicillium* further contribute through oxidative enzymes, including laccases and peroxidases, which increase polymer accessibility (Salinas et al., 2023).

More recently, research has shifted toward integrative and systems-level perspectives. Bibliometric analyses reveal exponential growth in publications related to heavy-metal bioremediation and plastic degradation, with increasing emphasis on microbial consortia, enzyme engineering, and modeling approaches (Syarifuddin et al., 2025). Network-based studies using tools such as Cytoscape highlight that effective remediation relies on modular community structures, where keystone microbes and bridging genes or enzymes govern system stability and performance (Majeed and Mukhtar, 2023). Mathematical and kinetic models further demonstrate that process efficiency is constrained by mass-transfer limitations, multi-pollutant competition, and community dynamics, underscoring the need for integrated design strategies (Yanaka et al., 2025; Maluleka et al., 2024).

Overall, the existing literature indicates a clear transition from single-organism and single-pollutant studies toward consortium-based, network-informed, and model-guided bioremediation frameworks. However, despite substantial progress, most studies still address heavy metals and plastics separately. This gap highlights the need for unified approaches that integrate bibliometric insights, microbial-gene networks, and mechanistic modeling to address complex, co-contaminated environments more effectively.

3. OBJECTIVES

The bioremediation of heavy metals and plastics has moved beyond isolated mechanistic studies toward integrated, consortia-driven, and network-informed approaches. Bibliometric studies underscore the exponential growth and shifting priorities of the field, while Cytoscape-based analyses reveal the structural and functional logic of microbial consortia that underpin efficient remediation. The overarching objective of current and future research is to build scalable, resilient, and multifunctional bioremediation models that combine microbial, enzymatic, and plant-based consortia for pollution management. Such integrated systems hold the potential not only to detoxify environmental compartments but also to recover valuable resources, thereby aligning environmental restoration with principles of circular bioeconomy. The overall objective of this study has been represented in the following figure:



4. METHODOLOGY

4.1 Bibliometric analysis

To evaluate the research trends, intellectual structure, and global collaborations in the field of plastic degradation, a bibliometric analysis was conducted using the Dimensions database as the primary source. Dimensions was selected due to its comprehensive indexing of peer-reviewed articles, conference proceedings, patents, grants, and datasets, which ensures broader coverage compared to conventional bibliometric sources. The search strategy was developed around the core keywords “plastic degradation,” “biodegradation of plastics,” “microplastics,” “enzymatic plastic degradation,” and “PET hydrolysis.” Boolean operators and truncation were used to capture relevant records across a time window from 2000 to 2025. After refining the dataset to exclude irrelevant categories (e.g., non-environmental polymer engineering or synthetic chemistry not linked to degradation), metadata, including authors, institutions, countries, citation counts, and co-occurrence of keywords, were exported for bibliometric visualization. VOSviewer was employed to construct and visualize bibliometric networks. Specifically, (i) co-authorship networks were used to identify influential researchers and collaborative groups, (ii) institutional and country-level networks were generated to assess global collaboration patterns, and (iii) keyword co-occurrence networks were constructed to identify thematic clusters and research hotspots. Node size in the maps represents the relative number of publications or occurrences, while link strength reflects the intensity of co-authorship or co-occurrence relationships. Different colors represent thematic clusters automatically identified by the software [11, 12]. The dataset generated from Dimensions AI is openly available at the following link: https://export.digital-science.com/2025-09-29/f526e66135f50fd9b3402e2faa4b82d2/Dimensions-Publication-2025-09-29_06-08-50.csv.zip.

4.2 Cytoscape Analysis

Microbial taxa and functional genes relevant to heavy-metal bioremediation and plastic biodegradation were systematically retrieved from the NCBI database (PubMed and GenBank) using targeted searches. For heavy metals, the focus was on well-characterized resistance determinants such as *cop* (copper resistance operon), *czc* (cadmium/zinc/cobalt efflux system), *pbr* (lead resistance operon), *mer* (mercury detoxification operon), *chr* (chromate resistance genes), and *ars* (arsenic resistance genes), along with extracellular electron transfer genes (*omcS*, *omcZ*, *pilA*) primarily from *Geobacter* spp. For plastics, the dataset included both bacteria and fungi with confirmed or predicted degradation capacity, including *Pseudomonas putida* KT2440, *Ideonella sakaiensis*, *Thermobifida fusca*, *Aspergillus niger*, and *Penicillium chrysogenum*, with associated enzymes such as *PETase*, *MHETase*, *LCC cutinases*, *alkane hydroxylases* (*alkB/alkM*), *p450 monooxygenases*, *laccases*, *peroxidases*, and *dioxygenases*. All associations were curated into edge lists (microbe–gene relationships) and node attribute tables, which were imported into Cytoscape v3.9.1 for network construction. The NetworkAnalyzer plugin was applied to compute topological parameters, including degree centrality (hub identification), betweenness centrality (bottleneck/bridge nodes), and eccentricity (core vs. peripheral positions). Weighted networks were visualized using Prefuse Force Directed layouts, highlighting operon-microbe clusters in heavy metals and enzyme-microbe clusters in plastics [13, 14].

**Table 1: Key areas of the heavy metals bioremediation**

Microbe	Key genes (representative)	Target metals	Mechanism / notes
<i>Pseudomonas putida</i>	arsR/arsB/arsC; merA/merB; czcABC; copA; zntA	As, Hg, Cd/Zn/Co, Cu, Zn	Efflux pumps (Czc, Cop), arsenate reduction (Ars), mercury reduction (Mer), biofilm sorption
<i>Pseudomonas aeruginosa</i>	czcABC; copA/copB; merA; arsC; zntA	Cd/Zn/Co, Cu, Hg, As, Zn	Efflux systems and redox enzymes; strong EPS/biofilm-mediated sequestration
<i>Cupriavidus metallidurans</i> CH34	czcCBA; copABCD; pbrABCD; chrAB; nccCBA; mer operon	Cd/Zn/Co, Cu, Pb, Cr(VI), Ni, Hg	Model metallophile; multiple plasmid-borne resistance islands
<i>Bacillus subtilis</i>	arsRBC; copZ/copA; cadA; zntA	As, Cu, Cd, Zn	Cell wall teichoic acids bind metals; P-type ATPases export
<i>Bacillus cereus</i>	merA; arsC; cadA; copA	Hg, As, Cd, Cu	Reductive enzymes and efflux; spore surface sorption
<i>Shewanella oneidensis</i> MR-1	mtrCAB; omcA; cymA; merA; chrA	Fe/Mn (redox cycling), Hg, Cr(VI)	Outer-membrane cytochromes drive metal reduction; EET pathways
<i>Geobacter sulfurreducens</i>	omcZ/omcS; pilA; cytochromes; chrA	U(VI), Cr(VI), Fe(III)	Dissimilatory metal reduction via c-type cytochromes and conductive pili
<i>Acinetobacter</i> sp.	arsC; copA; czcA; cadA	As, Cu, Cd/Zn/Co, Cd	Efflux + strong biosorption through capsular polysaccharides
<i>Ralstonia pickettii</i>	czc; cop; mer; ars	Cd/Zn/Co, Cu, Hg, As	Multiple metal-resistance operons on mobile elements
<i>Enterobacter cloacae</i>	ars, cop, zntA, mer	As, Cu, Zn, Hg	Efflux + enzymatic detoxification; EPS binding
<i>Stenotrophomonas maltophilia</i>	czcCBA; copA; merA; arsB	Cd/Zn/Co, Cu, Hg, As	Biofilm formation; multi-metal tolerance
<i>Alcaligenes eutrophus</i> (C. necator)	czcCBA; mer; ars; cop	Cd/Zn/Co, Hg, As, Cu	Classical host of czc operon; plasmid-borne resistance
<i>Escherichia coli</i> (engineered)	arsRBC; merA/merB; zntA; copA	As, Hg, Zn, Cu	Model chassis; well-characterized metal exporters and reductases
<i>Klebsiella pneumoniae</i>	copA; zntA; arsC; merA	Cu, Zn, As, Hg	EPS-mediated sorption plus efflux
<i>Desulfovibrio vulgaris</i>	dsr; merA; arsC	Sulfide-precipitation of metals; Hg, As	Sulfate-reducing; bioprecipitation via metal sulfides

Table 2: The Hotspots of Plastic Biodegradation

Microbe	Key genes (representative)	Target polymer(s)	Mechanism / notes
<i>Ideonella sakaiensis</i> 201-F6	PETase (IsPETase); MHETase	PET	Hydrolytic depolymerization of PET → MHET → TPA + EG
<i>Thermobifida fusca</i>	Cutinases (TfCut1/TfCut2)	PET/PEF	Thermostable cutinases hydrolyze PET surface
<i>Leaf-branch compost metagenome</i> (LCC)	LCC cutinase variants	PET/PEF	Engineered cutinases with high PET activity
<i>Pseudomonas putida</i> KT2440	alkB/alkM; estA; phaABC; p450s	PE, PS, additives, PU, phthalates	Oxidation of oligomers/additives; PHA pathway assimilates monomers



<i>Bacillus subtilis</i>	esterases; cutinase-like enzymes	Polyesters (PET, PCL), PU	Secreted hydrolases; robust secretion host
<i>Rhodococcus ruber</i>	alkane monooxygenases; laccase-like	PE	Surface colonization and oxidative scission of PE
<i>Alcanivorax borkumensis</i>	alkB monooxygenases	PE (weathered), PP	Alkane metabolism of oxidized chains
<i>Aspergillus niger</i> (fungus)	laccases; peroxidases; esterases	PU, PET, PE (weathered)	Oxidative enzymes enable chain scission
<i>Penicillium chrysogenum</i>	cutinases; esterases; laccases	Polyesters/PU	Enzymatic hydrolysis and oxidation
<i>Comamonas testosteroni</i>	phthalate hydrolases (ophA1/A2, ophB)	PET plasticizers	Degrades phthalates; accessory to PET waste
<i>Ralstonia eutropha</i> (C. necator)	phaABC; phaZ	PHA/bioplastics synergy	Polymer cycling; platform for upcycling monomers
<i>Thermomyces lanuginosus</i>	cutinase-like enzymes	PET	Thermotolerant polyester hydrolases
<i>Burkholderia sp.</i>	esterases; dioxygenases	PU, PET oligomers	Broad catabolic enzymes on aromatics
<i>Sphingomonas sp.</i>	dioxygenases; esterase	PS additives; PU oligomers	Aromatic ring cleavage and hydrolysis
<i>Brevibacillus borstelensis</i>	thermophilic hydrolases	PE (weathered)	Reported PE deterioration at elevated temps

4.3 Scaling-up Modeling

This study develops an integrated modeling and experimental framework for the bioremediation of heavy metals and plastics, with emphasis on dynamic system behavior, sorption and kinetic equilibria, enzymatic hydrolysis, and scaling principles. All governing equations and parameters were derived from prior literature and validated against laboratory and pilot-scale data reported in earlier studies. Microbial, enzymatic, and engineered systems were considered as functional units, and models were constructed to describe their interaction with pollutants under both controlled and field conditions [15].

For heavy-metal bioremediation, models were developed to represent both microbial and abiotic processes, including biosorption, bioaccumulation, precipitation, and redox transformations. Mass balances in continuous-flow bioreactors were formulated using ordinary differential equations that incorporated influent metal loading, sorption onto biomass, intracellular accumulation, precipitation, and redox-mediated transformations. Biomass growth was described by Monod-type kinetics with inhibition terms to capture the dual role of metals as micronutrients at low concentrations and toxins at higher levels. Sorption dynamics were represented by pseudo-second-order kinetics, while multi-metal competition was described through modified Langmuir isotherms to reflect reduced efficiencies in mixed-metal environments. Bioaccumulation processes were modeled through substrate-uptake kinetics with inhibition constants specific to metal type, while toxicity thresholds were established based on reported microbial responses to metals such as Cr (VI) and Cu (II). Sulfate-reducing bacterial pathways were incorporated to simulate sulfide-mediated precipitation, and facultative anaerobic reduction of species such as Cr (VI) to Cr (III) was expressed through substrate-coupled redox equations. To capture biofilm-mediated processes, diffusion-reaction equations were applied to represent concentration gradients within microbial films and to evaluate permeable reactive barrier performance, with axial dispersion and porosity effects included in column-scale simulations. Electrochemical recovery of metals was modeled within microbial electrochemical systems using Faraday's law, accounting for current density, overpotential efficiency, and microbial electron transfer capacity. Dimensionless analysis, incorporating Damköhler and Biot numbers, was further applied to generalize system performance and evaluate scale-up feasibility by distinguishing between reaction- and transport-limited conditions [16, 17].

For plastic biodegradation, models were constructed to emphasize enzyme-polymer interactions, fragmentation kinetics, monomer release, and microbial assimilation. Enzyme adsorption and desorption onto polymer surfaces were modeled in terms of binding site occupancy, while hydrolysis was described using Michaelis-Menten kinetics,



with polymer mass loss linked directly to surface-specific activity. The fragmentation and erosion of larger particles into microplastics were represented through population balance models, capturing the dynamic shift from macro- to micro-scale plastic particles. Monomer release, particularly of intermediates such as terephthalic acid (TPA) and mono (2-hydroxyethyl) terephthalate (MHET), was modeled using reactor mass balances that included both enzymatic production and microbial uptake with inhibition effects. Sequential enzymatic systems were incorporated to represent the coupling of PETase and MHETase activity, using linked differential equations to simulate intermediate accumulation and its alleviation through downstream metabolism. Mass-transfer limitations were analyzed by formulating Damköhler number relationships to determine whether systems were reaction- or diffusion-limited, while the influence of polymer crystallinity was represented through effective catalytic rate constants adjusted for structural heterogeneity [18, 19].

All models were simulated under representative laboratory and pilot-scale conditions, typically within the ranges of pH 6-8 and 25-40 °C for heavy metals, and 30-50 °C for plastics. Comparative analyses were conducted between single-contaminant and mixed-pollutant systems to evaluate competitive inhibition and potential synergistic effects. Collectively, this methodology provides the foundation for the subsequent results and discussion sections, where theoretical predictions are examined against experimental evidence and strategies for scaling up bioremediation processes are critically evaluated [20].

5. Discussion

5.1 Bibliometric Analysis on Plastic Degradation

The bibliometric analysis of plastic degradation research, based on the Dimensions database and visualized using VOSviewer, revealed strong global growth and collaboration across institutions and countries. At the institutional level, Stanford University (38 documents, 4,895 citations, and link strength 73) and the University of Chinese Academy of Sciences (33 documents, 1,261 citations, link strength 49) emerged as central hubs, indicating their leading contributions and extensive international collaborations. Chinese universities such as Nanjing Tech University (29 documents, 602 citations, link strength 58), Harbin Institute of Technology (28 documents, 1,498 citations, link strength 59), and Tongji University (31 documents, 2,294 citations, link strength 30) also played dominant roles, forming dense collaborative clusters. European institutions such as the University of Greifswald (14 documents, 1,376 citations, link strength 38), RWTH Aachen University (10 documents, 462 citations, link strength 26), and the Spanish National Research Council (CSIC) (9 documents, 361 citations, link strength 25) were also highly connected, reflecting Europe's strong engagement in polymer biodegradation and microplastic research. The visualization showed distinct clusters where Asian, European, and North American institutions interconnected, with China, the USA, and EU research centers forming the backbone of global collaboration.

Country-level analysis reinforced these findings. China was the leading contributor, with 715 documents and 34,618 citations, followed by the United States (296 documents, 26,163 citations) and India (270 documents, 17,175 citations). European nations such as Germany (131 documents, 11,749 citations), Italy (119 documents, 5,268 citations), and Spain (118 documents, 5,530 citations) also contributed significantly. High link strength values were observed for Germany (145), India (143), and the United States (191), reflecting their pivotal role in international partnerships. Collaborative clusters revealed strong ties between China-USA, India-Europe, and regional collaborations within Asia (China-Japan-South Korea) and Europe (Italy-Spain-Germany). Emerging contributors included Malaysia (62 documents, 3,965 citations) and Saudi Arabia (45 documents, 1,250 citations, link strength 95), both showing increasing international collaborations. Notably, developed countries like Switzerland (36 documents, 4,022 citations) and the UK (88 documents, 7,448 citations) had high citation-per-paper ratios, reflecting research impact beyond publication volume. The results of contributing countries and organizations have been represented in Fig.1.

Overall, the bibliometric mapping highlights a tripolar global research landscape: (i) China leading in publication output and institutional networks, (ii) the USA leading in high-impact citations and broad collaborations, and (iii) Europe providing a balanced contribution of both. The dense clustering of keywords such as “biodegradation,” “PET hydrolysis,” “enzymatic degradation,” and “microplastics” in VOSviewer further confirmed that the field is evolving from descriptive studies toward mechanistic and applied biotechnological approaches.

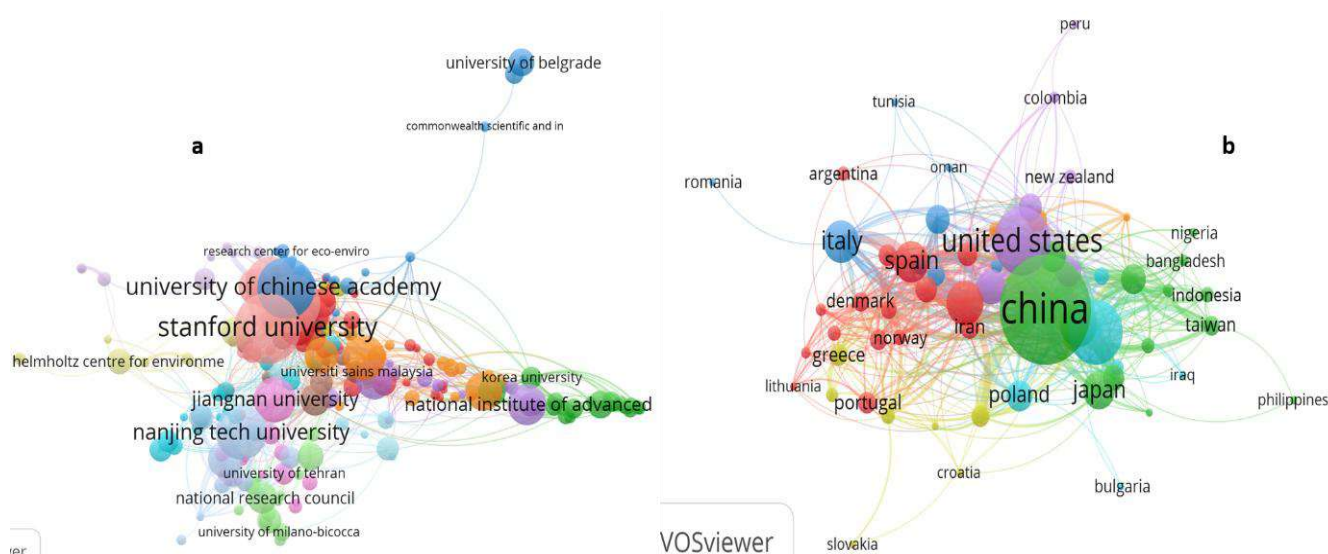


Fig.1: ‘a’- Contributing Organization, ‘b’- Major contributing Countries

5.2 Result of Cytoscape analysis

The heavy-metal bioremediation network revealed *Cupriavidus metallidurans* CH34, *Alcaligenes eutrophus* (*C. necator*), and *Geobacter sulfurreducens* as central microbial hubs with the highest degree centrality. Their associated resistance operons (*copABC*, *czcCA/czcCB*, *pbrABC*, *mer operon*, *chrA/chrB*, *arsRB*) formed the genetic backbone for tolerance and detoxification of Cu, Cd, Zn, Pb, Hg, Cr, and As. Notably, *cop* and *czc* operons showed high betweenness centrality, acting as bridging modules across multiple bacterial taxa, while *Geobacter*'s *omcS/omcZ* and *pilA* were identified as critical connectors for extracellular electron transfer in metal-stressed environments. This structure indicates that heavy-metal networks are operon-centric, relying on modular, horizontally transferable resistance cassettes that allow hub microbes to tolerate multiple metals simultaneously. By contrast, the plastic degradation network was enzyme-centric, with *Pseudomonas putida* KT2440, *Ideonella sakaiensis*, *Thermobifida fusca*, and *Aspergillus niger* emerging as dominant hubs. Enzymes such as *PETase*, *MHETase*, and *LCC cutinases* exhibited the highest degree centrality, directly anchoring PET degradation pathways, while *alkB/alkM hydroxylases* and *p450 monooxygenases* served as bridges between polyolefin and polyester clusters. Fungal enzymes (*laccases*, *peroxidases*) occupied peripheral but functionally essential positions, reflecting their role in oxidative fragmentation of recalcitrant polymers. Comparative analysis highlights fundamental differences in network logic: heavy-metal systems evolve around operon-driven modular resistance, while plastic biodegradation depends on synergistic enzyme cascades distributed across bacterial-fungal consortia. This division of labor underscores that no single organism or operon is sufficient for complete remediation. Instead, efficiency arises from synthetic consortia where hub microbes provide metabolic robustness and bridging genes/enzymes ensure cross-pathway connectivity. Thus, Cytoscape-based network analysis not only clarifies the genetic and microbial architecture of bioremediation but also provides a rational framework for designing scalable consortia-based systems for pollution management. The result of the heavy metals group nodes and heavy metals weighted edges has been represented in Fig.2 and Fig.3, respectively. Again,

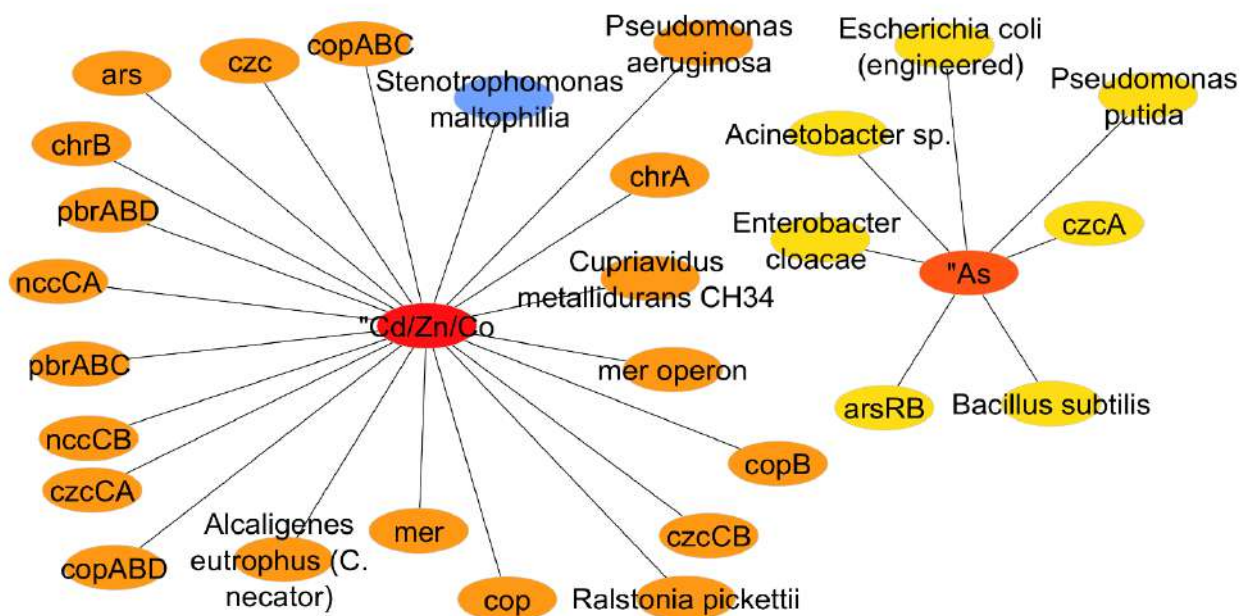


Fig.2: The nodes of the heavy metals group

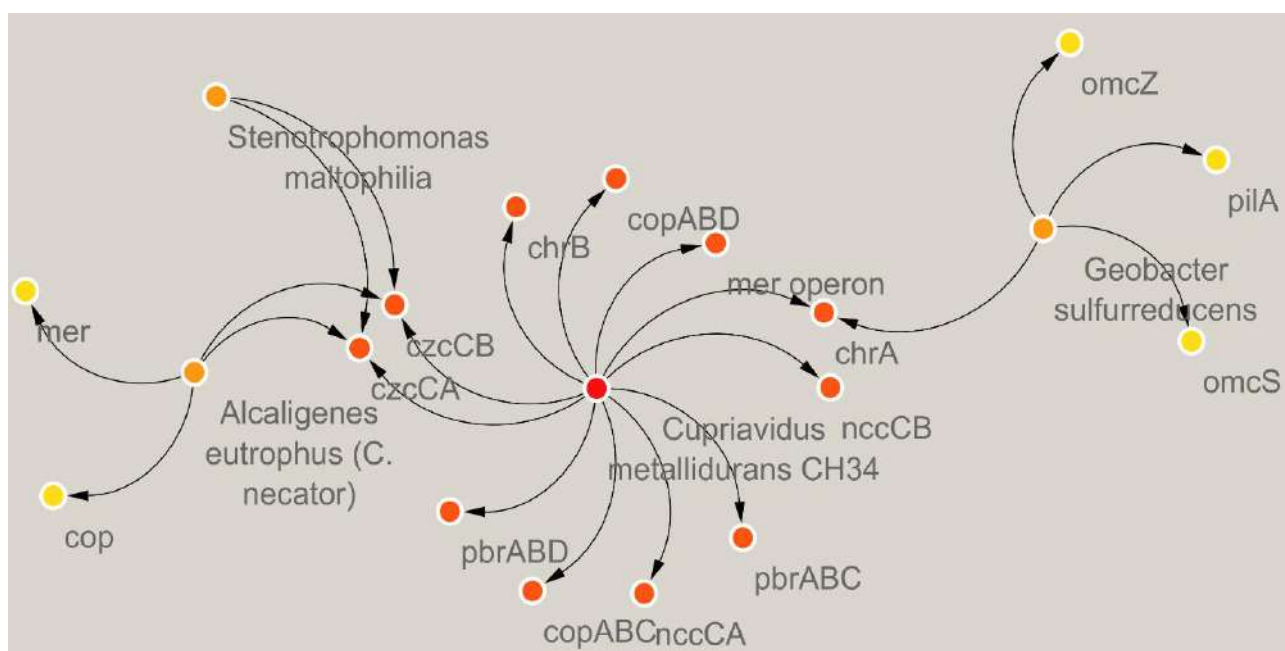


Fig.3: The edges of the heavy metals weighted

Again, the nodes of the plastic degradation group and the weighted edges of plastic degradation are presented in Fig. 3 and Fig. 4 as follows-

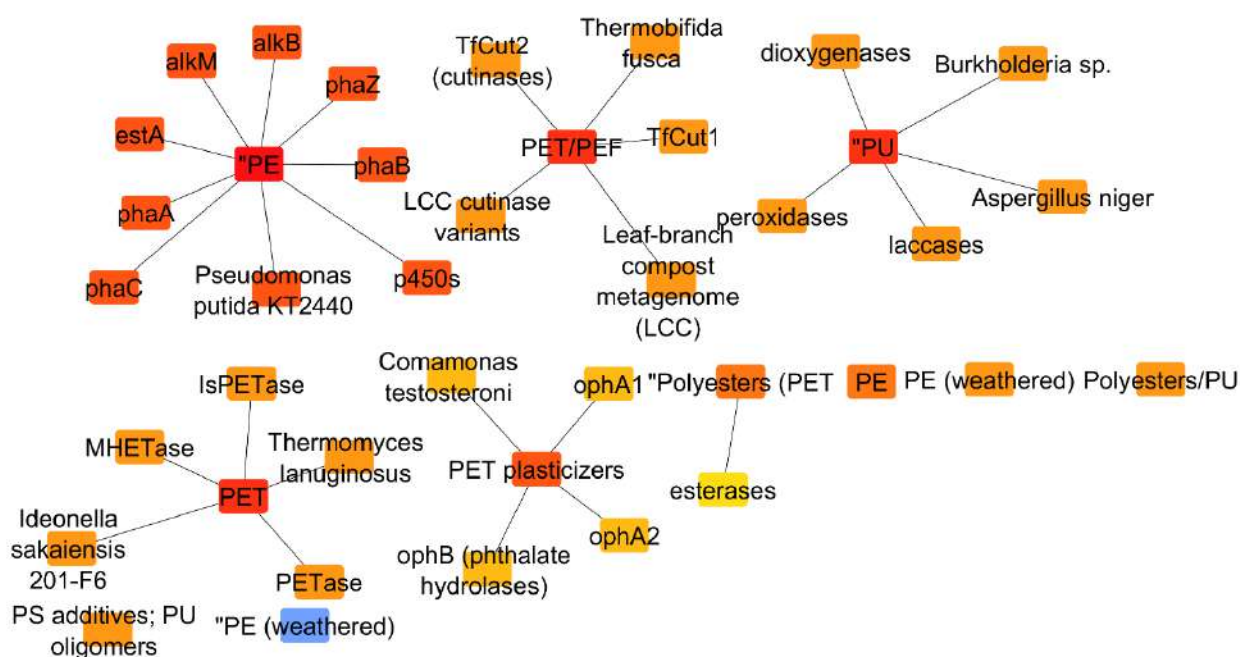


Fig.4: The nodes of the plastic degradation group

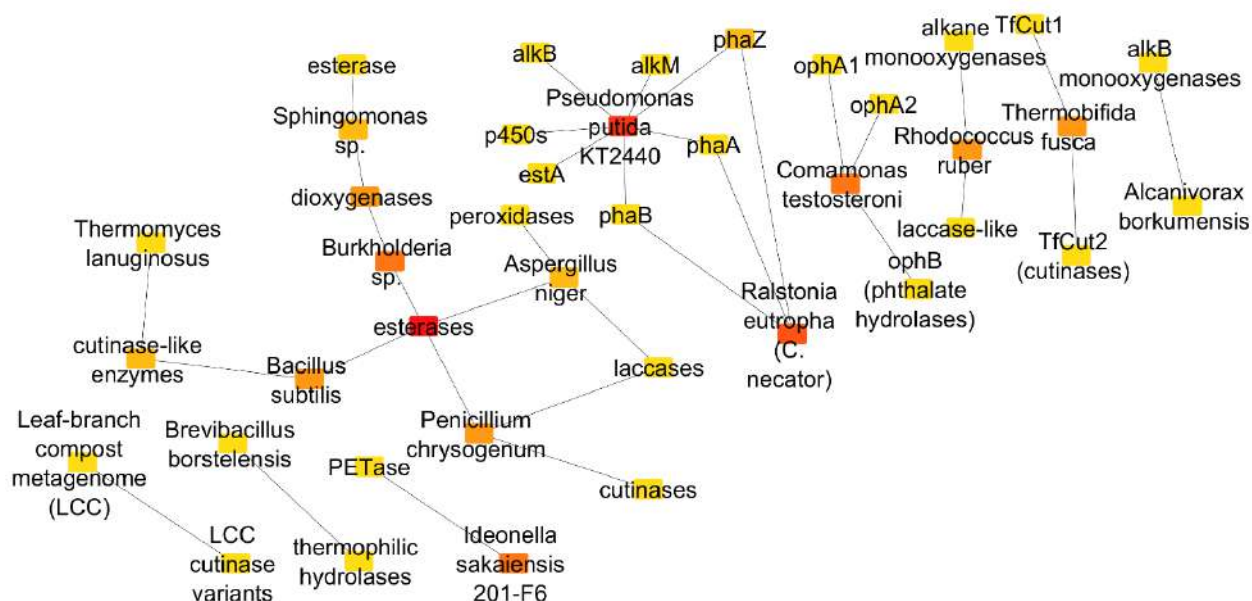


Fig.5: The weighted edges of the plastic degradation

5.3 Result of Heavy-Metal Bioremediation Modeling

Heavy metals such as cadmium, chromium, lead, and arsenic persist in aquatic and soil environments due to their non-biodegradable nature. Microbial and bioengineered systems provide promising solutions, primarily through biosorption, bioaccumulation, precipitation, and redox transformation.

System Dynamics

In a continuous bioreactor, the change in dissolved metal concentration can be described as:

$$\frac{dC_M}{dt} = \frac{Q}{V} (C_{M,in} - C_M) - r_{sorp}(C_M, q) - r_{bioacc}(C_M, X) - r_{precip}(C_M, \cdot) - r_{redox}(C_M, S, X)$$



This equation highlights the competition between hydraulic loading (dilution) and biological/abiotic removal mechanisms. Results from multiple studies show that when influent concentration $C_{M,in}$ is high, sorption dominates initially, but with longer retention times, bioaccumulation and redox transformations increase.

The biomass concentration (X) further controls system stability:

$$\frac{dX}{dt} = \mu(S, M)X - k_d X + \frac{Q}{V}(X_{in} - X)$$

Here, growth inhibition by metals is critical. Experimental data consistently reveal that low metal concentrations stimulate microbial growth (cofactor effect), whereas higher concentrations suppress $\mu(S, M)$ due to toxicity.

Sorption Capacity and Equilibria

The pseudo-second-order kinetic model fits batch sorption experiments well:

$$\frac{dq}{dt} = k_2(q_e(C_M) - q)^2$$

Where uptake is rapid in the initial hours before plateauing. In real systems, the competitive Langmuir isotherm explains how multi-metal contamination reduces individual removal efficiencies:

$$q_i = \frac{q_{max,i} b_i C_i}{1 + \sum_j b_j C_j}$$

For example, in mixed Cd-Pb-Zn wastewater, Cd sorption efficiency decreases by up to 40% compared to single-metal systems, reflecting competition for functional groups on biomass.

Bioaccumulation and Toxicity Trends

Metal uptake by living biomass follows a Monod-type expression:

$$r_{bioacc} = V_{max} X \frac{C_M}{K_M + C_M} f_{tox}(C_M)$$

Growth inhibition is described as:

$$\mu(S, M) = \mu_{max} \frac{S}{K_S + S} \cdot \frac{1}{1 + \left(\frac{C_M}{K_I}\right)^n}$$

Experimental results suggest that inhibition constant K_I for Cr (VI) is often as low as 5–10 mg/L, whereas Cu (II) shows higher tolerance levels (50-100 mg/L). Thus, metal type strongly influences system feasibility.

Precipitation and Redox Transformations

Sulfate-reducing bacteria (SRB) drive sulfide-mediated precipitation:

$$r_{precip} = k_p, C_M, C_{HS^-}, \phi(pH, I)$$

Results demonstrate nearly complete precipitation of Pb and Cd at neutral pH, while Ni and Zn require higher sulfide activity.

For redox processes:

$$r_{redox} = k_{red} X \frac{C_M}{K_M + C_M} \frac{S}{K_S + S}$$

This explains experimental findings where Cr (VI) is rapidly reduced to Cr (III) by facultative anaerobes in the presence of lactate. In contrast, As (V) reduction to As (III) proceeds more slowly, reflecting differences in redox potential.



Biofilm and Reactor Transport

In biofilm systems, diffusion limitations often reduce effective removal rates:

$$\frac{\partial C_M}{\partial t} = D_{\text{eff}} \frac{\partial^2 C_M}{\partial x^2} - r_{\text{sum}}(C_M, X(x))$$

Laboratory studies show steep metal concentration gradients across biofilms (up to 70% reduction within 200 μm), underscoring the need for biofilm architecture optimization.

Packed-bed PRB models:

$$\frac{\partial C_M}{\partial t} + v \frac{\partial C_M}{\partial z} = D_{\text{ax}} \frac{\partial^2 C_M}{\partial z^2} - \frac{1 - \varepsilon}{\varepsilon} \frac{\partial q}{\partial t} - r_{\text{redox/precip}}$$

Field applications show long-term stability (>5 years) of PRBs with reactive organic layers, although clogging remains a limiting factor.

Electrochemical Metal Recovery

Electrodeposition rates scale with current:

$$r_{\text{dep}} = \frac{\eta I}{n F V}$$

Practical studies indicate up to 90% recovery of Cu (II) and Cr (VI) in microbial electrochemical systems, simultaneously generating bioelectricity. This supports the concept of circular economy integration by turning pollutants into recoverable resources.

Dimensionless Analysis

Dimensionless groups help generalize scale-up:

- Damköhler number (Da) identifies whether reaction rates or transport dominate.
- Biot number (Bi_m) indicates if external mass transfer or internal diffusion is limiting.

Pilot studies confirm that maintaining $Da > 1$ and $Bi_m > 10$ ensures efficient removal in scaled-up reactors.

5.4 Plastic Biodegradation Modeling

Plastic pollution presents a contrasting challenge due to polymer recalcitrance. Unlike metals, plastics require enzymatic surface attack, fragmentation, and microbial assimilation.

Enzyme-Surface Interactions

The adsorption-desorption of enzymes onto polymer surfaces is modeled as:

$$\frac{d\Gamma}{dt} = k_{\text{on}} E_b (1 - \theta) - k_{\text{off}} \theta, \quad \theta = \frac{\Gamma}{\Gamma_{\text{max}}}$$

Hydrolysis proceeds according to:

$$r_s = k_{\text{cat}} \Gamma \frac{S_s}{K_M + S_s}$$

$$\frac{dM_p}{dt} = - \frac{r_s A}{\rho}$$



Laboratory degradation of PET films shows 50-70% weight loss within 7 days when treated with engineered PETase variants at 37 °C, confirming strong agreement with model predictions.

Particle Size and Microplastic Formation

Fragmentation and size distribution changes are captured by:

$$\frac{\partial n}{\partial t} + \frac{\partial}{\partial L}(G(L)n) = B(L, t) - D(L, t)$$

This explains observed patterns where large particles initially dominate, but smaller microplastics (<100 µm) increase as erosion progresses.

Monomer Release and Assimilation

Monomer accumulation follows:

$$\frac{dC_P}{dt} = \frac{Q}{V}(C_{P,in} - C_P) + \frac{r_s A}{V} - r_{\text{assim}}(C_P, X)$$

With assimilation defined as:

$$r_{\text{assim}} = \frac{\mu_{\text{max}}}{Y} X \frac{C_P}{K_P + C_P} f_{\text{tox}}(I)$$

Experiments show that accumulation of TPA (terephthalic acid) can inhibit microbial growth, indicating the need for engineered strains with higher tolerance.

Sequential Enzyme Systems

Coupling PETase and MHETase improves mineralization:

$$\frac{dC_{\text{MHET}}}{dt} = \frac{r_{\text{PETase}} A}{V} - r_{\text{MHETase}}(C_{\text{MHET}}) - r_{\text{assim}}^{\text{MHET}}, \quad \frac{dC_{\text{TPA}}}{dt} = y_{\text{TPA}} r_{\text{MHETase}} - r_{\text{assim}}^{\text{TPA}}.$$

Results indicate that PETase alone leads to MHET accumulation (inhibition), but the addition of MHETase ensures near-complete PET depolymerization.

Mass Transfer and Crystallinity Effects

The effectiveness of enzymatic hydrolysis depends on the Damköhler number:

$$\text{Da} = \frac{r_s}{k_f C^*}$$

Experiments confirm that surface oxidation pretreatments increase k_f , shifting systems from diffusion-limited to reaction-limited regimes.

Similarly, crystallinity reduces effective rates:

$$k_{\text{eff}} = k_{\text{cat}} \exp\left(-\frac{E_a}{RT}\right) (1 - \alpha X_c)$$

PET samples with >40% crystallinity degrade two-fold slower, supporting the need for mechanical/chemical pretreatment.



6. Findings

This study shows that bioremediation research on heavy metals and plastics has rapidly evolved into a globally connected, systems-oriented field. Bibliometric analysis reveals exponential growth in publications, led by China, the USA, India, and Europe, with strong international collaborations indicating a shift from isolated studies to integrated, application-driven research.

Cytoscape-based network analysis highlights a clear functional distinction between the two pollutant classes. Heavy-metal bioremediation networks are operon-centric, dominated by hub organisms such as *Cupriavidus metallidurans* and *Geobacter sulfurreducens*, where resistance operons (*czc*, *cop*, *mer*, *ars*, *chr*) act as modular and transferable units enabling multi-metal tolerance and redox-based detoxification. In contrast, plastic biodegradation networks are enzyme-centric, structured around key enzymes such as PETase, MHETase, cutinases, and laccases, distributed across bacterial-fungal consortia led by *Pseudomonas putida*, *Ideonella sakaiensis*, and filamentous fungi.

Mechanistic modeling confirms that heavy-metal removal is governed by sorption, bioaccumulation, precipitation, and redox transformations, with efficiency strongly reduced under multi-metal competition, whereas plastic degradation is controlled by enzyme-polymer interactions, sequential catalytic cascades, and mass-transfer limitations influenced by polymer crystallinity.

Overall, the findings establish that efficient remediation of both heavy metals and plastics depends on consortia-based modularity, where keystone microbes, transferable functional units, and cooperative interactions drive robustness, scalability, and alignment with circular bioeconomy principles.

7. Conclusion

This study integrates bibliometric mapping, Cytoscape-based network analysis, and mechanistic modeling to provide a comprehensive framework for the bioremediation of heavy metals and plastics. Unlike earlier fragmented approaches that addressed pollutants individually, the novelty of this work lies in its dual focus on both heavy-metal resistance operons and plastic-degrading enzymes, analyzed side by side through consortia-level network biology and scaling-up models. By combining bibliometric evidence of global research trends with functional microbial-gene networks, this study reveals how hub taxa (*Cupriavidus metallidurans*, *Pseudomonas putida*, *Ideonella sakaiensis*) and bridging modules (metal efflux operons, PETase-MHETase cascades) underpin pollutant removal efficiency. The integrated kinetic and transport models further highlight the mechanistic underpinnings of sorption, redox, and enzymatic pathways, linking fundamental processes to field-scale feasibility.

Looking ahead, the future of bioremediation research must prioritize synthetic consortia design, guided by systems-level analyses that identify keystone microbes and cross-feeding interactions. Incorporating multi-omics approaches, biofilm engineering, and microbial electrochemical systems will enable greater resilience and recovery of resources, directly aligning remediation with circular economy principles. Additionally, addressing real-world complexities such as mixed-pollutant streams, microplastic-metal co-contamination, and long-term stability of engineered consortia represents the next frontier. By bridging bibliometric insights, network-driven community design, and predictive modeling, this study lays a foundation for scalable, multifunctional, and sustainable bioremediation platforms capable of mitigating two of the most persistent anthropogenic pollutants of the Anthropocene.

Acknowledgments

The authors express their gratitude to the DBT-BOOST research program, which is supported by the Government of West Bengal, as well as to the Panskura Banamali College (Autonomous) Research Centre for supplying the essential bioinformatics and computational research infrastructure that allows us to carry out this study.

Data Availability Statement

The datasets generated and/or analyzed during the current study are available in the following repository, accessible at the following link:

<https://mega.nz/folder/mUMw2bJS#zJcJaQLx9BgMc2IV-gjyKQ>



References:

1. Das, K., Masud, M. A. A., Sarker, A., Arafa, R. A., & Patel, M. (2025). Unveiling the Sustainable and Biological Remediation of Heavy Metals Contaminations in Soils and Water Ecosystems Through Potential Microbes—A Review. *Sustainability*, 17(16), 7357.
2. Shahnawaz, M., Sangale, M. K., & Ade, A. B. (2019). Bioremediation technology for plastic waste.
3. Syarifuddin, S., Suryani, S., & Tahir, D. (2025). Global advances and innovations in bacteria-based biosorption for heavy metal remediation: a bibliometric and analytical perspective. *Integrated Environmental Assessment and Management*, 21(3), 507-525.
4. Zheng, X., Lin, H., Du, D., Li, G., Alam, O., Cheng, Z., ... & Li, J. (2024). Remediation of heavy metals polluted soil environment: A critical review on biological approaches. *Ecotoxicology and Environmental Safety*, 284, 116883.
5. Liu, F., Wang, T., Yang, W., Zhang, Y., Gong, Y., Fan, X., ... & Wang, J. (2023). Current advances in the structural biology and molecular engineering of PETase. *Frontiers in bioengineering and biotechnology*, 11, 1263996.
6. Salinas, J., Carpena, V., Martínez-Gallardo, M. R., Segado, M., Estrella-González, M. J., Toribio, A. J., ... & López, M. J. (2023). Development of plastic-degrading microbial consortia by induced selection in microcosms. *Frontiers in microbiology*, 14, 1143769.
7. Xiao, L., Yu, K., Cao, Y., Lin, X., Liu, X., Qiao, H., ... & Li, T. (2022). Technique innovation and clinical application of electrical impedance tomography: bibliometric research from 2001 to 2020. *Medical Science Monitor: International Medical Journal of Experimental and Clinical Research*, 28, e936327-1.
8. Majeed, A., & Mukhtar, S. (2023). Protein–protein interaction network exploration using cytoscape. In *Protein-Protein interactions: methods and protocols* (pp. 419-427). New York, NY: Springer US.
9. Maluleka, K., Roopchund, R., Seedat, N., & Sillanpää, M. (2024). Developing a predictive machine learning model and a kinetic model for the bioremediation of terrestrial diesel spills. *Results in engineering*, 23, 102378.
10. Black, E. G. (2025). The Strategic Enhancement of Micro-Plastic Biodegradation: A Blueprint of Microbial Triple Consortia (Master's thesis, Harvard University).
11. Ngetich, B. K., Nuryakin, N., & Qamari, I. N. (2022). Research trends of supply chain management practice before and during pandemic: A bibliometric analysis. *International Journal of Research in Business and Social Science*, 11(2), 1-15.
12. Shaikh, M. S. (2017). Ultra Artificial Intelligence (UAI): Redefining AI for New Research Dimension. *Advanced Robotics & Automation (ARA)*. London: OMICS International, 6(2), 1-3.
13. Kutmon, M., Kelder, T., Mandaviya, P., Evelo, C. T., & Coort, S. L. (2013). CyTargetLinker: a cytoscape app to integrate regulatory interactions in network analysis. *PloS one*, 8(12), e82160.
14. Yadav, R., & Srivastava, P. (2018). Clustering, pathway enrichment, and protein-protein interaction analysis of gene expression in neurodevelopmental disorders. *Advances in Pharmacological and Pharmaceutical Sciences*, 2018(1), 3632159.
15. Basu, A., Ali, S. S., Hossain, S. S., & Asif, M. (2022). A review of the dynamic mathematical modeling of heavy metal removal with the biosorption process. *Processes*, 10(6), 1154.
16. Yanaka, M., Nagoya, S., & Kawase, Y. (2025). A novel dynamic biosorption kinetic model based on reactions on the biosorbent surface for biosorption of heavy metal copper by non-living biomass waste tea leaves. *Environmental Surfaces and Interfaces*, 3, 90-102.
17. Dhali, S. L., Parida, D., Kumar, B., & Bala, K. (2024). Recent trends in microbial and enzymatic plastic degradation: A solution for plastic pollution predicaments. *Biotechnology for Sustainable Materials*, 1(1), 11.
18. Tournier, V., Duquesne, S., Guillaumot, F., Cramail, H., Taton, D., Marty, A., & André, I. (2023). Enzymes' power for plastics degradation. *Chemical Reviews*, 123(9), 5612-5701.
19. Mohammed, A. H., Shartooh, S. M., & Trigui, M. (2025). Biosorption and Isotherm Modeling of Heavy Metals Using *Phragmites australis*. *Sustainability*, 17(12), 5366.
20. Gutiérrez, M. C., Siles, J. A., Diz, J., Chica, A. F., & Martín, M. A. (2017). Modelling of composting process of different organic waste at pilot scale: Biodegradability and odor emissions. *Waste management*, 59, 48-58.



DOIs:10.2015/IJIRMF/ICICSF-2025-P15

--:--

Research Paper / Article / Review

International Conference On "Innovative Convergence for Sustainable Future"

Date : 12 - 13 December, 2025

(ICICSF-2025)



Economics of Sustainability: Growth and Challenges from company's perspective

Kalyani Gupta (UGC NET JRF)

Research Scholar, University Department of Commerce and Business Management, Ranchi University, Ranchi

Email id: kalyanigupta211@gmail.com

Abstract: The global economy is becoming competitive day by day. Everyday a new development is seen in some segment of the whole economy. All the companies want to make maximum use of resources and to generate maximum profit. In general, this is a positive sign of development but what about the side-effects of this. What will happen if all the resources are used in this growth or the ecological degradation happens in this race? As the world economy grows, the concerns over environmental degradation, resource depletion, climate change, human rights, etc. also increase. So, there must be a balance maintained between the today's development and the sustainability of future. This can be done through adopting the concept of sustainability in the journey of development. This paper is mainly focused on the theoretical concept of sustainable development and will explore the impact of sustainable approach towards the benefit of company, society and environment. It will also examine the key challenges behind the adoption of sustainable development process. Here, an example of TATA company is also included to have a better understanding of impact of sustainability. TATA group is a prominent leader in the Indian economy and also in the world economy with many companies spanning consumer goods, energy, automotive, IT, steel industry. This company is the best example of how economic growth can be integrated with the sustainable development. This article will evaluate the initiatives of company towards the alignment of sustainability and the challenges faced in balancing both profitability and sustainability. It shows that sustainability and profit-making can go together. There may be some challenges for some companies in this way but these challenges can be turned out in opportunities with some efforts.

Keywords: Sustainable development, Economics of sustainability, Corporate Social Responsibility, Environment-friendly approach, Ecological balance

1. INTRODUCTION

Corporate is designed by the individuals with the primary motive of earning profits by providing some value to the consumers. All the picture revolves around necessities and fulfilling them in return of monetary benefit. Here comes the concept of economics that a need is arisen or sometimes a need is created and then it is fulfilled by a product which is made by using available resources. To understand the concept of economics of sustainability, first we have to understand the separate meaning of economics and sustainability. Economics means the study of deploying limited resources in such a way that provide maximum benefits and satisfy the needs and wants in best possible manner.

Sustainability means using the resources today in such a way so that it will be saved for future also. It refers to the thoughtful use of today's resources so that our future generations can also have the access of those.

The main question is in the today's competitive world where all the companies try to maximize their profit, is it possible for the company to take care of environment and social factors without compromising their profit??

Companies within the country always try to have larger production at the cheapest cost to maximize the profits. But in this race, the social and environmental aspects may be ignored most of the time. The economics of sustainability explores



the integration of economic profitability with the environmental and social sustainability. Under traditional growth concept, company only focus on the financial performance and the main goal is to make more and more profits. But, in sustainable growth concept, company expands its operations and profits, but also make effort to minimize the negative impacts on the society and environment.

From a company's perspective, Sustainability encompasses environmental stewardship, social responsibility, and governance. Environmental stewardship refers the concern for environment. It means reducing harmful emissions, efficient and thoughtful use of natural resource, managing waste and preserving the ecological balance. Social dimension of sustainability includes the fair labor practices, considering human rights of employees, and provide them a good, healthy and safe environment to work and help them to maintain work-life balance. It also refers to the contribution in the development of society by providing some values. Governance includes the managing body of the company and stakeholders' participation in company's strategic decision. It includes the fair and ethical maintenance of financial statement and its full disclosure, and following all the norms of company's law. It concerns with the working of company's management. Thus, sustainability is a broad term. It includes internal environment as well as external environment of the company.

2. Review of literature

Joshua C. Farley¹ in his book "The Economics of Sustainability" tells that human society currently faces a number of unprecedented challenges, ranging from global climate change and biodiversity loss to peak oil and natural resource depletion. To build a sustainable economy, we must assess our needs and the available scarce resources to acquire them.

The book named as The Economics of Sustainable Development², edited by Farley, J. C. (2012) raised a concern about how sustainability is often ignored in the traditional economics where the definition of economics does not consider sustainability in proper way. Government action and intergovernmental coordination is important in the way of achieving sustainable development.

M, Narwal and T. Sharma in the article "Perceptions of corporate social responsibility in India: An empirical study"³(2008)³ says that the society takes a positive view of the social responsibility activities of company, which may help the companies in their long-term survival and competitiveness. Morality and ethics guide the business activities to being more socially responsible even without government pressure.

Ger A. J. Klaassen & Johannes B. Opschoor (1991)⁴ reviews different views of neo-classical and ecological economics on the sustainability of economic growth and welfare. Neo-classical economics says that due to substitution and technical progress, consumption can be sustained even if production depends on a natural resource that is being depleted. But ecological economics says that substitution possibilities are restricted. Welfare requires environmental compatibility and the explicit (collective) formulation of policies regarding the conservation of species, ecosystems and natural resources.

3. Objectives of study

- To explain the theoretical concept of sustainable development.
- To find out the needs of adopting it.
- To find if the spendings in sustainable development process negatively impact the profitability or not.
- To understand the challenges involved in the process of companies adopting sustainable development.

4. Research Methodology

This research is descriptive and exploratory in nature. Insights are gained through materials available on internet. For the example of Tata group, secondary data available on company's website, various newspaper and journals are used. Data are collected and presented to have the better understanding of scenario and conclusion is drawn.

5. Need of Sustainable development

Sustainable development means fulfilling the needs of present without compromising the ability of future generations to meet their own need. Government also forms some rules related to corporate accounting, CSR (Corporate Social Responsibility), waste management, treatment of polluted air and water, etc. But the main question is what were the



reasons which compel the people to bring this concept. Why the people felt the need of introducing sustainability in their developmental journey? In this segment of article, it is tried to discuss the possible reasons behind it. Following are some reasons found out during the research:

- **Finite resources and increasing consumption:** Limited natural resource is the main reason behind why there is a great demand of sustainable development. People has now understood that the treasure of resources can't be refilled within a few times. Some resources can take thousands of years to form. Resources like coal, petrol, freshwater, ore, etc. are limited and can be finished if used unlimitedly. It can cause problems for future generation. According to the World Economic Forum's Global Risks Report 2024⁵, the pace at which we're using our planet's resources, disrupted supply chains for critical goods and resources in future are the main risks. Global natural resource consumption is forecast to rise 60% by 2060, compared with 2020 levels, according to the United Nations.
- **Increased cost:** If any nonrenewable natural resource continues to deplete, then obviously the price will increase and this will affect the company negatively. Unthoughtful and inefficient use of resources increase the cost of production which is harmful for business, consumers, and environment at whole.
- **Consumer expectations:** Nowadays consumers have become more aware towards sustainability. They prefer those company who take care of the environmental, social and ethical aspect in doing their business. Some consumers are willing to pay even extra money for the sake of sustainability.
- **Gain trust:** Engagement in environmental-friendly product or process increase the brand value of company. People trust on these brands and want to be connected. Marketing become more effective.
- **Branding:** Company who pays attention towards the society and do something valuable for them hold a space in people's heart and mind. Those brands are more impactful and preferred among consumers.
- **Inclusive growth:** Sustainable development focus on the inclusive growth. No segment of the society should be deprived of the basic need while others enjoy luxury. The employees of the company are also taken care. If the workers are happy and satisfied then their output will automatically increase and so the profit of the company.
- **Investor's preference:** Investors prefer those institutions whose performance on ESG (Environmental, Social, and Governance) factors are satisfying. They know that these companies have more potential to survive and perform well in future.
- **Climate change:** Climate change is an important reason that have forced people to think about sustainability. Climate change has become a biggest concern for the world. Irregular rainfall, drought, extreme temperature, melting of glaciers, deteriorating health condition of people, losing ecological balance have made people's life tough. As per the report of NOAA Climate.gov as of June 25, 2025 Earth's temperature has risen by an average of 0.11° Fahrenheit (0.06° Celsius) per decade since 1850, or about 2° F in total⁶. If some actions are not taken properly, then the future will be worse. So, it is the high time to go towards the sustainability.
- **Regulatory risk:** Various new international and local laws are forming to make the world sustainable. If a company does not work sustainably, then there may be government intervention. Non-compliance of laws can lead to financial damage in the form of penalties. It can also damage the brand value and reputation in the market. So, it is better to transform the company according to the environment before any regulatory action. Companies must follow of all the environmental laws compliance.
- **Decrease in working capacity:** Pollution have created many issues in the people's life. People become ill frequently, various diseases catch the people and due to this working capacity also deteriorate. Nowadays, clean air, clean water, pure food has become difficult to get. It not only affects only on individual level but it also affects the company and the economy as whole.

6. Growth opportunity for company

Adopting sustainable development may seems a tough and costly thing to do, but it is indeed a great opportunity for any company to stand unique and profitable with a significant contribution towards the environment. This segment of article elaborates how this situation can be turned out to be a great opportunity and how the company can be benefitted by this:

- **Cost reduction:** Investment in different sustainable practices like, energy-efficient system, renewable energy sources, waste reduction mechanism, and resource management can cost high at the time but in the long run,



they all help in the saving of money. Companies that follow sustainable practices can reduce their cost of production. Efficient utilization and use of recycled product help in reducing the cost of production.

- **Premium pricing:** Consumers who are aware of the need of environmental protection and can afford higher price show more interest towards the sustainably produced products. They don't mind paying a little high price for the product. Here, the company may go for premium pricing for this niche market. Various organic and 100% natural product manufacturing companies are the suitable example of it.
- **Government schemes:** To promote sustainable development and support the companies to shift towards it, various schemes have been launched by the government of India. One example of this is PAT⁷ (Perform, Achieve and Trade) scheme, launched in 2012 for energy-intensive industries by Bureau of Energy Efficiency, in which companies that achieve energy-saving targets earn Energy Saving Certificates, which can be traded with underperforming companies. Thus, more energy-saving means more valuable certificates means more trade means more money.
- **Tax benefits⁸:** Various tax benefits are given to companies after achieving specific targets or lying in a particular category. India offers tax relief at both the central and state level. Additional incentives are available to investors in specific sectors, while India's special economic zones (SEZs) offer their own comprehensive tax relief.
- **Competitive advantage:** Environmentally-conscious customers prefer those companies who contribute towards the betterment of environment and society. This gives these companies a competitive advantage against other companies.
- **Innovation:** Companies who want to be a part of sustainable development always focus on innovative product which are less harmful for the environment and give more values to the society. Biodegradable packaging, low-emission vehicles, useful product from waste, alternatives of various harmful products are the examples of innovation.
- **Investor's choice:** Companies which are involved in sustainable practices and make environment-friendly product can get investment easily. Big investors analyze thoroughly the working of company before investing. Since upcoming era will be of sustainably developed product, so they become interested in these companies.
- **Easy to get finance:** Banks approve loan to the companies indulged in sustainable activities. Concessional interest rate is charged under various schemes. Borrowing cost is also less in these cases.
- **Consumer loyalty towards brand:** Consumer trust those brands which is known for ethical value. People feel proud to be a part of it in anyway. For example, TATA group is a great name in market which is well known for its value and contributions towards the society. People believe that this type of company will not make fool of consumers and will serve good.
- **Trend:** Nowadays, people become aware of the need of sustainability. People know the benefit of having those products which are good for them as well as good for environment and society. It has now become a trend to use eco-friendly product. Various company market their product as eco-friendly and cruelty free and make great profit. Social media has also contributed well in this. Recent studies found out that almost 90% of Millennials would choose a sustainable and eco-friendly product over any non-sustainable counterparts⁹.

7. Practices that make a company sustainable

- **Carbon-efficiency:** Companies try to reduce carbon emission throughout the activities and try to achieve a goal of carbon neutrality. Companies try to continue further production at lower carbon emission per unit of output.
- **Renewable source of energy:** Companies are reducing their dependence on fossil fuels and consider more to renewable source of energy. Solar energy contributes a significant part in total energy consumption. Government as well as private companies invest in the renewable energy projects. As per the report of Ministry of New and Renewable Energy, Government of India, published on 13 NOV 2024 by PIB Delhi¹⁰, India's total renewable energy installed capacity surged by an impressive 24.2 GW (13.5%) in just one year, reaching 203.18 GW in October 2024, up from 178.98 GW in October 2023.
- **Optimum utilization of resources:** All the resources are utilized in a way that there is minimum or no wastage. Sustainable companies spend on their research and development to find more efficient way of resource utilization. In this way, companies achieve two benefits. First, it can contribute towards sustainability, and secondly, it can reduce its cost of production.



- **Waste management:** Companies should make a proper waste management system. All the dirty water and air should be processed and filtered before releasing it into environment. Other wastes which can be recycled should go for recycling. Other harmful wastes should be disposed in a proper way to minimize the bad effect on environment and society.
- **Environment-friendly practices:** Companies should try to find the environment-friendly alternatives for the products which are harmful for the environment. One example of it, is the use of paper bags instead of plastic. Nowadays, various e-commerce companies send the parcel in paper packing which is a good initiative towards the environment protection. Some food delivery companies give the option not to send cutlery, so, if no need, the person can deny for it.
- **Corporate Social Responsibility (CSR):** According to United Nations Industrial Development Organization¹¹, Corporate Social Responsibility is a management concept whereby companies integrate social and environmental concerns in their business operations and interactions with their stakeholders.
In India, as per section 135 of Companies Act, 2013, CSR provisions apply to companies meeting any of the following criteria in the immediately preceding financial year:
 - Net worth: INR 500 crore or more
 - Turnover: INR 1000 crore or more
 - Net profit: INR 5 crore or more
 Such companies must spend a minimum of 2 percent of their net profit over the last three years on CSR activities.¹²
- **Less polluted alternatives:** Shift from petroleum-based vehicles to electronic vehicle is also a great step towards sustainability. Petroleum is a fossil-based fuel and take thousands of years to form and are limited available. If it is used unlimitedly at regular basis, it will be vanished soon. Oil mining is a polluting process and its new reservoirs are very difficult to find and involve complex process. So, it is a great step towards sustainability if we achieve significant share of it in market. Automobile industry can manufacture more electric vehicle with high capacity and efficiency.

8. Examples of a sustainable company and its practices towards sustainability:

A case study of Tata group

Tata group holds an important space in Indian as well as international market. This group consists of various company under the name of it, like, Tata Steel, Tata Motors, Tata Power, Tata chemicals, Tata Consultancy Service (TCS), Tata Consumer Product, Titan, etc. This group has been a great example of leadership with trust. The name Tata is enough for the people to trust the company and product. It has done many works for the betterment of environment and society without compromising for its profitability.

“Sustainability is the biggest challenge for humankind for the next decades to come, and we definitely need to address this.” - N Chandrasekaran, Chairman, Tata Sons¹³

¹⁴Tata group is a prominent multinational conglomerate, established by Jamshedji Tata, in 1868. Its headquarter is in Mumbai. Tata group operates worldwide with a mission 'To improve the quality of life of the communities we serve globally, through long-term stakeholder value creation based on Leadership with Trust'. It has over one million people employed in total. It is well known for its values and ethical practices.

¹⁵Tata Sustainability Group has been formed in 2014 partnering with Tata companies to embed sustainability in their business strategies, and thereby demonstrating responsibility to the planet and people. It works on the dimensions like, governance, corporate social responsibility, supply chain management, climate change and energy, safety and diversity, water, circular economy, etc. Some activities of Tata Sustainability Group are highlighted here:

- At the Tata group, the Tata Code of Conduct serves as the ethical roadmap for companies and employees¹⁶.
- CSR programme of the company focuses on the area of education, livelihoods and skill development, rural development, water and sanitation, healthcare and strengthening services.¹⁷
- In FY19, the group has spent INR 1,095 crore on CSR expenditure and has positively impacted 11.7 million lives.¹⁸
- Tata group is well-known for its working environment. Workers get the safe environment to work. Appropriate training and development program is organised for its employees. Risks at workplace are assessed and proper measures are taken to mitigate the risk.¹⁹



- Accidents are reported immediately, root causes behind it are investigated and corrective measures are taken to ensure the non-happening of that again. Also, this is shared and deployed across the Group companies.²⁰
- The company ensure long-term security of raw materials and boost competitiveness by shifting towards industrial processes that minimises waste and focuses on resource productivity. For it, the company has been working on three-pronged approach:²¹
 - i. Creating awareness
 - ii. Applying the CE (Circular Economy) concept to identify business opportunities.
 - iii. Policy advocacy on resource productivity
- Company follows Water Footprint Assessment (WFA) framework since 2012 to develop water sustainability strategy. It is an approach that allows companies to identify and manage water-related business risks, understand and mitigate their adverse impacts on ecosystems and communities, and contribute to more sustainable management of shared freshwater resources. With this approach, some of the companies of Tata group have reported 25-30% fresh water consumption by recycling more water.²²
- Tata Group has developed a Biodiversity Management Framework that guides companies in identifying, managing, and mitigating their impacts and dependencies on nature, ensuring that Tata companies contribute meaningfully to biodiversity conservation while strengthening long-term business sustainability.²³
- Tata Chemicals, a company of Tata group launched first-ever centre of excellence for conservation of marine biodiversity and coastal ecosystem in India in 2018.

Table 1: Total Revenue of Tata group year-wise

Year	Revenue (in INR)
2024-25	15.34 lakh crore
2023-24	11.12 lakh crore
2022-23	12 lakh crores
2021-22	9.6 lakh crore
2020-21	7.89 lakh crore
2019-20	7.5 lakh crore

(source: Tata Group)

It is clear from the table that the revenue of the Tata group has been improving year-wise, despite huge investment towards social and environmental sustainability. It is a common belief among people that Tata companies never compromise with its value. It takes care of all the three P's - people, planet and profit very efficiently. The example of Tata company shows that how companies can contribute to the society and also satisfies all its stakeholders. This group has taken many initiatives towards sustainability and has been successful as a business.

9. Challenges behind sustainable development

It sounds very fascinating to adopt sustainability with profitability, but it is not that much easy for all. Various aspects have to be considered while talking about it. Some of the challenges are written as follows:

- **High cost:** Cost of installing energy-efficient machinery is very high. It is true that in the long run, this high cost will be neutralised and result in even less cost of production, but many firms can't afford investing a huge amount in those assets at once.
- **Requires technical knowledge:** Sustainable development requires technical knowledge to assess the cost and maintain them so that level of profitability does not go down in long run. Various system to be installed also need professionals to operate in an efficient way
- **Skilled labour force:** To incorporate sustainability in the working of the firm, skilled labours are required so that they can adopt the new system and operate it efficiently.
- **Research and development:** Companies have to constantly invest in their Research & Development and come with the more innovative product and energy-efficient process and activities.
- **Reduced Profit:** A part of company's profit go in the form of CSR which cut down the company's profit. Companies try to cut cost and more and more profit but, in this case, company has to forget a part of their profit



10. Conclusion:

It is important to be concerned about the environment as well as company. A proper balanced approach is important to have so that both are fulfilled. As the environment is deteriorating, it is important to work together so that we can save it for our future generation. It is not only important for the future generation but it is important for today's generation also. Many problems have already arisen where a quick action is needed. Companies should be liberal and ethical to contribute to the society and environment. It is true that it is difficult for many firms to adopt new technology at once and bring a sudden change but a gradual shift can be made towards it. Companies take all the resources from the society, so it is the duty of the company to return back its favour in some form. Social responsibility and sustainable development are not the burden but it is an opportunity to make the society and environment better as per the capacity along with earn profit by being innovative. It is never an obstacle in the growth of company but it is an opportunity to be stand out unique and more profitable.

Adopting sustainability doesn't mean mere responsibility and threat to profit, but it can be opportunity to stand different and innovative in the market. It cannot hamper the growth of company if it knows how to convert it in a bigger opportunity. For a company to be sustainably growing, it has to always focus on innovative and efficient approach.

References

1. Farley, J. C. (2012). The economics of sustainability. *Sustainability: multidisciplinary perspectives*. Sharjah: Bentham Science, 40-60.
2. https://books.google.co.in/books?hl=hi&lr=&id=9kO0sU1xH0oC&oi=fnd&pg=PR13&dq=economics+of+sustainability&ots=1SzMOB4BXR&sig=NhY7noOLeIKtae_6I_PvN919jVI&redir_esc=y#v=onepage&q=economics%20of%20sustainability&f=false
3. Narwal, M., & Sharma, T. (2008). Perceptions of corporate social responsibility in India: An empirical study. *Journal of Knowledge Globalization*, 1(1), 61-79.
4. Klaassen, G. A., & Opschoor, J. B. (1991). Economics of sustainability or the sustainability of economics: different paradigms. *Ecological economics*, 4(2), 93-115.
5. <https://www.weforum.org/stories/2024/03/sustainable-resource-consumption-urgent-un/>
6. <https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature>
7. <https://thecsrjournal.in/eco-friendly-brands-in-india-on-their-voyage-of-sustainability/>
8. <https://www.pib.gov.in/PressReleasePage.aspx?PRID=2038503>
9. <https://www.india-briefing.com/doing-business-guide/india/taxation-and-accounting/tax-incentives-for-businesses>
10. <https://www.pib.gov.in/PressReleasePage.aspx?PRID=2073038>
11. <https://www.unido.org/our-focus/advancing-economic-competitiveness/competitive-trade-capacities-and-corporate-responsibility/corporate-social-responsibility-market-integration/what-csr>
12. <https://ca2013.com/135-corporate-social-responsibility/>
13. <https://www.tata.com/newsroom/business/embracing-planet-future-sustainability-aalingana>
14. <https://www.tata.com/investors/companies>
15. <https://www.tatasustainability.com/AboutUs/TataSustainabilityGroup>
16. <https://www.tatasustainability.com/Home/Governance>
17. <https://www.tatasustainability.com/Home/ourFocusAreas>
18. <https://www.tatasustainability.com/SocialAndHumanCapital/CSR>
19. <https://www.tatasustainability.com/SocialAndHumanCapital/SafetyDiversity>
20. <https://www.tata.com/careers/safety-and-health-policy0>
21. <https://www.tatasustainability.com/Environment/CircularEconomy>
22. <https://www.tatasustainability.com/Environment/Water>
23. <https://www.tatasustainability.com/Environment/Biodiversity>
24. <https://www.tata.com>



DOIs:10.2015/IJIRMF/ICICSF-2025-P16

--:--

Research Paper / Article / Review

International Conference On "Innovative Convergence for Sustainable Future"

Date : 12 - 13 December, 2025

(ICICSF-2025)



A Fresh Perspective on Risk Management in Steel Company Construction Projects: A Comprehensive Literature Review

Kaushik Chopra

Research Scholar, Dept of Management, Jharkhand Rai University, Ranchi

Email: choprak427@gmail.com

Dr. Harmeet KaurDean, Dept of Commerce and Management.
Jharkhand Rai University, Ranchi

Abstract: The construction sector is widely recognized for being extremely risky due to the intricate nature of its operations and constantly changing project settings, which create a climate of uncertainty that needs to be considered during the decision-making process. Because of this, we have created this treatise to clarify the principles of risk management by offering a succinct new literature review for risk management in the construction industry. Our rationale for this endeavor is that, throughout time, experts and researchers in the construction industry have recognized this field as critical to corporate organizations and as the most talked-about topic. It is impossible to include every definition of risk, so we have attempted to include the most recent research in this study. Most of this study is a survey of the literature; it examines works that discuss risk concepts, construction risk management, and industry practices.

1. INTRODUCTION

Every human endeavor has some risk and uncertainty. Everyone agrees that the business sector has higher risk than other industries. There is risk involved in every business choice and entrepreneurial action. A risk is an event that carries some degree of uncertainty and can have both good and negative effects. Positive risks present opportunities that are convenient, but negative risks pose a threat and are therefore inconvenient [1]. Positive and negative outcomes are implied by the more convenient and less convenient risks, respectively. The CI does, however, faceless uncontrollable risks; however, these could occasionally have negative effects including increased costs, schedule delays, and subpar performance. The complexity of the planning, design, and construction processes, the existence of several interest groups, and the availability of materials are the variables that contribute to this kind of result [2]. Regarding the negative effects of risk, [3] made it clear that people are risk adverse and that people detest risk; as a result, risk management (RM) plays a crucial role in mitigating or eliminating risk through RM's many activities. [4] Claimed that RM has several intricate aspects connected to the CI, with effects that extend beyond its immediate bodily harm to the financial and cultural processes, as well as the functioning of society. All construction projects are risky by nature because of their design, organizational and financial setups, and demands for technology and resources, according to [5]. For this reason, risk management in construction projects is dynamic rather than static. The argument put up by [6] is that the industry must minimize risks and uncertainties to assess their impact and identify the project's most and least viable sections. The responsibility of risk management (RM) is to identify hazards, quantify their likelihood and expected impact, and treat them by eliminating or lessening their effects with the least number of resources. Many industries, including the environment, public safety, enterprise management, and healthcare, are developing and using RM. The topic of this essay is RM in the building industry. Said that when



RM is put into practice, it safeguards creative ventures, which are necessary to achieve a competitive edge and be successful in the market but invariably entail risky choices and actions. Effective risk management could enhance the capacity to successfully oversee innovative project management at every level. Since the management literature has only just begun to express interest in implementing RM in building projects, there is currently a dearth of research in many areas. This document was created with the purpose of elucidating the fundamentals of risk management through a brief new proposal for a risk management literature review. Thus, the goals of the study are to examine the body of literature that already exists on risk, risk management, and risk concept and techniques. The theoretical framework, which includes a definition of risk, risk management, and the risk management method, is covered in the following section.

2. Literature review

2.1 Risks in construction

There is a risk to human life associated with every human endeavor. However, construction operations are more likely to involve risk due to the intricacy of the job required [8]. Because of this intricacy, the portion of risk associated with construction is likewise more varied and fluctuates in degree [9]. Numerous scholars have attempted to define risk in a variety of ways; often, these definitions were adapted to the goals of the projects they were working on at the time. However, the degree to which an establishment values applied management greatly influences how risk is defined [10]. Risk is a term used to characterize a scenario in which there is prior documentation and experience based on which actions are performed by estimating a potential outcome [11].

A risk is present whenever a choice is made that involves both a continuum of potential outcomes and specific probability associated with those outcomes [12]. Moreover, [13] contend that risk is sometimes interpreted broadly, going beyond a financial definition, to include the likelihood of suffering a loss, injury, setback, disadvantage, or destruction. In a similar vein, [14] suggests that risk is associated with a lack of knowledge or prior experience in a particular circumstance that a decision maker is managing. Moreover, risk is defined as the potential for an investor's claim in building activity to fall short of the predetermined feasibility benchmarks [15]. Each of these authors put out the argument that risk is an unpredictable event that results from imaginable but unanticipated circumstances. Events that are imaginable are those that give advance notice of their arrival, whereas unexpected occurrences happen suddenly. Each of these authors put out the argument that risk is an unpredictable event that results from imaginable but unanticipated circumstances. Events that are imaginable are those that give advance notice of their arrival, whereas unexpected occurrences happen suddenly.

Numerous definitions have revealed that risk affects or has an impact on any endeavor involving construction. A variety of terms, including monetary loss, property damage, personal injury, and even a mix of all of these, can be used to calculate the effects [13]. [16] Indicates that the presence of a risk element may have an impact on project performance, quality, potency, capacity, and financial cost. According to [2], in an unpredictable environment, planning, design, and development activities related to building are susceptible to specific elements. As a result, the environment in which construction projects are carried out is characterized by a variable level of risk and uncertainties that may result from known or unknown circumstances [12]. These kinds of contingencies are random events whose probability distribution is uncertain.

Depending on one's perspective, risks can be categorized in a variety of ways. Some are categorized according to their likelihood of happening, while others are categorized according to the potential effects they may have on construction activities, including their types and sources. Despite these different classifications, they all work toward the same goal, which is to generate risk lists that are used to identify potential risks and serve as a valuable tool for risk management.

[17] [18] are some examples. [18] Went on to say that risks associated with construction can be categorized not only by how they affect the project but also by where they originate from. [19] On the other hand said that risks are primarily divided into two groups based on where they originate from: internal and external.



There are three categories of hazards: known risks, unknown risks, and unknown dangers [12]. The first group consists of the fewest modifications, which are common and unavoidable aspects of construction projects. Predictable risk events with a known probability of occurrence and impact fall under the second group. The last group is made up of things whose likelihood of happening cannot be estimated. As per reference [20], it is possible to categorize the risk according to the sources that are related to the stakeholders. As an illustration, consider the risks related to time, the environment, cost, and safety. Technical, political, social, and economic hazards are among the subcategories of human risks connected to construction projects, along with legal, financial, health, managerial, and cultural concerns. [21] Divided danger into ten groups, which were as follows:

Design: Design flaws include erroneous amounts, a lack of coordination, a hurried job, hiring unqualified designers, and inconsistent bill of materials, drawings, and requirements.

Physical: Mishaps due to inadequate safety protocols, defective material supply, material and equipment security, public safety, and different labor and equipment productivity

Logistics: Inadequate site assessment, erroneous project schedule, lack of manpower, supplies, and equipment, intense bidding rivalry, vague job scope, and inadequate contractor-side interactions with field offices

Legal: The parties to the contract may have legal conflicts during the building phase; unclear work laws; trouble obtaining permissions; delayed dispute resolutions; lack of specialized arbitrators to facilitate quick settlements

Environmental: Environmental issues include bad weather, a long distance to the location, and natural disasters like earthquakes and floods.

Construction: Misunderstandings of the drawings and specifications, actual quantities deviating from the contract quantities, design modifications, lower work quality due to time constraints, hurried bidding, and undocumented change orders are some of the reasons for the gaps between the implementation and the specifications.

Management: Inadequate communication amongst stakeholders, unclear planning because of the intricacy of the project, modifications in management techniques, lack of information availability (including uncertainty), and resource management

Cultural: customs and religion

Financial: Unexpected political situations, inflation, contractor financial failure, currency rate fluctuations, delayed contract payments, poorly managed cash flow, and monopolization of goods because of closure

Political: New laws or acts of the government, inflation, and erratic security conditions (invasion).

2.2 Risk management in construction:

[8] Stipulates that risk management plays a vital part in mitigating the hazards experienced in the construction industry since it offers a methodical approach to allocating risk to construction projects, enabling projects to be managed with a greater degree of expectation and anticipation. As per [10], risk management (RM) in continuous integration (CI) refers to the evaluation and handling of the inherent risks associated with a project. Simultaneously, RM refers to the methodology and measures implemented to mitigate potential disruptions that may arise throughout a project's operations [22]. Basically, risk management (RM) is necessary for the efficient identification and management of risk. Proactively addressing potential future occurrences of risks is considered effective risk management [23].

Thus, RM that values preventive actions implements an emergency plan that raises the likelihood that the project's goals and objectives will be met [24]. [18] Highlights that risk management (RM) entails maximizing



the benefits of favorable events and minimizing the consequences of unfavorable ones. Put differently, risk management (RM) involves managing events that have the potential to cause a risk rather than taking a passive approach and responding to them afterwards. The goals of the project are the focus of every risk control measure that is implemented. A significant portion of construction activity is comprised of RM. [11] Made the claim that the need to manage risk in building projects is growing constantly due to the projects' complexity,

size, competition, client and consumer expectations, political and economic difficulties, and extremely challenging physical conditions. Both the likelihood and the magnitude of an event's impact will be decreased by comprehensive risk management. According to [25], risk management (RM) is a coordinated set of actions and techniques used to guide an organization and control the various risks that may impair its capacity to accomplish goals. By ensuring that the decision-maker is aware of and comprehends the risks, RM helps to prevent disasters or lessen their impact.

It addresses the steps involved in identifying, evaluating, allocating, and managing every project risk [26]. Managing risks in a project requires a grasp of the risk management process (RMP). When handling risks, all RMP phases must to be followed to effectively carry out the procedure inside the project. The following are its principal phases: [12] [28] [29] [30].

2.2.1 Risk identification (ID)

This is the RMP's initial step, and it entails recording every possible risk that could arise for the project [31]. Organizations can learn about the regions that are exposed to risk through risk identification (RI), which serves as the foundation for subsequent stages of risk analysis and control. When properly implemented, risk-informed investing (RI) guarantees effective risk management since unidentified loss sources might intensify into uncontrollable events with unanticipated consequences [32]. The focus is on both the inability to recognize risk factors that could result in loss and the inability to recognize opportunities when they present themselves. The consequences of failing to recognize positive risks are equivalent to those of failing to recognize negative risks [32]. Risk identification (RI) entails determining every scenario and risk that could potentially impact the organization, together with the factors that give rise to these possibilities and dangers. Hence, risk identification makes it easier to research areas and activities where organizational resources are vulnerable, which may have an impact on the organization's capacity to meet its objectives [32]. It is necessary to have primary project documents to carry out RI effectively. To create a comprehensive list of hazards, the project charter, scope statement, and project management plan (including the work breakdown structure) must be accessible. It is challenging to properly analyze the risks associated with a project without these components as a frame of reference. It goes without saying that to implement RI, one must also comprehend the company culture and the RM plan. These establish the framework for evaluating the risks. The organization's risk culture may include RI activities that are either discouraged or preferred by the company, as indicated by the RM strategy. As per reference [33], the data can stimulate contemplation regarding various risk issues and worries when assessed through the application of RI methodologies and instruments. As diverse as the projects they support are the tools and technologies used in RI. However, certain sets of tool and technique types are most employed. The most well-known ones include expert systems, Delphi technique, questionnaires, interviews, and brainstorming.

2.2.2 Risk assessment/analysis

Risk assessment is followed by risk identification. According to [34] and [35], the next stage of risk management is risk assessment. As per reference [8], risk assessment is a technique that leverages accessible data to ascertain the frequency of occurrence and severity of repercussions in risk mitigation. Once the risks in a project have been identified, [36] states that the process of qualitative risk assessment must be carried out. This involves additional analysis through the evaluation and estimation of the probability of risk occurrence as well as its impact on each risk. Here, a number of variables need to be considered, including the degree to which a risk affects project objectives and how manageable it is, the time of an occurrence, and the likelihood of an occurrence and how it relates to other risks. Each of these elements helps to clarify the risk and makes it possible to respond to each one in a suitable and appropriate manner. Risk analysis techniques are divided into two categories: qualitative and quantitative approaches [31] [38]. Qualitative approaches work well when risks can



be categorized as low, medium, or high on a descriptive scale. In contrast, the quantitative approaches rely on estimates from arithmetic and statistics to ascertain the likelihood and consequences of the hazards that have been identified [39]. The several risk analysis methods are compiled in the table below; all of these methods are applied in the building industry.

Risk Analysis	
Qualitative	Quantitative
Direct judgment	Probability analysis
Ranking options	Sensitivity analysis
Comparing options	Scenario analysis
Descriptive analysis	Simulation analysis

Table 1: Different Risk Analysis Techniques (Ward & Chapman, 1997)

2.2.3 Risk responses (RRs)

The RMP's key element, risk response, decides what steps—if any—will be done to address the risks that were assessed throughout the identification, qualification, and quantification stages [31]. RRs, according to [8], are steps done to get rid of, lessen, or transfer a risk or its effect. Planning for a mandatory action to be taken into consideration in the event that a risk event occurs is part of the risk response process. To make sure that the risk strategy produces the desired result, it also comprises, if necessary, taking planned action and monitoring the effects of these measures. The process of determining a risk response involves putting out a number of options to reduce or eliminate an anticipated risk and designating the best option as a response [41]. "Process of identifying/developing risk response options and determining actions for treating the risk, targeting enhancing opportunities and reducing any threats to projects objectives" is what [42] defines as risk response (RR). Therefore, risk reduction (RR) is the process of choosing a suitable course of action to lessen a risk's adverse effects. Because building projects are unique, there are significant and constantly changing risks involved. Therefore, after the preliminary phases of risk identification, evaluation, and allocation, it is imperative to develop suitable responses to these risks. RR is the planned papers technique for RM that is used to manage risk during the project, according to [43]. This phase entails implementing appropriate strategies to achieve project goals. Various response strategies about dangers are advised by some studies [44]. [12] Separated the response strategies into three by merging avoidance and reduction, whereas [45] maintained that there are four unique ways to respond to hazards in a construction project: risk avoidance, reduction, transfer, and risk retention. However, [43] showed that risk reactions can be divided into two categories: acceptance and mitigation/avoidance.

2.2.4 Risk control

The results of the identification, evaluation, and development of suitable responses to risks must be implemented. Implementing the risk strategy, which ought to be a crucial component of the project plan, is part of risk monitoring and control. When monitoring and controlling, there are typically two main obstacles to overcome. The first is implementing the risk plans and making sure they remain effective. Creating substantial documentation to back up the procedure is the second. Ensuring the utilization of the earlier phases is one of the steps in the description of the RM flow used in this study. This is to guarantee that the dangers that have been recognized and deemed significant are likewise managed in the same manner that it was structured within the response phase.

As the continuous process moves forward, it is also feasible to discover new risks that arise in the control stage. Risk control, according to [46], seeks to minimize risks, reduce variances, and raise project value. In order to successfully accomplish project objectives, risks are managed at this level of the RMP. Risk control is predicated on taking a proactive rather than a reactive approach to putting the appropriate safeguards in place and continuously improving them. There are no pre-made approaches to reduce risks.



Nonetheless, the corrective actions listed below can help manage the hazards connected to building projects [47] [36]:

- Plans, estimates, and the scope of work should be adjusted to account for potential risks.
- When necessary, develop backup plans to handle expected risks and keep a close eye on potential threats.
- Make the right choices. Inform everyone who might be affected about any potential hazards.

3. Methodology

One step in the work technique was a literature search. The study was carried out using both published and unpublished theoretical and empirical literature. The primary focus of this study is a review of the literature on risk detection in the construction sector. This is due to the fact that risk and risk management are ideas that have been discussed for a long time. In order to determine the purpose of the study, a review of the literature on risk management was conducted. The review covered the following topics: the definition of risk, the idea of risk management, and the techniques used to identify and analyze hazards in building projects.

4. Insights gained from the literature review

According to this study, risk management entails determining, evaluating, and prioritizing risks by keeping an eye on, managing, and allocating managerial resources in a coordinated and cost-effective manner in order to minimize the possibility of unfavorable events and to maximize the accomplishment of project goals. Benefits from managing risks can include finding a better alternative course of action, feeling more confident about achieving the project's goal, increasing chances of success, fewer surprises, more accurate estimates, and less effort duplication.

Furthermore, the literature analysis emphasized that risk management included not just anticipating and correcting problems ahead of time, but also preparing for unforeseen future issues. The study went on to demonstrate that concerns about potential threats to a project serve as a way to both lower project losses and turn risks into opportunities that, as suggested by [48], may result in environmental benefits, economic profitability, and other advantages. Without a doubt, this study has also demonstrated that creating a list of risks required for a certain project is a wise and proactive task that a project team should undertake.

This suggests that it will be nearly hard to respond to risk associated with a project if it is not first discovered, which will have an impact on the project as a whole. According to the study, risk management (RM) needs to be a coordinated, integrated effort that involves the entire project team in order to facilitate successful risk management. It cannot be a stand-alone procedure. Furthermore, not every project risk has a completely negative impact; some present a chance to investigate areas that could lead to revenue for the company.

5. Conclusion

The majority of research has concentrated on specific facets of project management; however, this work has reviewed literature that links risk management to the achievement of all project goals, including those pertaining to budget, schedule, quality, environment, and safety. In order to accomplish the goal of this investigation, a review of risk concepts, risk management, and risk analysis/assessment techniques was conducted. The literature demonstrated that the critical stages of the risk management process are risk identification, risk analysis and assessment, risk response, and risk control. Prior to being managed or lessened, risks need to be recognized. As a result, this study comes to the conclusion that risk management need to be regarded as the most important task for a project's effective completion. According to the study's findings, risk identification methods include the following: expert systems, checklists, Delphi methodology, questionnaires, interviews, expert opinion, and documentation reviews. Two types of methodologies are created for risk analysis: qualitative methods and quantitative methods. According to published research, the most common risk response strategies



are risk avoidance, risk reduction, risk transfer, and risk retention. The report goes on to say that concerns about potential dangers considered for a project are a way to turn risks into opportunities that can result in financial profitability, in addition to lowering project losses.

References:

1. Johnson, T. (2008). Project Management Professional (PMP) exam success series: certification exam manual. Texas: Crosswind Project Management Inc
2. Creedy, G.D. (2005). Risk factors leading to cost overrun in the delivery of highway construction projects. PhD thesis, Queensland University of Technology, Australia
3. Laryea, S. (2008). Risk pricing practices in finances, insurance and construction. In: COBRA Research Conference, September 4th – 5th, Dublin Institute of Technology
4. Loosemore, M., Raftery, J., Reily, C. & Higgion, D. (2006). Risk management in projects. London: Routledge
5. Edwards, P.J. & Bowen, P.A. (2005). Risk and risk management in construction: a review and future direction for research, engineering, Construction and architectural management, 5(4): 339- 349.
6. Zayed, T. Amer, M. & Pan, J. (2007). Assessing risk and uncertainty inherent in Chinese highway projectusing AHP, International journal of project management, 26: 408-419
7. Vargas-Hernández, J.G. (2011). Modeling Risk and Innovation Management. Advances in Competitiveness Research, 19 (3-4), 45-57.
8. Olamiwale, I.O. (2014). Evaluation of Risk Management Practices in the Construction Industry in Swaziland. Master of Quantity Surveying Thesis, Tshwane University of Technology, Pretoria, South Africa.
9. Dey, P.K. & Ogunlana, S.O. (2004). Selection and application of risk management tools and technique for build-operate-transfer-projects, Industrial management and data system, 4: 334- 336.
10. Simu, K. (2006). Risk management in small construction projects. Licentiate dissertation. Department of Civil and Environmental Engineering, Lulea. LTU
11. Oztas, A. & Okmen, O. (2004). Risk analysis in fixed price design-build construction projects, built and environment, 39, 229-237.
12. Smith, N.J., Merna, T., & Jobbling P. (2006). Managing Risk in Construction Projects. 2nd edition Oxford: Blackwell Publishing
13. Abassi, G. Y., Abdel-Jaber, M. S. & Abu-Khajedart, A. (2005). Risk analysis for the major factors affecting the construction industry in Jordan, Emirate, Journal of engineering research, 10: 41-47.
14. Al-Salman, A. (2004). Assessment of risk management perception and practices of construction contractors in Saudi Arabia. Master of Science, Fahd University of Petroleum & Minerals.
15. Warszawski, A., & Sacks, R. (2004). Practical Multifactor Approach to Evaluating Risk of Investment in Engineering Projects, Journal of Construction Engineering and Management, 130(3), 357-367
16. Mills, A. (2001). A systematic approach to risk management for construction. Structural survey, 19(5): 245-252.
17. Wong, J.T.Y. & Huie, E.C.M. (2006). Construction project risks: further considerations for contractors' pricing in Hong Kong. Construction management and economics, 24: 425 -438.
18. Klemetti, A. (2006). Risk management in construction project networks. Laboratory of Industrial Management, Helsinki University of Technology.
19. El-KarimiAzari, A., Mousavi, N., Mousavi, F.S., & Hosseini, S. (2011). Risk Assessment model selection in Construction Industry. Iran University of Science and Technology, Islamic Azad University and Tarbiyat Modares University, Tehran, Iran.
20. Zou, P.X.W., Zhang, G. & Wang, J. (2007). Understanding the key risks in construction projects in China. International journal of projects management, 25: 601- 614.
21. Kishan, P., Bhavsar, J.J., & Bhatt, R. (2014). A Study of Risk Factors Affecting Building Construction Projects, International Journal of Engineering Research & Technology, 3(12), 831- 835
22. Skorupka, D. (2008). Identification and initial risk assessment of construction projects in Poland. Journal of management in engineering, 24(3): 120- 127.
23. Kerzner, H. (1998). Project management: a system approach to planning, scheduling and control. New York, Chi Chester: Johnwill.
24. Adnan, H. (2008a). An Assessment of Risk Management in joint venture projects (JV) in Malaysia, Asian Social Science, 4(6), 99-106.
25. AS/NZS ISO 31000: 2009 Risk Management Principles and Guidance. Retrieved from



- http://www.finance.gov.au/sites/default/files/COV_216905_Risk_Management_Fact_Sheet_FA3_230820_10_0.pdf. Accessed: 16/01/2016.
26. _230820_10_0.pdf. Accessed: 16/01/2016.
 27. Association for Project Management. (2000). Project Management Body of Knowledge, 4th edition, Project Risk Analysis and Management, a guide by APM.
 28. Tuncel, G., & Alpan, G. (2010). Risk assessment and management for supply chain networks: A case study, *Computers in Industry*, (61), 250–259
 29. Giannakis, M., & Louis, M. (2011). A Multi-agent based frame work for supply chain risk management, *Journal of Purchasing and Supply Management*, (17), 23–31
 30. Mazouni, M.H. (2008). Pour une Meilleure Approche du Management des Risques : De la Modélisation Ontologique du Processus Accidentel au Système Interactif d'Aide à la Décision, Thèse de Doctorat de l'Institut National Polytechnique de Lorraine, Université de Nancy, France.
 31. Ubani, Chinenye, E., Amade, Benedict, Okorocho, Aku, K., Agwu, A., & Okogbuo, F. (2015). Project Risk Management Issues in the Nigerian Construction Industry, *International Journal of Engineering and Technical Research*, 3(1): 217-232.
 32. Tchankova, L. (2002). Risk identification: basic stage in risk management. *Environmental Management and Health*, 13(3): 290-297. Towers Perrin. 2008. Towers Perrin Risk and Opportunity WhitePaper. Available from: <http://www.towersperrin.com> [Accessed 05/01/2016].
 33. Kuang, Z. (2011). Risk Management in Construction Projects: Application of Risk Management in Construction Period. Bachelor of Architectural Technology and Construction Management. Via University College, Horsens Campus, Denmark.
 34. DEAT (2006) Risk Management, Integrated Environmental Management Information Series 23, Department of Environmental Affairs and Tourism (DEAT), Pretoria-South Africa. <http://www.deat.gov.za>. Accessed [03/01/2016]
 35. Cooper, D., Grey, S., Raymond, G. & Walker, P. (2005). Managing risks in large projects and complex procurement. Chichester: John Wiley.
 35. Nguyen, N. P. & Li, Y. (2012). "Critical analysis of risk management and significant impacts of its application on Sichuan Post- earthquakes Reconstruction project". Master of Science Thesis. Umea University, Sweden
 36. Schatteman, D., Herroele, W., Vandvonder, S. & Boone, A. (2008). Methodology for integrated risk management and proactive scheduling of construction projects, *Journal of construction engineering and management*, 134(1): 885-893.
 37. Winch, G., (2002). "Managing construction projects, an information processing approach". Oxford: Blackwell Publishing.
 38. Chapman C. & Ward S. (1997). "Project Risk Management: Processes, Techniques and Insights"
 39. El-Dash, K. (2008). Construction risk management application and education selected. Proceeding from the 12th International Congress on Project Engineering, 390-403.
 40. Opolot, P.K., Buys, N.S. & Slabber, J.M. 2009. Risk management in the South African construction industry. Available from: <http://www.yumpu.com/document/view/11842795/risk-management-in-the-south-Africa-construction-industry.html>. Accessed: 10/01/2016
 41. Lisa Turnbough, P.E. (2005). Risk management on large capital projects. *Journal of professional issues in engineering and practices*, 365-374.
 42. Wang, M. & Chou, H. (2003). Risk allocation and risk handling of highway projects in Taiwan. *Journal of management in engineering*, 19(22): 60-68.
 43. PMI. (2008). A Guide to the Project Management Body of Knowledge. Project Management Institute, Newtown Square, PA.
 44. Zenghua, K. (2011). Risk Management in Construction Projects. VIA University College, Horsens Campus, Denmark.
 45. Dada, J.O. (2010) Strategies for mitigating risk in construction projects. In proceedings of the 40th Annual general meeting/conference of the Nigerian Institute of Building, 7th- 11th July 2010, Asaba, Delta, Nigeria, 28-35.
 46. Lester, A., (2007). Project management, planning and control, 5th edition. Oxford: Elsevier Ltd Light Press.



DOIs:10.2015/IJIRMF/ICICSF-2025-P17

--:--

Research Paper / Article / Review

International Conference On "Innovative Convergence for Sustainable Future"

Date : 12 - 13 December, 2025

(ICICSF-2025)



Hybrid Smart Voting Framework with Facial Biometric and Dynamic QR Code Credentials

^{1*}Kriti Sharma, ¹Mukesh Kumar, ¹Md Elias Ansari, ²Kailash Pati Dutta

¹Student, Department of Information Technology, Jharkhand Rai University, Ranchi, Jharkhand, India

²Associate Professor, Faculty of CSE & IT, Jharkhand Rai University Ranchi, Jharkhand, India

Email: kritisharma6206@gmail.com,

Abstract: In the digital era, electronic voting (e-voting) systems play a crucial role in ensuring secure, transparent, and accessible democratic processes. However, issues such as voter identity theft, system tampering, and duplication of credentials continue to threaten election integrity. This research paper proposes a Hybrid Smart Voting Framework that integrates facial biometric authentication with dynamic QR code-based credentials to enhance security and transparency in electronic voting systems. The proposed framework utilizes convolutional neural networks (CNN) for facial recognition and time-sensitive encrypted QR codes for session-based voter authentication. This dual-layer security approach effectively reduces identity duplication, replay attacks, and vote manipulation. Experimental evaluation shows significant improvements in authentication accuracy, spoof detection, and system robustness when compared with traditional biometric voting systems. The results demonstrate that hybrid multimodal authentication can provide a secure and scalable foundation for next-generation digital voting systems.

Keywords: Smart Voting, Facial Recognition, Dynamic QR Code, Biometric Authentication, Secure E-Voting, Deep Learning

1. INTRODUCTION

The rapid growth of information and communication technologies has significantly transformed traditional democratic processes, particularly voting systems. Conventional paper-based voting methods often suffer from challenges such as long queues, human errors, ballot manipulation, and delayed result declaration. To overcome these issues, electronic voting (e-voting) systems have been introduced to enhance efficiency, accessibility, and transparency. However, despite their advantages, e-voting systems face serious security threats including voter impersonation, credential duplication, data tampering, and cyber-attacks.

Biometric authentication has emerged as a powerful solution to address voter identity verification issues. Among various biometric modalities, facial recognition is non-intrusive, user-friendly, and cost-effective, making it suitable for large-scale deployment. Nevertheless, facial biometric systems alone are vulnerable to spoofing attacks, replay attacks, and static credential misuse. Many existing systems rely on single-factor authentication, which limits their robustness.

To address these challenges, this research proposes a Hybrid Smart Voting Framework that combines facial biometric authentication with dynamic QR code-based credentials. The integration of deep learning-based facial recognition and time-bound encrypted QR codes introduces a dual-layer security mechanism. This approach ensures that each voting session is uniquely authenticated, significantly reducing the risks of identity theft and duplicate voting. The proposed framework aims to provide a secure, scalable, and transparent solution for modern digital elections.

2. LITERATURE REVIEW

Extensive research has been conducted on the application of biometric technologies in electronic voting systems. Arputhamoni and Saravanan (2021) developed a smart voting system using facial and fingerprint recognition with convolutional neural networks. Their approach improved authentication accuracy but faced scalability issues in large



electorates. Bhuvaneswary et al. (2022) implemented a fingerprint and face recognition-based voting machine suitable for controlled environments; however, it lacked support for remote voting.

Nagar and Kaur (2021) provided a comprehensive review of facial recognition techniques used in elections, identifying challenges such as illumination variations, image resolution, and processing overhead. Sundararajan and Venkatesh (2020) highlighted privacy risks and secure data transmission issues in biometric e-voting systems. Several studies explored RFID and Aadhaar-enabled voting systems, which enhanced voter identification but relied on static credentials, making them susceptible to replay attacks.

Recent research emphasizes the importance of combining biometric authentication with cryptographic techniques. Liu et al. (2023) proposed a publicly verifiable biometric e-voting system, focusing on transparency rather than session security. Despite these advancements, most systems fail to implement dynamic, time-bound credential mechanisms. This research fills this gap by introducing a hybrid framework that integrates facial biometrics with dynamic QR code encryption to enhance security and reliability.

3. OBJECTIVES

The primary objective of this research is to design and develop a secure hybrid authentication framework for electronic voting systems that can effectively address issues related to voter identity verification and election integrity. The study aims to integrate facial biometric authentication with dynamic QR code-based credentials in order to reduce risks such as identity duplication, spoofing attacks, and replay attacks. Another key objective is to improve overall authentication accuracy, system reliability, and user convenience in comparison to existing biometric voting solutions. Additionally, the research seeks to evaluate the performance of the proposed framework against traditional voting systems in terms of accuracy, latency, security, and scalability, thereby demonstrating its suitability for real-world digital election environments.

4. RESEARCH METHODOLOGY

The proposed Hybrid Smart Voting Framework follows a modular architecture designed to ensure security, reliability, and scalability. The system consists of three major modules: facial biometric verification, dynamic QR code generation, and secure voting management.

In the facial biometric verification module, live facial images of voters are captured using a camera and processed through a convolutional neural network. The CNN model performs feature extraction and compares the captured image with pre-registered facial templates stored in the database. The model is trained on diverse datasets to handle variations in lighting, facial expressions, and angles, thereby improving recognition accuracy and spoof resistance.

Once the voter's identity is successfully verified, the system activates the dynamic QR code generation module. This module creates a unique, session-based QR code containing encrypted information such as voter ID, session timestamp, and authentication token. Advanced Encryption Standard (AES-256) is used to encrypt the QR data, and the QR code is designed to expire within a predefined time window. This ensures that the credential cannot be reused or intercepted for malicious purposes.

The secure voting module enables authenticated voters to cast their votes. Votes are encrypted and stored in a secure database along with audit logs and time-stamped metadata. This design ensures transparency and traceability while preserving voter anonymity. The modular approach allows independent operation of each component while collectively providing a robust multi-layer security mechanism.

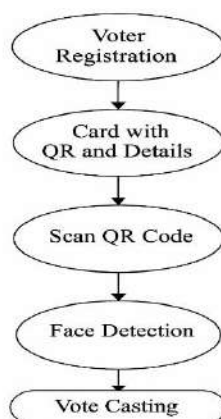


Fig: Flow Diagram of Secure E-Voting System

5. ANALYSIS AND DISCUSSION

The proposed framework was evaluated using a controlled experimental setup involving 2,000 facial images captured under varying environmental conditions. The implementation utilized Python for system logic, TensorFlow for deep learning-based facial recognition, OpenCV for image processing, AES encryption for QR code security, and MySQL for vote storage.

Comparative analysis with existing biometric and RFID-based voting systems reveals that the hybrid framework delivers superior performance across multiple parameters. The integration of dynamic QR codes significantly reduces authentication latency while enhancing session security. The time-bound nature of QR credentials effectively eliminates replay and duplication attacks.

From a security perspective, the combination of biometric and cryptographic techniques creates a strong defense against spoofing and identity theft. The system also demonstrates scalability potential for large-scale elections, provided adequate infrastructure support. User feedback indicates improved trust and convenience due to the seamless two-step authentication process.

6. FINDINGS

The experimental evaluation of the proposed Hybrid Smart Voting Framework demonstrates that the integration of facial biometric authentication with dynamic QR code credentials significantly enhances the overall performance and security of electronic voting systems. The system achieved a high authentication accuracy of 98.9%, indicating reliable voter identification even under varying lighting and environmental conditions. The reduced average latency of 1.9 seconds confirms the suitability of the framework for real-time voting scenarios.

Additionally, the spoof detection rate improved substantially, showing strong resistance against fraudulent attempts such as image replay and identity duplication. The dynamic QR code mechanism effectively minimized the risk of credential reuse, thereby strengthening session-level security. Overall, the findings validate that the hybrid approach provides a robust, efficient, and user-friendly solution for secure digital voting.

7. RECOMMENDATIONS

Based on the findings of this study, several recommendations are proposed to further enhance the effectiveness and applicability of the Hybrid Smart Voting Framework. The system can be strengthened by integrating blockchain technology to maintain immutable and transparent audit trails for vote verification. Adoption of cloud-based infrastructure is recommended to support scalability and handle large voter databases during national-level elections. Privacy-preserving techniques such as federated learning should be considered to protect sensitive biometric data while improving model performance. Furthermore, compliance with national and international data protection regulations should be ensured to build public trust and facilitate real-world deployment of the system.



8. LIMITATIONS

Despite its advantages, the proposed framework has certain limitations that need to be addressed in future work. The system's performance is dependent on stable internet connectivity, particularly during dynamic QR code generation and validation. Facial recognition accuracy may slightly degrade under poor lighting conditions or with low-resolution camera hardware. Large-scale deployment would require substantial computational resources, storage capacity, and advanced infrastructure to manage biometric data securely. Additionally, ethical concerns and privacy issues related to biometric data collection and usage remain critical challenges that must be carefully managed through strict regulatory compliance and data protection mechanisms.

9. CONCLUSION

This research presents a comprehensive Hybrid Smart Voting Framework that integrates facial biometric authentication with dynamic QR code credentials to enhance the security and reliability of electronic voting systems. By combining deep learning-based facial recognition with time-bound encrypted QR codes, the proposed system effectively addresses critical challenges such as identity theft, credential duplication, and vote manipulation.

Experimental results demonstrate significant improvements in authentication accuracy, system responsiveness, and spoof detection compared to conventional voting systems. The hybrid approach not only strengthens election integrity but also enhances voter confidence and usability. The framework is adaptable for both online and booth-based voting environments, making it suitable for modern democratic processes.

Future enhancements may include the integration of blockchain technology for immutable audit trails, privacy-preserving federated learning models, and compliance with evolving data protection regulations. Overall, the proposed framework offers a scalable and secure foundation for next-generation digital governance.

10. ACKNOWLEDGMENT

We sincerely express our heartfelt gratitude to everyone who supported and guided us in preparing this research proposal titled "Hybrid Smart Voting Framework with Facial Biometric and Dynamic QR Code Credentials".

We extend our special thanks to our mentors and professors for their invaluable guidance, constructive feedback, and continuous encouragement throughout the development of this work.

We are also grateful to Jharkhand Rai University for providing essential academic resources, research facilities, and an encouraging learning environment.

We would like to acknowledge the conference organizers for offering us this esteemed platform to present our work and contribute to ongoing discussions in the cybersecurity community. This study is still in its early stages, and we look forward to further advancements toward building more secure and reliable voting systems. The authors sincerely thank Jharkhand Rai University once again for its continuous academic support.

REFERENCES:

1. S. J. J. Arputhamoni and A. G. Saravanan, "Online Smart Voting System Using Biometrics Based Facial and Fingerprint Detection on Image Processing and CNN," 2021 Third International Conference on Intelligent Communication Technologies and Virtual Mobile Networks (ICICV), Tirunelveli, India, 2021, pp. 1-7, doi: 10.1109/ICICV50876.2021.9388405.
2. N. Bhuvaneswary, C. V. Reddy, C. Aravind and K. H. Prasad, "Smart Voting Machine using Fingerprint Sensor and Face Recognition," 2022 International Conference on Applied Artificial Intelligence and Computing (ICAAIC), Salem, India, 2022, pp. 1159-1166, doi: 10.1109/ICAAIC53929.2022.9792643.
3. Nagar, A., & Kaur, M. (2021). "Biometric Authentication in Elections: A Review of the Face Recognition Techniques." *International Journal of Computer Applications*, 176(1), 24-32. This paper reviews the use of biometric



systems, including face recognition, in elections. It highlights the advantages and challenges of using face recognition for voter authentication.

4. Sundararajan, V., & Venkatesh, S. (2020). "E-Voting Systems: Challenges, Security, and the Role of Biometrics." *Proceedings of the International Conference on Cybersecurity and Computer Networks*. Springer, pp. 34-45. Discusses the role of e-voting systems in modern democracies and how biometric technologies, particularly face recognition, can improve the security and accuracy of election processes.
5. Estonian National Electoral Committee (2018). "Estonia's Digital Election System and the Role of Biometric Identification." Estonian e-Government Portal. Provides an overview of Estonia's electronic voting system, with a focus on digital ID and future prospects for integrating face recognition as part of its biometric authentication process.
6. Narayan, S., & Sethi, A. (2019). "Face Recognition-Based Biometric Voter Authentication System for Elections." *International Journal of Advanced Research in Computer Science and Electronics Engineering*, 8(4), 56-65. A detailed analysis of how face recognition technology can be implemented in the voting system, including proposed algorithms and system architecture.
7. International Telecommunication Union (2020). "Biometric Solutions for Election Systems." ITU Telecommunication Development Sector Report. This report focuses on how biometric technologies, including face recognition, can help improve the accuracy, security, and accessibility of election systems worldwide.
8. Kumar, A., & Sinha, M. (2018). "Smart Election Voting System Using Facial Recognition." *International Journal of Computer Applications*, 181(13), 1-5. Presents a design for a smart election voting system using face recognition, including details on algorithm selection, system integration, and database management for voter authentication.
9. IEEE Standards Association (2017). "Biometric Authentication Standards for Elections." IEEE Standards for Security and Privacy. Discusses the importance of establishing standards for biometric authentication, with a specific focus on the integration of facial recognition into election systems.
10. Hassan, H., & Patel, S. (2020). "Challenges in Implementing Biometric Voting Systems: A Case Study of India and UAE." *Journal of International Electoral Systems*, 12(3), 98-1.
11. Kumar, G., Kaushik, R., Kumar, K., & Birla, V. (2020). Design and development to face recognition system by synthesizing AADHAR enabled platform for online voting. *International journal of innovative research in computer science & technology (IJIRCST)*, 8 (3), 242-246.
12. Priyadarshini, M. R., Shangamithra, M. D., Swathi, M. T., Subhaharini, M. G., & Sreenivasan, M. L. (2020). Design and realization of RFID based smart voting system with frontal face recognition technique. *International journal of innovative research in technology*, 6 (12), 338-343. Basha,
13. Dutta KP, Mahanti GK. Meta-heuristic optimization algorithms for simultaneous optimization of sidelobe level and directivity of uniformly excited concentric ring array antennas. *International Journal of Microwave and Wireless Technologies*. 2020;12(2):183-192.
14. Dutta, K.P., Sundi, S., Khalkho, S.S., Tirkey, J., Hembrom, K.K. (2021). Minimization of Sidelobe Level of Uniformly Excited Concentric Circular Array Antenna Using Evolutionary Technique. In: Raj, J.S., Ilyasu, A.M., Bestak, R., Baig, Z.A. (eds) *Innovative Data Communication Technologies and Application. Lecture Notes on Data Engineering and Communications Technologies*, vol 59. Springer, Singapore.



DOIs:10.2015/IJIRMF/ICICSF-2025-P18

--:--

Research Paper / Article / Review

International Conference On “Innovative Convergence for Sustainable Future”

Date : 12 - 13 December, 2025

(ICICSF-2025)



Promoting Justice and Responsibility in Health and Environment: A Legal Perspective

Kuldeep Kumar Mahto

LL.M. Student Department of Legal Studies, Jharkhand Rai University, Ranchi

Email- kuldeepkrmahto71@gmail.com

&

Dr. Smita Pandey,

Associate Professor and Associate Dean, Department of Legal Studies, Jharkhand Rai University

Abstract :Health and environmental well-being are fundamental human rights enshrined in both international and domestic legal frameworks. The intersection of law, health, and environment has gained increasing relevance in the 21st century due to rising global health crises, climate change, and environmental degradation. This paper explores the concept of justice and responsibility through a legal lens, emphasizing the role of judicial activism, statutory mandates, and policy interventions in ensuring a balanced relationship between human health and environmental sustainability. It examines how principles such as “Polluter Pays,” “Precautionary Principle,” and “Right to Health” have evolved under Indian constitutional jurisprudence, particularly through landmark judgments of the Supreme Court of India. The paper also analyzes international obligations under the Paris Agreement, the WHO Constitution, and the UN Sustainable Development Goals (SDGs). By integrating legal, ethical, and policy perspectives, this study argues that promoting justice and responsibility in health and environment is crucial for achieving intergenerational equity and sustainable development.

Keywords: Environmental Justice, Right to Health, Sustainable Development, Legal Responsibility, Climate Governance

1. INTRODUCTION

The relationship between health and environment has become a cornerstone of sustainable human existence in the 21st century. The degradation of the environment directly translates into public health crises — ranging from respiratory diseases caused by air pollution to waterborne infections and mental health disorders linked to climate anxiety. These issues highlight the urgent need to establish justice and responsibility as guiding principles in environmental and health governance.

Environmental degradation, largely caused by industrialization, urbanization, and unsustainable consumption, disproportionately affects marginalized communities, thereby creating a **justice gap**. Similarly, health disparities rooted in environmental causes challenge the idea of equity in public health. Recognizing this, legal systems across the world have evolved to incorporate environmental and health justice within their constitutional and statutory frameworks.

In India, the **Constitution** provides a strong foundation for integrating environmental and health concerns. Through judicial interpretation, **Article 21** — the right to life — has been expanded to include the **right to a healthy environment** and **right to health**. The judiciary’s activism has bridged the gap between policy intent and enforcement, ensuring that health and environmental protection are treated as fundamental rights rather than policy goals (Singh, 2019).



At the global level, the **United Nations Sustainable Development Goals (SDGs)**, the **Paris Agreement (2015)**, and the **World Health Organization's framework** on environmental health reinforce the need for collective legal responsibility in achieving sustainability. This paper analyzes the evolution of justice and responsibility in health and environment through a legal perspective, with emphasis on India's constitutional and judicial framework alongside relevant international commitments.

2. Historical Background

The relationship between human health, environmental protection, and justice has evolved over several centuries, reflecting changes in human understanding of nature, science, and governance. Historically, the concept of environmental and health responsibility emerged as societies began to recognize the harmful consequences of industrialization, urbanization, and unregulated economic development.

2.1 Early Developments (Pre-20th Century)

In the pre-industrial period, health and environmental issues were treated as localized public concerns rather than matters of justice or legal responsibility. Ancient civilizations, including those in India, had community-based health and sanitation systems. The **Indus Valley Civilization** (c. 2500 BCE) demonstrated awareness of urban hygiene through advanced drainage and waste management systems. Similarly, the **Atharva Veda** and **Charaka Samhita** contained references to environmental purity and the balance between nature and health.

However, with the onset of the **Industrial Revolution (18th–19th centuries)**, unchecked industrial growth led to pollution, disease outbreaks, and environmental degradation. This period witnessed the first instances of public health legislation such as the **Public Health Act, 1848** in Britain, marking the beginning of state responsibility toward sanitation and health protection.

2.2 Emergence of Modern Environmental and Health Movements (20th Century)

The early 20th century saw the gradual realization that human well-being and environmental sustainability were interdependent. In India, the **Bhore Committee Report (1946)** was among the first national documents linking environmental hygiene and public health. Post-independence, India adopted a constitutional framework emphasizing the welfare state model, which inherently included duties related to environmental protection and public health.

Globally, awareness intensified after the publication of **Rachel Carson's "Silent Spring" (1962)**, which exposed the dangers of pesticide pollution and catalyzed modern environmental activism. The 1970s marked a turning point:

- The **1972 United Nations Conference on the Human Environment (Stockholm Declaration)** introduced the idea of environmental protection as a fundamental human right.
- The **World Health Organization (WHO)** expanded its focus to include environmental determinants of health.
- India responded by enacting landmark legislations such as the **Water (Prevention and Control of Pollution) Act, 1974** and the **Air (Prevention and Control of Pollution) Act, 1981**, integrating environmental health within statutory governance.

2.3 Constitutional and Judicial Evolution in India (Post-1980s)

The 1980s and 1990s represented a **judicial renaissance** in India, where courts actively interpreted the Constitution to address environmental and health issues. The **Bhopal Gas Tragedy (1984)** highlighted the devastating health and environmental consequences of industrial negligence and triggered legal reforms emphasizing corporate accountability.

The **Supreme Court**, through progressive interpretations of **Article 21**, elevated the right to a clean environment and health to the status of **fundamental human rights**. Key cases such as *M.C. Mehta v. Union of India* (1987) and *Vellore Citizens Welfare Forum v. Union of India* (1996) integrated international environmental law principles into domestic jurisprudence, transforming India into a leader in environmental constitutionalism.



Simultaneously, India participated in global environmental governance efforts — ratifying the **Rio Declaration (1992)**, establishing the **Ministry of Environment and Forests**, and later forming the **National Green Tribunal (2010)** to ensure access to environmental justice.

2.4 Contemporary Era (2000–Present)

In the 21st century, environmental and health justice have become central to discussions on **climate change, sustainable development, and human rights**. The **Paris Agreement (2015)** and the **Sustainable Development Goals (SDGs)** explicitly recognize the intersection of environmental protection and human health. In India, recent developments, such as the Supreme Court's 2024 recognition of the **“Right to be Free from Adverse Effects of Climate Change”**, signify the legal system's evolving commitment to intergenerational and ecological justice.

Today, environmental and health responsibility extends beyond state actors to include corporations, international institutions, and individual citizens. The discourse has shifted from reactive environmental protection to **preventive, participatory, and justice-based governance**, where law serves as a tool for sustainability, equity, and accountability.

3. Contemporary Issues in Promoting Justice and Responsibility in Health and Environment

The intersection of health and environment has become increasingly complex in the 21st century due to global industrialization, urbanization, and climate change. Despite robust constitutional and judicial developments, several **contemporary challenges** continue to hinder the realization of justice and responsibility in this domain. These challenges are multidimensional — legal, administrative, economic, and ethical — and demand integrated policy and legal responses.

3.1 Climate Change and Health Emergencies

Climate change represents the most significant contemporary threat to both environmental and public health. Rising temperatures, extreme weather events, and changing rainfall patterns contribute to **vector-borne diseases, heat stress, food insecurity, and water scarcity**. According to the World Health Organization (2023), climate change could cause approximately 250,000 additional deaths per year between 2030 and 2050 due to malnutrition, malaria, and heat exposure.

The **Supreme Court of India's 2024 recognition of the “Right to be Free from Adverse Effects of Climate Change”** marks a major judicial step in addressing this issue (SCC Online SC 425). However, the absence of specific climate legislation limits enforceability. The **Climate Change Bill** proposed in 2022 remains pending, underscoring a gap between judicial recognition and legislative action.

3.2 Air Pollution and Urban Environmental Justice

India is home to several of the world's most polluted cities. Air pollution contributes significantly to respiratory illnesses, cardiovascular diseases, and premature deaths. Despite the **Air (Prevention and Control of Pollution) Act, 1981**, and multiple judicial interventions (e.g., *M.C. Mehta v. Union of India*, 2018, on Delhi pollution), enforcement remains inadequate. Weak monitoring systems, political interference, and poor urban planning perpetuate a **cycle of environmental injustice**, where marginalized populations living in industrial and congested areas bear the highest health burdens.

Recent policy efforts such as the **National Clean Air Programme (NCAP, 2019)** have set ambitious reduction targets, but implementation at the state level is inconsistent due to lack of resources and coordination.

3.3 Waste Management and Public Health Risks

Improper management of solid, plastic, and biomedical waste has emerged as a major environmental health issue. The **Solid Waste Management Rules (2016)** and **Biomedical Waste Management Rules (2018)** provide regulatory frameworks, yet poor segregation, disposal, and recycling practices continue. Illegal dumping and open burning release toxic pollutants, causing both **air contamination** and **groundwater pollution**, especially in urban slums and peri-urban regions.



The COVID-19 pandemic exposed weaknesses in biomedical waste handling, leading to significant risks for sanitation workers and surrounding communities. Ensuring justice in this area requires improved **waste governance**, **worker safety**, and **community-level participation**.

3.4 Industrialization, Mining, and Corporate Accountability

Large-scale industrial and mining projects, though economically beneficial, have resulted in displacement, deforestation, and pollution, often violating environmental clearance conditions. Cases such as the **Sterlite Copper Plant closure (Tamil Nadu, 2018)** highlight the conflict between industrial interests and community rights to health and environment.

Despite the **Polluter Pays Principle**, corporate accountability remains weak due to limited penalties and lack of transparency in environmental impact assessments (EIA). The dilution of the **EIA Notification, 2020**, drew criticism for reducing public participation and post-facto clearances — undermining environmental justice and democratic oversight.

3.5 Water Scarcity and Contamination

Water scarcity, coupled with contamination from industrial effluents and agricultural runoff, presents a serious health and environmental challenge.

The **Water (Prevention and Control of Pollution) Act, 1974** has been ineffective in addressing issues like groundwater depletion and toxic discharge. Judicial interventions (e.g., *Paryavaran Suraksha Samiti v. Union of India*, 2017) have mandated effluent treatment plants, but compliance remains poor. Contemporary water-related conflicts — such as inter-state river disputes and urban water shortages — reveal the lack of an integrated **water governance model** that considers both ecological sustainability and human health.

3.6 Environmental Disasters and Public Health Crises

Events like the **Bhopal Gas Tragedy (1984)**, **Vizag Gas Leak (2020)**, and recurrent **floods and landslides in Himalayan regions** expose the continuing failure of disaster preparedness and industrial safety regulations. Such disasters disproportionately affect poor and vulnerable groups, raising serious questions of **environmental justice and compensation**.

The absence of a comprehensive **Public Health and Environmental Emergency Framework** in India limits the ability of authorities to coordinate rapid, equitable responses to crises that cross sectoral boundaries.

3.7 Digital Divide and Environmental Data Transparency

A less-discussed but emerging issue is the **digital divide** in environmental data access. While laws such as the **Right to Information Act (2005)** promote transparency, environmental monitoring data are often inaccessible, incomplete, or manipulated. Communities affected by pollution or health hazards frequently lack the technological and legal capacity to seek justice. Ensuring **data justice**—transparent, real-time access to environmental and health information—has become a new frontier for promoting accountability.

3.8 Intersectionality and Environmental Inequality

Women, children, indigenous communities, and low-income groups experience the most severe environmental health burdens.

For instance, tribal populations in mining regions face exposure to heavy metals, contaminated water, and deforestation-related displacement.

Feminist and indigenous perspectives emphasize that **environmental justice must include social justice**—ensuring that vulnerable populations have voice, representation, and reparative remedies in legal and policy frameworks.

3.9 Globalization and Cross-Border Health–Environment Challenges

Contemporary environmental and health issues transcend national borders. Climate-induced migration, transboundary air pollution, and hazardous waste trade (regulated under the **Basel Convention, 1989**) create shared responsibilities among nations.



India's regional cooperation under the **South Asia Cooperative Environment Programme (SACEP)** reflects emerging awareness of transnational environmental justice.

However, weak enforcement of international environmental law and limited funding for global health adaptation remain pressing challenges.

3.10 Technology, AI, and Environmental Governance

The integration of **artificial intelligence (AI)** and **remote sensing** in monitoring pollution, climate patterns, and disease outbreaks offers new possibilities for environmental governance.

However, this technological advancement raises questions about **data privacy**, **algorithmic bias**, and **equity in access**.

The ethical use of technology must therefore be guided by legal principles of **transparency**, **inclusivity**, and **accountability**, ensuring that innovation serves justice rather than reinforcing inequality.

Synthesis

These contemporary issues demonstrate that the promotion of justice and responsibility in health and environment extends far beyond traditional environmental law.

It now requires a **holistic approach**—integrating climate governance, public health law, human rights, and technology policy.

Addressing these issues is vital for achieving **sustainable development**, **intergenerational equity**, and the **constitutional promise of dignity and well-being** for all.

4. Methodology / Approach

This study follows a **doctrinal legal research methodology** combined with a **comparative policy review** approach. It primarily relies on qualitative analysis of constitutional provisions, statutory enactments, and landmark judicial pronouncements that shape the legal understanding of health and environment in India.

The research is based on the following steps:

1. **Constitutional and Statutory Analysis:** Examining how Indian law embeds environmental and health justice through specific provisions and legislative measures.
2. **Judicial Review:** Studying major Supreme Court and National Green Tribunal (NGT) decisions that define legal responsibility and justice in environmental and health issues.
3. **Policy Evaluation:** Reviewing national and international policies such as India's National Action Plan on Climate Change (NAPCC), WHO's environmental health framework, and SDG commitments.
4. **Comparative Perspective:** Drawing insights from international environmental jurisprudence to contextualize India's approach in the global framework.

This approach allows for a holistic understanding of how **law operates as a tool of justice, accountability, and sustainability** in both environmental and health domains.

5. Analysis

The findings of this study reveal that both health and environmental justice have evolved from being peripheral policy concerns to becoming central constitutional guarantees. However, an analytical examination of these developments shows that the realization of justice and responsibility in this sphere depends on how effectively **law, policy, and governance** intersect and function in harmony.

5.1 Constitutional Morality and Judicial Responsibility

The Indian judiciary has expanded the meaning of **Article 21** to protect life in its fullest sense—encompassing clean air, safe water, and adequate health standards. This interpretation reflects a shift from *procedural legality* to *substantive justice*.



Through cases like *M.C. Mehta* and *Vellore Citizens Welfare Forum*, the judiciary has demonstrated moral leadership in ensuring that the right to life is not merely the right to exist but the right to live with dignity and health in a clean environment.

This transformation aligns with the concept of **constitutional morality**, where courts uphold the ethical and moral commitments embedded in the Constitution rather than waiting for legislative action. The judiciary's willingness to fill policy gaps exemplifies **judicial responsibility as a tool of environmental governance**.

However, despite this proactive judicial stance, enforcement often falters at the administrative level. The frequent non-compliance with court orders by industries and local bodies indicates a **justice-implementation gap**, where the law recognizes rights but fails to ensure their practical realization.

5.2 Balancing Development and Justice

A core legal dilemma lies in balancing **economic development** with **environmental and health justice**. Industrial expansion and urbanization are often justified in the name of public interest and economic progress. Yet, this progress frequently imposes disproportionate environmental burdens on marginalized communities.

This conflict exposes an **inequitable distribution of environmental risks**, leading to what scholars term *environmental injustice*.

The judiciary's adoption of the **Doctrine of Sustainable Development** in *Vellore Citizens Welfare Forum* was a turning point. By requiring that development be ecologically sustainable and socially equitable, the Court recognized that justice extends to future generations as well.

Nevertheless, large-scale industrial projects, mining, and deforestation continue to cause irreversible ecological and health harm, highlighting the **tension between legal ideals and political-economic realities**.

5.3 From Responsibility to Accountability

Legal responsibility entails more than statutory compliance; it signifies a duty of care and accountability to the community and the environment. In practice, responsibility in India often becomes fragmented among multiple agencies—environmental ministries, health departments, and local governments—resulting in a **diffusion of accountability**.

The **Polluter Pays Principle** and **Precautionary Principle** seek to clarify responsibility by assigning liability for harm and mandating preventive action. However, their implementation remains inconsistent. For example, while the NGT has imposed significant fines on polluting industries, the lack of transparency in fund utilization and weak monitoring reduce deterrence.

A stronger framework of **corporate environmental accountability**—modeled on international best practices such as environmental impact disclosures and sustainability audits—is needed to convert responsibility into enforceable accountability.

5.4 Policy Coherence and Governance Gaps

Policy fragmentation remains one of the greatest obstacles to achieving justice in health and environment.

- Environmental laws and public health laws operate largely in silos.
- Coordination between the **Ministry of Environment, Forest and Climate Change (MoEFCC)** and the **Ministry of Health and Family Welfare** is limited.
- Overlapping mandates among Pollution Control Boards, NGT, and local authorities create administrative confusion.



The **National Action Plan on Climate Change (NAPCC)** provides a useful integrative model, but it still lacks robust local implementation. Policies must therefore adopt a **cross-sectoral governance approach**, where environmental quality, public health, and human rights are addressed together rather than in isolation.

5.5 International and Ethical Dimensions

International law reinforces the moral and legal obligation to safeguard health and environment. The **Paris Agreement (2015)** emphasizes the health co-benefits of climate mitigation, while the **WHO Constitution (1948)** recognizes health as a right dependent on social and environmental conditions.

India's commitment to the **Sustainable Development Goals (SDGs)**, particularly SDG 3 (Good Health and Well-being) and SDG 13 (Climate Action), provides a normative framework for integrating justice and responsibility into national governance.

Yet, the real challenge lies in **translating international commitments into domestic enforcement**.

Beyond law, there is an ethical dimension — the concept of **intergenerational equity** — which requires current generations to act as trustees of the planet for future ones. This principle, rooted in both international environmental law and Indian jurisprudence (*State of Himachal Pradesh v. Ganesh Wood Products*, 1995), redefines responsibility as a moral as well as legal duty.

5.6 The Way Forward

The analysis underscores that the pursuit of justice and responsibility in health and environment must move from reactive litigation to proactive governance.

Key steps include:

- Establishing **integrated legal frameworks** connecting health and environmental policies.
- Strengthening **local-level environmental health governance** through community participation.
- Incorporating **climate-health indicators** into public policy evaluation.
- Ensuring **corporate accountability** through mandatory environmental and health disclosures.

Ultimately, justice in this domain cannot be confined to courtroom remedies; it must permeate every layer of governance, economics, and ethics. A truly just and responsible society recognizes that environmental sustainability and public health are not competing interests but **mutually reinforcing rights** central to human dignity.

6. Results / Findings

6.1 Constitutional Integration of Environmental and Health Justice

The **Constitution of India** embeds the concepts of justice and responsibility within its fundamental framework.

- **Article 21** guarantees the right to life, which has been judicially interpreted to include the right to live in a clean and healthy environment (*Subhash Kumar v. State of Bihar*, 1991).
- **Article 47** imposes a duty on the State to raise the level of nutrition and improve public health.
- **Article 48A** directs the State to protect and improve the environment.
- **Article 51A(g)** makes it a fundamental duty of citizens to protect and improve the natural environment.

These provisions collectively transform environmental and health protection from mere policy objectives into enforceable legal obligations, establishing the **constitutional morality of sustainability**.



6.2 Judicial Expansion: Case Law Evolution

The Indian judiciary has played a pioneering role in promoting justice and responsibility in environmental governance.

(a) M.C. Mehta v. Union of India (1987) – Oleum Gas Leak Case

In this landmark case, the Supreme Court introduced the doctrine of **absolute liability**, holding hazardous industries strictly responsible for environmental damage irrespective of negligence. This decision not only strengthened environmental accountability but also recognized the direct relationship between industrial pollution and public health risks.

(b) Vellore Citizens Welfare Forum v. Union of India (1996)

The Court formally introduced the **Precautionary Principle** and the **Polluter Pays Principle** into Indian law, emphasizing preventive action and financial responsibility for environmental damage. The case set a precedent for integrating sustainable development into judicial reasoning, linking environmental degradation to long-term public health impacts.

(c) Subhash Kumar v. State of Bihar (1991)

This case explicitly recognized the **right to pollution-free water and air** as part of Article 21. The Court observed that environmental pollution directly affects human health, and thus any action threatening public health is violative of the fundamental right to life.

(d) Municipal Council, Ratlam v. Vardhichand (1980)

In one of the earliest environmental justice decisions, the Court held that municipal bodies cannot ignore their statutory duties under the pretext of financial incapacity. The ruling underscored **public health as a legal obligation** and laid the foundation for environmental governance at the local level.

(e) In Re: Right to be Free from Adverse Effects of Climate Change (2024)

The Supreme Court recognized a **new fundamental right against adverse climate impacts**, interpreting it as a natural extension of Article 21. This judgment marks a major milestone, connecting climate change, environmental justice, and health rights in one constitutional framework.

Collectively, these cases demonstrate how the judiciary has operationalized justice and responsibility through legal innovation, thereby advancing the cause of environmental and health protection.

6.3 Institutional and Policy Developments

(a) National Green Tribunal (NGT)

Established under the **National Green Tribunal Act, 2010**, the NGT provides a specialized judicial forum for environmental cases. It ensures **speedy justice**, **scientific expertise**, and **principle-based adjudication**. Notable cases such as the *Art of Living Foundation case (Yamuna floodplain restoration)* reflect its proactive approach in enforcing environmental responsibility.

(b) National Action Plan on Climate Change (NAPCC), 2008

NAPCC represents India's primary climate governance framework, integrating environmental sustainability with human well-being. Its missions — particularly the National Solar Mission and National Water Mission — emphasize sustainable resource use to safeguard both environmental and health outcomes.

(c) Public Health Legislation

Statutes like the **Epidemic Diseases Act, 1897** and the **Disaster Management Act, 2005** illustrate the State's responsibility in protecting public health during emergencies. The COVID-19 pandemic demonstrated how environmental factors, such as urban air quality and sanitation, directly influence public health resilience.



6.4 Global Commitments and International Legal Obligations

India's participation in international environmental and health governance strengthens its domestic legal framework:

- **UN Framework Convention on Climate Change (UNFCCC)** and **Paris Agreement (2015)** commit nations to reducing greenhouse gas emissions to mitigate health risks linked to climate change.
- **WHO Constitution (1948)** recognizes health as a fundamental right and obligates states to provide conditions conducive to healthy living.
- **Stockholm Declaration (1972)** and **Rio Declaration (1992)** established the foundation for environmental responsibility and sustainable development principles.
- **SDG 3** (Good Health and Well-Being) and **SDG 13** (Climate Action) reflect the global integration of health and environmental justice within sustainable development frameworks.

7. Discussion / Conclusion

The integration of health and environment under a justice-oriented legal framework represents a transformative shift in governance. India's constitutional and judicial developments demonstrate how **law can act as both protector and promoter** of sustainable development. The recognition of the right to health and a clean environment as part of Article 21 has empowered citizens to demand accountability from both State and corporate entities.

However, challenges persist. **Implementation gaps, institutional overlap, and limited public participation** continue to hinder progress. Environmental and health policies often function in silos, leading to fragmented governance. Moreover, enforcement mechanisms for environmental crimes and industrial violations remain weak, especially at the local level.

To truly promote justice and responsibility, the following policy measures are essential:

1. **Integrated Governance:** Health and environment ministries should collaborate on shared objectives such as air quality management, water sanitation, and disease prevention.
2. **Community Participation:** Environmental justice demands the active involvement of local communities in decision-making, ensuring that policies reflect ground realities.
3. **Strengthened Accountability:** Industries must adopt transparent reporting mechanisms on environmental compliance, and government agencies should enhance public access to environmental information.
4. **Judicial Reforms:** Specialized environmental courts should be expanded at the state level to reduce case pendency and ensure scientific adjudication.
5. **Climate Justice and Human Rights:** The recognition of climate-related harms as human rights violations can enhance global accountability frameworks.

Promoting justice and responsibility in health and environment is not merely about legal compliance; it is about **ethical stewardship**. As the Supreme Court observed in *Vellore Citizens Welfare Forum (1996)*, the balance between development and environment must be maintained to ensure intergenerational equity. The path forward lies in transforming law from a reactive instrument of redress into a **proactive mechanism of prevention**, ensuring that the environment and human health are protected as inseparable components of human dignity.

REFERENCES

1. Birnie, P., Boyle, A., & Redgwell, C. (2009). *International Law and the Environment* (3rd ed.). Oxford University Press.
<http://oceanlaw.ru/wp-content/uploads/2017/10/International-Law-and-the-Environment-Third-Edition-Patricia-Birnie.pdf>



2. Divan, S., & Rosencranz, A. (2021). *Environmental Law and Policy in India: Cases, Materials and Statutes* (4th ed.). Oxford University Press.
<https://ia802907.us.archive.org/33/items/in.ernet.dli.2015.474253/2015.474253.Environmental-Law.pdf>
3. Nitish Gogoi and S. S. Sumesh. (2023). Environmental Injustice and Public Health in India: Towards a “Decolonial Intersectional Environmental Justice” Framework 24(2), 112–130.
<https://www.epw.in/engage/article/environmental-injustice-and-public-health-india>
4. Thomas J. Schoenbaum (2015). *International Environmental Law and Policy* (3rd ed.). Carolina Academic Press
<https://cap-press.com/pdf/9781531006136.pdf>
5. Sunil Chauhan (2019). *Climate Change, Disasters and Security Issues, Concerns and Implications for India*
<https://cipe.umd.edu/conferences/epckdi/9.PDF>
6. Dr. Ashutosh Mishra & Dr. Prakash Tripathi Environmental Justice: A New Challenge to the Developing India, The Seybold report
https://admin369.seyboldreport.org/file/V18I03A137_ZH DUW-43AubIp54fPJZnm.pdf
7. Mishra, R. (2022). *Right to Health through the lens of various laws and Judicial Pronouncements in India. International Journal for Innovative Research in Multidisciplinary Field*, 13(1), 45–58.
<https://www.ijirmf.com/wp-content/uploads/IJIRMF202105029.pdf>
8. Rajagopal, B. (2003). *International Law from Below: Development, Social Movements and Third World Resistance*. Cambridge University Press.
https://assets.cambridge.org/052181/6467/frontmatter/0521816467_frontmatter.pdf
9. Deepu P. (2019). *Human Rights and Environmental Protection – An Integrated Approach*
<https://jsslawcollege.in/wp-content/uploads/2021/08/HUMAN-RIGHTS-AND-ENVIRONMENTAL-PROTECTION-%E2%80%93AN-INTEGRATED-APPROACH.pdf>

Statutes and Case Laws

- ❖ *M.C. Mehta v. Union of India*, AIR 1987 SC 1086.
- ❖ *Vellore Citizens Welfare Forum v. Union of India*, (1996) 5 SCC 647.
- ❖ *Subhash Kumar v. State of Bihar*, AIR 1991 SC 420.
- ❖ *Municipal Council, Ratlam v. Vardhichand*, AIR 1980 SC 1622.
- ❖ *In Re: Right to be Free from Adverse Effects of Climate Change*, (2024) SCC Online SC 425.
- ❖ *State of Himachal Pradesh v. Ganesh Wood Products*, (1995) 6 SCC 363.
- ❖ *The Constitution of India*, 1950.
- ❖ *The Environment (Protection) Act*, 1986.
- ❖ *The Air (Prevention and Control of Pollution) Act*, 1981.
- ❖ *The Water (Prevention and Control of Pollution) Act*, 1974.
- ❖ *The National Green Tribunal Act*, 2010.

International Sources

- United Nations Framework Convention on Climate Change (1992).
<https://unfccc.int/resource/docs/convkp/conveng.pdf>
- Paris Agreement (2015).
https://unfccc.int/sites/default/files/english_paris_agreement.pdf
- World Health Organization Constitution (1948).
<https://apps.who.int/gb/bd/pdf/bd47/en/constitution-en.pdf>
- United Nations Sustainable Development Goals (2015).
<https://sustainabledevelopment.un.org/content/documents/1758GSDR%202015%20Advance%20Unedited%20Version.pdf>
- UNEP (2022). *Environmental Rule of Law: First Global Report*.
https://wedocs.unep.org/bitstream/handle/20.500.11822/43943/Environmental_rule_of_law_progress.pdf?sequence=3
- Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal, 1989.
<https://www.basel.int/TheConvention/Overview/TextoftheConvention/tabid/1275/Default.aspx>



DOIs:10.2015/IJIRMF/ICICSF-2025-P19

--:--

Research Paper / Article / Review

International Conference On "Innovative Convergence for Sustainable Future"

Date : 12 - 13 December, 2025

(ICICSF-2025)



Judicial Responses to Custodial Violence: A Call for Sustainable Police System.

¹ Madhu Singh, ² Sristi Roy

¹ Designation – Student, University/College – Jharkhand Rai University, State – Jharkhand, Country – India.

² Designation- Faculty associate University/College – Jharkhand Rai University, State – Jharkhand, Country – India.

Email - smadhusingh733@gmail.com

Abstract: Custodial violence still counts among India's worst human rights problems, assaulted the core values of fairness, freedom, equal treatment, and respect written into its institution law. Even though the Constitution sets clear rules and courts have spoken on this many times, mistreatment in custody - like torture or suspicious deaths keeps happening. This piece looks at how judges in India reacted to such violence by recumbent major decisions, shaping legal meaning, and setting up protective steps during arrests and detention. This paper takes a look at how the judiciary has tackled violence dissecting landmark decisions, statutory protections and the evolving jurisprudence, under Articles 20, 21 and 22 of the Constitution. This work is based on new data collected in the field, but on a deep analysis of existing legal sources: current laws, judicial precedents, and documentation from global rights organizations. Landmark shifts in legal understanding are clearly illustrated in cases such as D.K. Basu v. State of West Bengal (1997), Nilabati Behera v. Orissa (1993), and Prakash Kadam v. Ramprasad Vishwanath Gupta (2011). These cases were looked at to see how well they actually worked on the ground. Courts may order changes, but law officer often don't follow through. To fix this mess, one idea stands out - a law officer setup that lasts, respects basic rights, shows its workings clearly, owns up when wrong, keeps courts watching closely, lets people complain without fear, gets new laws shaped right, all lined up with global rules like what's laid down in the UN anti-torture treaty.

Keywords: Custodial Violence, Judicial Accountability, Human Rights, Police Reform, Sustainable Policing, Constitutional Safeguards

1. INTRODUCTION

Custodial violence is still a major problem and a tragic human rights issue in India's legal system. It includes lots of mistreatment, like physical and mental abuse, sexual assault, wrongful imprisonment, and even deaths while someone's in police or court custody. Even though India's Constitution says everyone should be treated equally and with dignity, many police stations and prisons don't seem to care about the law. Each instance of custodial abuse is a crime but also a letdown to the values of justice that India is built on.

In The Indian Constitution dealt with some Articles such as 20(3), 21 and 22 which protect people from illegal detention without a specific reason, protect from testify against themselves and also dealt with being treated abusively. Article 22 is most crucial because it dealt with safeguard for being taken into custody and also Article 21 is significant because it dealt with everyone has to right to life and freedom. Courts have interpreted this to mean that people should live with respect and not to be tortured and forced anyone. There are some laws such as the Bharatiya Nyaya Sanhita, 2023 (BNS), Bharatiya Sakshya Adhiniyam, 2023(BSA), and Bharatiya Nagarik Suraksha Sanhita, 2023(BNSS), that are supported to stop illegal detention and forced questioning and also imprisonment. The Bharatiya Nyaya Sanhita 2023 (BNS) contains several provisions that can be relevant in cases of custodial death. There are groups like the National Human



Rights Commission (NHRC) that were created to watch out for human rights abuses and suggest what should be done about them. Although, with all these laws and groups, custodial violence and deaths still happen way too often.

In National Crime Records Bureau (NCRB) shows a data from 2017 to 2023, in this data there were hundreds of people deaths in custody, but only some police officers were convicted. And also the report from organizations such as Commonwealth Human Rights Initiative (CHRI) and Human Rights Watch (HRW) dealt with torture has become normal during the investigations, because people are not good ways to investigate, and politicians get involved. The United Nations and human rights groups have often said they're worried that India hasn't made torture a specific crime, even though it agreed to the United Nations Convention Against Torture (UNCAT).

The judiciary have been beneficial in fighting custodial violence. In the case *D.K. Basu v. State of West Bengal* (1997), *Nilabati Behera v. State of Orissa* (1993), and *Prakash Singh v. Union of India* (2006), the Supreme Court of India has made some significant rulings. These rulings tried to define who is responsible, set rules, and protect human rights in legal system. These decisions said that violence and torture is against basic rights and if someone dies in custody in that case government will be responsible. But violations have not stopped. Without changes to the system, good oversight, and a change in how the police act, custodial violence will keep happening and make people question India's democracy.

The custodial abuse is not just a violation of someone rights, it also violates the idea of justice. It kills trust in the police, it creates fear instead of respect, and make government system is immoral. In the democracy system policing and morality is play a significant role. It means making sure the police follow the Constitution and international human rights standards. To fix this, we need to combine court oversight with changes in the law, government accountability, new technology, and a change in ethics.

Problem Statement

Despite consistent judicial intervention, progressive constitutional interpretation, and a series of guidelines aimed at curbing abuse, custodial violence remains deeply entrenched in India's law enforcement system. The persistence of such violations points to a profound gap between judicially mandated safeguards and their on-ground enforcement. The problem lies not in the absence of legal standards but in the failure of institutional mechanisms to operationalize them effectively.

The primary issues identified include:

- **Inadequate Enforcement of Judicial Guidelines:** Many states have failed to implement the directives issued in *D.K. Basu* and *Prakash Singh* concerning arrest procedures, police accountability, and oversight bodies.
- **Absence of a Comprehensive Anti-Torture Law:** India's continued failure to enact legislation in conformity with the UNCAT leaves victims without an effective statutory remedy.
- **Institutional Impunity and Weak Accountability:** Police officers accused of custodial deaths or torture are rarely prosecuted, and disciplinary actions are often delayed or diluted.
- **Lack of Independent Oversight Mechanisms:** Police Complaints Authorities and Human Rights Commissions often lack investigative powers, funding, or political independence.
- **Cultural and Structural Problems within Policing:** A coercive investigation culture, inadequate training, and pressure to produce quick results perpetuate reliance on violence.

This research, therefore, seeks to critically examine how judicial responses have shaped the legal landscape on custodial violence, why these interventions have fallen short in practice, and how India can evolve toward a sustainable, transparent, and humane policing model that upholds both justice and human dignity.

2.Literature Review

2.1 Introduction: The Scope of Custodial Violence Research

Custodial violence has long been acknowledged as one of the most serious and persistent human rights concerns in India, attracting deep attention from scholars, courts, and international watchdogs. It represents the tension between state power and individual liberty — a direct challenge to constitutional guarantees under Articles 20, 21, and 22. The



existing literature shows that while judicial activism has played a pivotal role in strengthening the rights of detainees, the lack of consistent enforcement and accountability mechanisms continues to undermine these gains. Research on custodial violence in India generally revolves around three interrelated themes: the evolution of judicial safeguards, the implementation gap in enforcement, and the urgent need for comprehensive and sustainable police reforms.

2.2 Historical Perspective and Foundational Studies

Saini (1994), in his seminal work *“Custodial Torture in Law and Practice with Reference to India”* published in the *Journal of the Indian Law Institute*, traced the historical trajectory of custodial abuse and the systemic failures of the Indian criminal justice system. He argued that legal provisions alone are ineffective without strong institutional safeguards and independent oversight. Saini’s study remains foundational in understanding how impunity for custodial violence persists despite the existence of a progressive constitutional and statutory framework. He concluded that custodial abuse is symptomatic of deep institutional dysfunction — a product of weak supervision, inadequate accountability, and a culture of coercion within law enforcement.

2.3 The Evolution of State Accountability and Public Law Compensation

In the case of *Nilabati Behera’s v. State of Orissa* (1993) further inspired academic discourse on *public law compensation* as a tool for ensuring state accountability. Scholars such as Bidkar (2025) emphasize that this doctrine represents a shift from the traditional tort-based liability model to one grounded in constitutional responsibility. However, Bidkar also highlights that compensation, though significant, often remains a reactive remedy incapable of preventing future abuses without systemic reform.

2.4 Institutional Culture and the Problem of Impunity

Human Rights Watch (2016), in its influential report *“Bound by Brotherhood: India’s Failure to End Killings in Police Custody,”* revealed that custodial torture is not an aberration but an institutionalized method of investigation in India. The report highlighted the culture of solidarity among police personnel that protects offenders and discourages accountability. It attributed the persistence of abuse to poor training, resource constraints, and pressure to extract confessions. Similarly, the Commonwealth Human Rights Initiative (CHRI) has repeatedly reported that compliance with the Supreme Court’s directives in *Prakash Singh v. Union of India* (2006) remains limited and uneven. Many states have failed to establish independent Police Complaints Authorities or implement fixed tenures for senior officers, perpetuating a system vulnerable to political interference and corruption.

2.5 Empirical Insights into Police Accountability

Adding an empirical dimension to the debate, Lamba and Jain (2023) conducted a detailed study on *Police Accountability and Custodial Violence in India*. Their research demonstrated that most violations occur due to poor awareness among officers about detainees’ rights, lack of fear of punishment, and weak internal monitoring mechanisms. They concluded that effective reform must go beyond legal codification to address institutional behaviour, ethical orientation, and the moral psychology of policing. The study strengthens the argument that reforms should combine legal, administrative, and ethical interventions to ensure both accountability and humane law enforcement practices.

2.6 Comparative Perspectives from Global Jurisdictions

The Oxford Human Rights Hub (2025) contributed a comparative perspective, noting that nations with statutory anti-torture laws, independent investigation agencies, and mandatory recording of interrogations such as the United Kingdom and South Africa exhibit significantly lower rates of custodial abuse. This comparative perspective underscores the necessity for India to adopt statutory reforms and institutional independence as central pillars of sustainable policing. The study concludes that lessons from these countries demonstrate how the combination of legal clarity and structural oversight can effectively prevent abuse while preserving law enforcement efficiency.

2.7 Contemporary Studies and Statistical Trends

Srivastava and Varun (2025), writing in the *International Journal of Advanced Research in Science, Communication and Technology*, evaluated *D.K. Basu v. State of West Bengal* (1997) and its impact on procedural safeguards during arrest and detention. They noted that although the Supreme Court’s guidelines were groundbreaking, their implementation has been inconsistent due to lack of codification and bureaucratic resistance. Supporting this finding,



the *Crime in India* reports by the National Crime Records Bureau (NCRB) from 2018–2023 reveal that while hundreds of custodial deaths were recorded, very few resulted in convictions. The data highlights the continued gap between judicial mandates and ground realities, suggesting that procedural reforms must be reinforced with legal sanctions and independent monitoring.

2.8 Synthesis and Emerging Consensus

The reviewed literature — encompassing scholarly writings, judicial analyses, and human rights reports — converges on a common conclusion: the judiciary has played an indispensable role in constructing a robust human rights jurisprudence, yet its effectiveness has been compromised by weak implementation, fragmented oversight, and cultural inertia within policing institutions. Scholars widely agree that custodial violence is not just a legal issue but a structural and ethical crisis that demands comprehensive reform. Sustainable solutions must extend beyond courtroom pronouncements to include legislative clarity, administrative accountability, technological transparency, and moral transformation within the police force. Only through such multi-layered and coordinated reforms can India realize the constitutional promise of justice, dignity, and equality for every individual in state custody.

3.Objectives of the Study

- In this study mainly focuses on the evolution of judicial responses and the development of constitutional safeguards against custodial abuses in India.
- To examine legal framework.
- To explore the human rights violation.
- To assess the impact of custodial violence.
- To assess the extent to which judicial guidelines have been implemented at the state and institutional levels.
- Explore the gap between legal pronouncement and administrative enforcement mechanisms.
- And also, the purpose reforms aimed at set up a sustainable, rights – based, and accountable police system.

4.Significance of the Study

This study is important because it bridges the gap between judicial theory and administrative practice. It progressing traditional legal analysis to consider sustainability and ethics as central components of police reform. By examining judicial pronouncements alongside legislative inertia and administrative challenges, the research offers a holistic understanding of how India can reconcile law enforcement with human rights. It contributes to the ongoing discourse on police accountability by proposing an integrated reform model that aligns legal principles with institutional behaviour and public trust. Ultimately, it reaffirms that the fight against custodial violence is not just a legal battle but a moral imperative essential to the survival of constitutional democracy.

5.Methodology

This research employs a doctrinal and analytical methodology, focusing on qualitative legal analysis rather than empirical data collection. The doctrinal approach is particularly suited for examining how the judiciary has interpreted and expanded the scope of constitutional protections in cases of custodial violence, while the analytical dimension evaluates the effectiveness of these judicial interventions in real-world settings.

Research Design

The research design is structured in three stages:

- Doctrinal Analysis – Reviewing constitutional and statutory frameworks that govern custodial conduct and individual rights.
- Judicial Interpretation – Studying landmark judicial decisions and identifying evolving trends in human rights jurisprudence.
- Comparative and Prescriptive Evaluation – Drawing lessons from international legal systems and proposing reforms to establish a sustainable, rights-based policing model in India.



Sources of data collection

Primary legal sources: Constitutional provisions (Articles 20, 21, 22), statutory provisions (CrPC, Indian Penal Code, Evidence Act), and landmark judgments such as *D.K. Basu v. State of West Bengal* (1997), *Nilabati Behera v. State of Orissa* (1993), *Prakash Singh v. Union of India* (2006), and *Paramvir Singh Saini v. Baljit Singh* (2020).

- Secondary sources: Scholarly articles, law journals, human rights reports, NCRB and NHRC data, and policy documents from government and civil society organizations such as Human Rights Watch, the Commonwealth Human Rights Initiative (CHRI), and the Bureau of Police Research and Development (BPRD).
- Comparative legal materials: International conventions like the United Nations Convention against Torture (UNCAT), and best practices from jurisdictions such as the United Kingdom, South Africa, and the European Union.

Analytical Framework

The analytical framework integrates three core dimensions:

- Legal Dimension: Examining constitutional provisions, judicial precedents, and legislative gaps.
- Institutional Dimension: Assessing administrative and procedural compliance within policing systems and investigating barriers to implementation.
- Human Rights Dimension: Evaluating the intersection between state power and individual dignity, using international standards as benchmarks.

6. Finding/ Analysis

The analysis reveals that the Indian judiciary has played a pivotal role in recognizing and addressing custodial violence by expanding the scope of Article 21 of the Constitution to include the right to live with dignity and freedom from torture. Landmark judgments such as *D.K. Basu v. State of West Bengal* (1997) and *Nilabati Behera v. State of Orissa* (1993) established detailed procedural safeguards and introduced public law compensation for victims of state abuse. These decisions represent milestones in India's human rights jurisprudence, demonstrating judicial sensitivity toward custodial injustices.

However, the findings show that despite these progressive judicial standards, custodial violence persists due to implementation failures and institutional weaknesses. The directives issued in *D.K. Basu* and *Prakash Singh v. Union of India* (2006) have not been uniformly enforced across states. Reports by the NHRC, CHRI, and NCRB indicate that custodial deaths continue to occur frequently, while convictions of police personnel remain extremely low. This gap highlights that judicial pronouncements alone cannot bring reform without administrative commitment and legislative backing.

The study also finds that structural and cultural issues within policing—such as colonial-era laws, hierarchical control, political interference, and pressure to secure confessions—sustain coercive practices. Inadequate human rights training and lack of psychological support further contribute to this environment of impunity. Even technological interventions like CCTV installations, mandated in *Paramvir Singh Saini v. Baljit Singh* (2020), often fail in practice due to poor maintenance and weak oversight.

Another major finding concerns the limitations of judicial remedies. While compensation for victims signifies acknowledgment of state responsibility, it remains a reactive measure rather than a preventive one. The absence of a comprehensive anti-torture law and independent investigative agencies means that accountability mechanisms remain fragmented and ineffective.

Comparative analysis with countries such as the United Kingdom and South Africa shows that statutory reforms, independent oversight authorities, and mandatory recording of interrogations significantly reduce custodial abuse. These international examples underscore the need for India to complement judicial activism with legislative codification and institutional reform.

In conclusion, the findings affirm that while judicial responses have laid the normative and moral foundation against custodial violence, real change requires a multi-dimensional strategy. Sustainable policing must combine judicial



vigilance with legislative action, administrative autonomy, technological transparency, and ethical reorientation of the police force. Only such an integrated approach can bridge the gap between legal ideals and practical justice, ensuring accountability and human dignity within India's custodial system.

7. Discussion

Indian courts have really led the way in defining and protecting human rights when it comes to violence in police custody. By how they've interpreted Article 21 of the Constitution, they've made it clear that the right to life includes the right to live with dignity and not be tortured. Big cases like *D.K. Basu v. State of West Bengal* (1997) and *Nilabati Behera v. State of Orissa* (1993) show how the courts have moved from just following the letter of the law to really focusing on human rights. These judgments acknowledged how widespread torture is in custody and made constitutional rights actually mean something by requiring certain procedures and awarding compensation when the state causes harm.

But even with the courts setting a good example, violence in custody is still a big, ongoing issue. This shows that there are limits to what the courts can do to make sure their decisions are followed. Court rulings, even when good, often just state what should be done because there's no way to enforce them, the government is slow to act, and there's political meddling. The courts have said over and over that the police, who are supposed to protect the law, can't break it themselves. But because they can get away with it, abuse in custody continues. The fact that torture still happens, even years after the *D.K. Basu* case, shows that there's a real problem between what the law says and how things actually work in India's police system.

Another key thing to talk about is how the courts have gone from just making judgments to pushing for change. They've not only explained what the Constitution means but also given instructions for changing policies and institutions. The *Prakash Singh v. Union of India* (2006) judgment is a big one here, with its instructions on police independence, set terms for officers, and the creation of State Security Commissions and Police Complaints Authorities. Even with all this, most states haven't fully followed through, which shows that there's a lack of political will and government responsibility. This means that court orders need strong support from lawmakers and the government to really make a difference.

Also, the courts have realized that we need things like technology and better procedures to stop abuse in custody. In *Paramvir Singh Saini v. Baljit Singh* (2020), the Supreme Court ordered that CCTV cameras be installed in all police stations and places where people are held. This is supposed to make things more transparent and discourage illegal actions. But reports from different states show that this isn't always happening, often because there isn't enough money, things aren't maintained well, and there's no independent oversight. So, the court's focus on using technology to make things transparent needs to be backed up by laws and government supervision.

The courts have also worked to deal with compensation and responsibility. By developing the idea of public law compensation, they've made sure that people who are tortured in custody, or their families, get some kind of payment for the violation of their rights. But while this is important, it's just a reaction to what's already happened. Without ways to prevent abuse—like early warning systems, internal checks, and independent investigations—these payments don't really get rid of the culture of impunity that allows custodial violence to continue.

So, this shows that there are two problems: the courts have been active in creating a strong set of human rights laws, but the lack of real change in police institutions has weakened the impact of these laws. For India to go beyond just court decisions and make real change, reforms need to include clear laws, government responsibility, open technology, and ethical behaviour. It's from this that the idea of a sustainable police system comes—a system designed to make sure that protecting human rights is the basis of law enforcement, not something that gets lost along the way.

Sustainability connected with police system

To build a police system in India that lasts, we need to rethink how law enforcement works. It's about balancing power with responsibility, getting the job done with understanding, and following the rules while being ethical. A police system that lasts isn't just about how it's run; it's a basic promise of our Constitution. It comes from the ideas of fairness, equality, and respect that are written in our Constitution. To make this shift, we need to fix things in four main areas: the laws, how the police are run, the tech they use, and their ethics.



Legal Reforms

The first step in a police system that is reliable is to have strong laws that clearly say that torture by police is a crime. Even though India has signed an agreement against torture with the United Nations, we still don't have a specific law against it, which is a big problem. We need a strong Anti-Torture Act that defines what torture is, makes superiors responsible for what their officers do, and makes sure that there are independent investigations and prosecutions when it happens. The law should also protect people who report torture, make sure victims get paid and helped to recover, and require that all deaths in police custody are reported. Also, guidelines from court cases should be written into law so that everyone follows the same rules across the country. This would make the rules clearer, make people more responsible, and show that India is serious about human rights.

Administrative Reforms

It's important to restructure how the police are run to make sure they last and are open about what they do. We need independent groups to handle complaints against the police, both at the state and local levels. These groups need to have the power to investigate wrongdoing and violence in custody and take action. Police officials should have fixed terms in their jobs to reduce political interference. How well they do their jobs should be based on their behaviour, discipline, and respect for human rights, not just on how many cases they close or how many confessions they get. Also, having special human rights units within police departments could help keep an eye on things, investigate problems within the department, and make responsibility a normal part of how things are done, instead of something forced from the outside.

Oversight on Technology

Technology can really help make sure the police are open, responsible, and that things can be traced back to who did them, especially in custody. The Supreme Court has said that there must be cameras in all police stations and lock-ups. This should be turned into a nationwide system of digital oversight. Systems that monitor things in real-time, digital records of who is in custody, and cameras worn by officers during arrests can create records that can be checked and discourage abuse. Systems that use could help spot patterns of behaviour that are suspicious, and digital records of interrogations make sure that people can be held responsible for what they do. But these tech tools must be used with care to protect privacy and with court supervision to prevent them from being misused.

Training in Ethics and Human Rights

The most important thing is to change how police officers think to see policing as a service to the public, not just a way to use force. Training programs in human rights, understanding, how to handle stress, and communication skills should be part of every officer's training. The training should focus on following the law and understanding and believing in the values of the Constitution. gender sensitivity, working with the community, and ways to interrogate people without violence can help build trust and respect between the police and the community. Good behaviour should also be encouraged through performance reviews and awards that reward honesty and treating people well.

In short, a police system that lasts is one that balances the power of the law with a sense of right and wrong but. It's a system where the law applies not only to the people but also to those who are supposed to what? enforce the law. Getting to a system like that requires the courts, government, and the people to all work together. When policing is guided by good ethics, responsibility, and respect for others, India will not only keep its promise written in the Constitution but also gain back the trust in its justice system. A police system that lasts is not just something that is useful, is a real example of democracy in action.

8.Limitations

As a doctrinal study, the research is limited by its reliance on secondary data. It does not include field interviews or statistical analysis. However, this limitation is mitigated by the depth of legal materials and the comparative insights drawn from international jurisdictions, ensuring analytical rigor and practical relevance

9.Conclusion

In India, judicial responses to custodial violence have significantly contributed to the elaboration of human rights jurisprudence and realization of constitutional guarantees. The Indian judiciary, via a progressive interpretation of Article 21 of the Constitution has been able to turn the right to life and personal liberty into a bulwark against not just torture or inhumane treatment, but also arbitrary deprivation of dignity. In *D.K. Basu v. State of West Bengal* (1997) and



Nilabati Behera v. State of Orissa (1993), the Supreme Court held that custodial torture is a breach, not simply a physical breach, because it undermines the very premise of constitutional democracy. These decisions originated procedural safeguards in the person's arrest or detention, brought accountability systems in the cases of custodial torture, and helped to develop the theory of public law compensation for victims of the state, in hopes of mediating against the abuse of state power.

While these judicial precedents have made some progress, the endurance of custodial torture and custodial deaths expose the vast amount of space between judicial pronouncements and lived realities. Courts have laid down the law, and they have been very clear, but a lack of legislative frameworks, the inertia of institutions, and a lack of independence when there has been change, creates a lack of clarity and mitigates the practical impacts of judgments. The judiciary can make interpretations and directions, but, without parallel change in the policing, system of prison administration, or the administration of criminal justice, the directions will not yield those sustainable outcomes that would allow for improvement of policing and criminalizing some behaviours which warrants custodial treatment. The problem of custodial violence condition remains, be it in police reforms, poverty reduction, or criminal justice system reform.

10.Future Scope

Future research should focus on empirical assessment of judicial directive implementation across states, explore restorative justice models for institutional accountability, and study the integration of mental health and stress management for police officers. Comparative analyses with countries like the UK and South Africa could also guide India in framing a comprehensive anti-torture regime.

References

1. Baxi, U. (1982). How India's legal setup started falling apart. Published by Vikas.
2. Gaur, K. D., 2016, Criminal Law - Examples & Resources, published by LexisNexis.
3. Human Rights Watch. (2021). Tied Through Loyalty: Abuse and Killings Inside Police Custody Across India.
4. Kumar, R. (2023). Changes in jail systems along with safeguarding rights in India. Indian Journal of Law and Justice, 14(2), 55–76.
5. Law Commission of India. (2017). 273rd Report on how to put into action the UN anti-torture treaty.
6. Mukherjee, A. (2022). How courts handle deaths in custody - A close look. NUJS Law Review, 15(1), 33–59.
7. National Human Rights Commission (NHRC), 2023 - Yearly Review of Jail-Related Fatalities and Law Enforcement Oversight.
8. Nilabati Behera versus the government of Orissa, a court case from 1993 found in volume 2 at page 746 of the Supreme Court Cases.
9. D.K. Basu versus West Bengal case, decided in 1997, reported in volume one of Supreme Court Cases at page 416.
10. Prakash Kadam versus Ramprasad Vishwanath Gupta, 2011, volume 6, page 189 of Supreme Court Cases.
11. Paramvir Singh Saini versus Baljit Singh, decided in 2020, reported in volume 3 of the Supreme Court Cases at page 588.
12. Rao N along with Singh P published a piece in 2020 titled Judicial Activism and Custodial Accountability found in volume 47 issue 3 of the Indian Bar Review ranging from page 120 up to 141.
13. Custodial violence in India: Legal gaps and the quest for police accountability. (2025). *Law Journals Net*, Vol.7 Issue 2. Retrieved from <https://www.lawjournals.net/assets/archives/2025/vol7issue2/7059.pdf> *Law Journals*
14. Prevention of custodial violence in India and the role of legal mechanisms. (2025). *IJCRT*. Retrieved from <https://www.ijcrt.org/papers/IJCRT2505851.pdf>
15. Amnesty International. (2017). India: “Denied”: Failures in Accountability for Torture and Ill-treatment by Police.



DOIs:10.2015/IJIRMF/ICICSF-2025-P20

--:--

Research Paper / Article / Review

International Conference On “Innovative Convergence for Sustainable Future”

Date : 12 - 13 December, 2025

(ICICSF-2025)



Risk and Return in Sustainable Investing: An Empirical Analysis of Indian ESG Mutual Funds

¹ Manas Kumar Kushwaha, ² Dr. Amar Kumar Choudhary

¹ Research Scholar (JRF), University Department of Commerce and Business Management, Ranchi University, Ranchi, Jharkhand, India

² Associate Professor, Head & Dean, University Department of Commerce and Business Management, Ranchi University, Ranchi, Jharkhand, India

¹ Email- kumarmanas1724@gmail.com

Abstract: This study presents a quantitative evaluation of the performance of active and passive Indian Environmental, Social, and Governance (ESG) mutual fund schemes relative to the BSE 100 Total Return Index (TRI) benchmark. Using annualized returns, standard deviation, and beta for nine representative schemes, three established risk-adjusted performance measures the Sharpe Ratio, Treynor Ratio, and Jensen's Alpha are employed to assess managerial effectiveness and the impact of cost structures over the study period. The analysis reveals a systematic and substantial effect of expense ratios on investor outcomes. Across all examined funds, Direct Plans consistently delivered superior risk-adjusted returns, reflected the higher Sharpe and Treynor Ratios, in comparison to their Regular Plan. In many cases, the higher cost burden of Regular Plans fully absorbed the value generated by the portfolio manager, resulting in negative Jensen's Alpha and illustrating the extent to which distribution fees decline the performance. Results also indicate significant heterogeneity in active managerial skill. The ICICI Prudential ESG Fund emerged as the top performer, with its Direct Plan generating a positive Alpha of 6.50%, demonstrating superior stock selection and portfolio management. Conversely, the Mirae Asset Nifty 100 ETF produced a negative Alpha, consistent with its passive structure, tracking error, and expense drag. Overall, the evidence confirms that while certain active ESG managers successfully create alpha, this value accrues fully to investors only through Direct Plans. These findings underscore the primacy of cost efficiency in ESG fund selection and strongly support prioritizing Direct Plans to mitigate value erosion, enhance risk-adjusted returns, and optimize long-term investment outcomes in the Indian ESG mutual fund market.

Key Words- ESG, ESG Funds, Sustainable Investing, ESG Mutual Funds, Risk-Adjusted Performance, Sharpe Ratio, Treynor Ratio, Jensen's Alpha.

1. INTRODUCTION:

The global investment landscape is witnessing a major shift as environmental, social, and governance (ESG) factors move from being a niche concern to becoming a keystone of financial strategy. Around the world, investors are increasingly viewing corporate sustainability not only as a moral responsibility but also as an essential driver of long-term value creation. This shift has fuelled the rapid expansion of sustainable finance, with ESG-focused mutual funds emerging as a preferred route for both retail and institutional investors seeking to align their portfolios with ethical and sustainability objectives. In India one of the fastest-growing economies with ambitious sustainability targets ESG investing is gaining strong traction and evolving into a significant trend. ESG is a philosophy that includes environmental, social, and governance factors in business and investment decisions. It originated from the term “responsible investment”. Environmental, Social, and Governance (ESG) investing also known as sustainable investing or Socially Responsible Investment is an approach that channels funds into companies committed to ethical practices as well as financial performance. Under ESG criteria, firms are assessed on their environmental stewardship, their contributions to social welfare, and their adherence to strong management and corporate governance standards (Ibef,



2024). Investors who prioritize ESG standards typically avoid investing in companies that do not meet defined environmental, social, or governance benchmarks. For instance, they may exclude chemical producers linked to severe pollution or businesses known for unethical labour practices. This paper seeks to examine the performance of Indian ESG mutual funds by comparing their risk-adjusted returns with those of traditional market benchmarks. Using established measures such as Sharpe Ratio, Treynor Ratio and Jensen's Alpha, with aims to deliver an evidence-based assessment.

1.1 SUSTAINABLE INVESTING:

Sustainable investing seeks to first generate financial returns like traditional investing and support positive impact in society by investing in companies that are environmentally responsible, socially conscious and well governed. In other words, Sustainable investing is an investment strategy that considers both financial performance and the wider effects of investments on society and the environment. This approach incorporates environmental, social, and governance (ESG) criteria into decision-making to encourage responsible corporate behaviour and support long-term value generation. The Global Sustainable Investment Alliance (GSIA) defines sustainable investment as an investment approach that considers environmental, social, and governance (ESG) factors in portfolio selection and management. The term ESG considerations are integrated to identify opportunities and risks, aiming to align financial goals with broader societal values and sustainable outcomes. One of the core claims of sustainable investing is that it encourages companies to adopt more sustainable practices, thereby generating beneficial outcomes for both the environment and society (Marti et al., 2023). Sustainable investing methods have shifted over time. While traditional ethics-based tactics such as negative screening remain common, newer strategies now emphasize improving risk-adjusted returns rather than relying solely on ethical considerations. (Bernow et al., 2017). Modern sustainable investing covers all asset classes and regions, building on its ethical and socially responsible roots while integrating financial returns with global economic, environmental, and social challenges (Krosinsky et al., 2012). Long-term value-oriented investing involves a strategy designed to align with the Sustainable Development Goals (SDGs). This approach assumes that the UN 2030 Agenda for Sustainable Development (UN, 2015) will be partially realized, making the SDGs a pertinent consideration for the long-term perspective of both companies and investors (Schoenmaker, D. 2018).

➤ Key drivers of Sustainable Investing:

Sustainable investing, also known as ESG investing, has grown from a niche strategy into a significant force in the financial world. Its rise is driven by a combination of factors, including changing investor preferences, market dynamics, and a shifting regulatory landscape.

- **Growing Investor Demand:** Many investors especially those from younger generations seek to align their financial choices with their personal values on environmental and social matters.
- **Stronger Financial Performance:** Growing evidence indicates that firms demonstrating robust ESG practices tend to achieve stronger long-term financial performance and show greater resilience to various risks.
- **Regulatory Pressure:** Governments and global organizations are introducing policies and regulations that encourage sustainable business practices, motivating both companies and investors to incorporate ESG principles.
- **Increased Data and Transparency:** Improved access to ESG data and ratings enables investors to more effectively assess and compare the sustainability performance of various companies.

1.2 ESG INVESTING IN INDIA:

ESG investing refers to an investment strategy that evaluates companies not only on traditional financial metrics but also on their performance across Environmental, Social, and Governance (ESG) dimensions. It is also known as sustainable, socially responsible, or impact-oriented investing. The ESG framework encompasses three core dimensions. **Environmental (E)** evaluates an organization's impact on and stewardship of the natural environment, including carbon emissions, resource efficiency, renewable energy use, pollution control, and deforestation policies. **Social (S)** assesses how the company engages with employees, suppliers, customers, and communities, considering labour standards, human rights, diversity and inclusion, data privacy, and community development. **Governance (G)** examines leadership and decision-making structures, including board composition, executive compensation, transparency, internal controls, shareholder rights, and anti-corruption measures. At a broad level, ESG investing can be divided into three primary approaches, each with its own goal. The first is ESG integration, which focuses on enhancing a portfolio's risk-return



profile by incorporating environmental, social, and governance factors into investment decisions. The second is values-driven investing, where investors align their holdings with their personal ethics, principles, or beliefs. The third is impact investing, which aims to deploy capital to drive positive social or environmental change such as supporting initiatives that speed up the transition to a low-carbon economy (Giese et al., 2019). The rapid expansion and global success of ESG investing have significantly influenced the Indian market. Over the past four years, Assets under Management (AUM) have nearly doubled, reaching approximately \$40.5 trillion in 2020. Since the launch of the Nifty 100 ESG Index in 2011, it has consistently surpassed the performance of its benchmark, delivering returns of 10.6% compared with 9.1% from the conventional Nifty 100 Index. This trend highlights the increasing interest and participation of Indian investors in ESG-focused investments (Seth et al., 2021).

➤ **EVOLUTION OF ESG INVESTING IN INDIA:** There are several factors that have contributed to the expansion of ESG investment in India. These factors are as follow-

- **Commitment to Green Growth:** In line with the 2015 Paris Agreement, India's NDCs for 2021–2030 estimate an investment need of about US \$2.5 trillion, underscoring its pursuit of sustainable, low-carbon development and the SDGs.
- **Global Capital Inflows:** ESG-oriented international funds are steadily increasing their exposure to Indian equities; GSIA reports that 41 such funds now allocate roughly 25% of assets to Indian stocks, indicating growing investor interest.
- **Rising Domestic Interest:** Indian institutions such as SBI, Quantum, and Kotak Mahindra are expanding their ESG offerings and aligning with the UN Principles for Responsible Investment.
- **Policy and Regulatory Support:** India has introduced reforms to promote renewable energy, strengthen corporate ethics, and improve mandatory and voluntary ESG disclosures.
- **Growth of ESG Indices:** New benchmarks including the S&P BSE Greenex, S&P BSE Carbonex, S&P BSE 100 ESG Index, NIFTY 100 ESG Index, and NIFTY 100 Enhanced ESG Index to track and evaluate corporate ESG performance.

➤ **ESG POLICY REFORMS IN INDIA:**

- **2008 – First ESG Index:** CRISIL, with S&P and KLD Research, launched the S&P ESG India Index as the country's first investable ESG benchmark.
- **2009–2011 – Policy Guidelines:**
2009: MCA released India's first CSR guidelines.
2010: DPE issued CSR rules for CPSEs.
2011: MCA introduced National Voluntary Guidelines (NVGs) and mandated Business Responsibility Reports (BRR).
- **2013 – MSCI ESG Index:** MSCI launched the India ESG Leaders Index.
- **2014 – Companies Act:** Section 135 mandated eligible companies to allocate at least 2% of average profits to CSR activities.
- **2015 – Priority Sector Lending:** RBI added renewable energy and social infrastructure to banks' priority sector lending.
- **2018 – Green Bonds:** SEBI issued national guidelines for green bonds, making India the second country globally with such regulations.
- **2019 – Updated NVGs:** MCA revised the NVGs into the National Guidelines on Responsible Business Conduct (NGRBC) aligned with SDGs and UNGP principles.
- **2021 – BRSR Framework:** SEBI mandated the top 1,000 listed firms to disclose sustainability practices under the Business Responsibility and Sustainability Reporting format.
- **2023 – New ESG Fund Categories:** SEBI allowed mutual funds to introduce six ESG strategies—Exclusion, Integration, Best-in-Class, Impact Investing, Sustainable Objectives, and Transition-related approaches.

2. REVIEW OF LITERATURE:

1. **Singh et al. (2023):** They highlight the core issues regarding ESG mutual funds that ESG mutual funds in India face several challenges, including a lack of standardized, credible data, limited track records, and underperformance, which complicates comparisons and verification. Investor conservatism and insufficient technical expertise within the financial sector further slow the adoption of ESG investments in the country
2. **Vishali and MK (2024):** They indicate that ESG mutual funds in India are ESG mutual funds in India are growing slowly due to investor caution. Performance metrics show ICICI Prudential ESG Fund as the strongest



performer and Aditya Birla Sun Life ESG Fund as the weakest. SEBI's Social Stock Exchange (SSE) also promotes impact investing by providing a regulated platform for social enterprises to raise capital.

3. **Banu et al. (2021):** They did their study on A study on SBI's ESG mutual funds found that the SBI Magnum Equity Fund targets long-term gains through ESG-compliant investments. Its AAUM rose from ₹1,601.80 crore to ₹2,690.30 crore over five years, reflecting 13.59% annual growth. Strengthening its portfolio and sectoral analysis could help attract more investors.
4. **Hauff and Nilsson (2022):** Their study found investors prefer inclusion-based ESG strategies, valuing companies with strong ESG practices mainly for their perceived financial quality. In-house ESG expertise further boosts confidence, signalling financial strength. Overall, investor perceptions of ESG funds are shaped more by expected financial performance than by sustainability alone.
5. **Abate et al. (2021):** Their study on 634 European mutual funds investigated whether funds with high ESG ratings perform better than those with low ratings. The research found that high-ESG-rated funds are more efficient, outperforming funds with low ESG ratings when considering factors like risks and costs. This suggests that incorporating ESG criteria can lead to superior fund performance.
6. **Dikolli et al. (2022):** The study found that ESG funds, particularly index-based ones, are significantly more inclined than non-ESG funds to vote in favor of environmental, social, and governance proposals. This pattern suggests a stronger commitment to sustainability and provides evidence countering claims of greenwashing, with shareholder voting emerging as a key indicator of genuine ESG engagement.
7. **Jin, I. (2018):** Their study evaluates responsible investing (RI) using a modified Fama-French five-factor model on 1,425 US equity funds from 2009 to 2016. It finds that RI funds hedge against ESG-related systematic risk, which is significantly priced in the market, and provide downside protection that cannot be achieved through diversification alone.
8. **Raghunandan and Rajgopal (2022):** The study of US ESG funds (2010–2018) found many failed to meet stated ESG goals, holding poorly compliant firms and investing in high-emission companies. They also underperformed financially and charged higher fees, reflecting reliance on voluntary disclosures over actual compliance.
9. **Folqué et al. (2021):** Their study found that advanced sustainable investment (SI) strategies reduce ESG and carbon risks more effectively than older methods such as negative screening. By emphasizing positive impact and improved data, these strategies help fund managers meet regulations, enhance competitiveness, and support genuine sustainable development.
10. **Yue et al. (2020):** Their study analysing data from December 2014 to December 2018 and found that sustainable funds carried lower risk but did not consistently outperform traditional funds. While they performed better during periods of high volatility, no clear advantage appeared in risk-taking markets. The results suggest no overall dominance of sustainable funds, with the Fama–French three-factor model best explaining their returns.

2.1 NEED FOR THE STUDY:

Although global and domestic interest in sustainable finance is rising, empirical research on India's ESG mutual funds remains limited. Most existing studies focus on Europe and the US and offer mixed findings, some highlight better efficiency and downside protection, while others show underperformance and higher fees. This study fills a major gap in assessing the risk-adjusted performance of Indian ESG funds by applying Sharpe, Treynor, and Jensen's Alpha to measure managerial efficiency. It focuses on the market-wide disparity between Direct and Regular plan returns, isolating the impact of higher expense ratios on investor outcomes. The findings provide evidence to inform fund selection and support strategies for maximizing long-term returns in India's evolving ESG investment landscape.

3. OBJECTIVE OF THE STUDY:

- To empirically assess and quantify the true performance efficiency of Indian ESG Equity Mutual Funds by comparing their risk-adjusted returns against the BSE 100 TRI benchmark, utilizing the Sharpe Ratio, Treynor Ratio, and Jensen's Alpha.
- To compare the performance differential between the Direct Plans and Regular Plans of Indian ESG funds, highlighting the impact of expense ratios on risk-adjusted returns.



4. RESEARCH METHODOLOGY:

This study employs a quantitative and comparative research design to analyse the financial performance of 9 Indian ESG Mutual Funds using three-year annualized performance data as of August 31, 2025. The research based on secondary data, including the Net Asset Values (NAV) of selected funds from official websites of AMCs and financial data portal like Value Research Online, market index values, and the risk-free rate, collected for a specified period. The analysis will be conducted by using key risk-adjusted performance metrics, namely the Sharpe ratio, Treynor ratio, and Jensen's alpha with the focuses on comparing the returns and risk-efficiency of Direct versus Regular plans against the BSE 100 Total Return Index (TRI) benchmark.

Performance Metrics: This study employs three key risk-adjusted performance metrics to evaluate the efficiency and managerial skill of the ESG mutual funds:

I. **Sharpe Ratio:** Measure the funds excess return for the total risk taken (volatility).

$$\text{Sharpe Ratio} = \frac{R_p - R_f}{\sigma_p}$$

II. **Treynor Ratio:** Measure the funds excess return for the systematic (market) risk take.

$$\text{Treynor Ratio} = \frac{R_p - R_f}{\beta_p}$$

III. **Jensen's Alpha:** Measure the fund managers ability to generate above the market expected return for a given level of systematic risk.

$$\text{Jensen's Alpha} = R_p - [R_f + \beta_p(R_m - R_f)]$$

Where:

- R_p = Annualized Return of the fund
- R_f = Risk-Free Rate (5.57% NIFTY 182 Day T-Bill Index)
- R_m = Market Return (13.41% BSE 100 TRI)
- σ_p = Annualized Standard Deviation of the fund
- β_p = Beta of the fund

5. DATA ANALYSIS:

Table 1: Details of ESG Equity Funds (As on 31-Aug-2025)

Fund Name	Net Assets (Cr.)	Expense Ratio (%)	Top Three Holdings	Top Three Sectors
SBI ESG Exclusionary Strategy Fund	₹5,605 Cr	1.94%	HDFC Bank, ICICI Bank, Infosys	Financial, Consumer Discretionary, Technology
ICICI Prudential ESG Exclusionary Strategy Fund	₹1,477 Cr	1.01%	ICICI Bank, Sun Pharmaceutical, Bharti Airtel	Financial, Technology, Consumer Discretionary
Axis ESG Integration Strategy Fund	₹1200 Cr	1.34%	ICICI Bank, HDFC Bank, Bharti Airtel	Financial, Technology, Consumer Discretionary
Kotak ESG Exclusionary Strategy Fund	₹850 Cr	0.88%	HDFC Bank, Bharti Airtel, Eternal	Technology, Financial, Consumer Discretionary
Aditya Birla Sun Life ESG Integration Strategy Fund	₹605 Cr	1.44%	ICICI Bank, HDFC Bank, Kotak Bank	Financial, Technology, Consumer Discretionary



Invesco India ESG Integration Strategy Fund	₹453 Cr	0.98%	HDFC Bank, ICICI Bank, Infosys	Financial, Technology, Consumer Discretionary
Quant ESG Integration Strategy Fund	₹273 Cr	0.92%	Bajaj Auto, DLF, Zydus Wellness	Financial, Healthcare, Consumer Discretionary
Quantum ESG Best In Class Strategy Fund	₹106 Cr	0.75%	TVS Motor, The Indian Hotels, HDFC Bank	Consumer Discretionary, Financial, Consumer Staples
Mirae Asset Nifty 100 ESG Sector Leaders ETF	₹97 Cr	0.06%	ICICI Bank, HDFC Bank, Reliance Industries	Financial, Energy and Utilities, Technology

Source: Author's Own Compilation (based on data obtained from <https://valueresearchonline.com>)

The data in the table 1 show that Indian ESG funds vary in size but are largely similar in strategy. SBI's ESG Exclusionary Strategy Fund is the largest, while smaller passive funds like the Mirae Asset Nifty 100 ESG Sector Leaders ETF offer lower expense ratios. Portfolio analysis reveals significant overlap most hold ICICI Bank and HDFC Bank and are concentrated in Financials, Technology, and Consumer Discretionary sectors indicating a limited investment universe dominated by a few large-cap companies.

Table 2: Key Variables for Performance Analysis

Fund Name	Annualized Return (Direct Plan) (%)	Annualized Return (Regular Plan) (%)	Annualized Standard Deviation (%)	Beta (β)	Risk-Free Rate (%) *
SBI ESG Exclusionary Strategy Fund	12.88	12.25	11.91	0.91	5.57
ICICI Prudential ESG Exclusionary Strategy Fund	19.05	17.83	12.21	0.89	5.57
Axis ESG Integration Strategy Fund	12.63	11.59	12.44	0.88	5.57
Kotak ESG Exclusionary Strategy Fund	14.58	13.01	12.12	0.93	5.57
Aditya Birla Sun Life ESG Integration Strategy Fund	13.67	12.45	12.93	0.94	5.57
Invesco India ESG Integration Strategy Fund	13.64	12.13	12.71	0.92	5.57
Quant ESG Integration Strategy Fund	15.39	13.73	16.41	1.09	5.57
Quantum ESG Best In Class Strategy Fund	13.43	12.30	12.46	0.94	5.57
Mirae Asset Nifty 100 ESG Sector Leaders ETF	12.14	12.20	12.44	0.98	5.57

Source: Author's Own Compilation (based on data obtained from <https://valueresearchonline.com>)

*(Risk-Free Rate value taking from **NIFTY 182 Day T-Bill Index**)

DATA INTERPRETATION (Table 2): The data highlight several notable patterns. Direct plans consistently deliver higher returns than regular plans across all funds, reflecting the drag of higher expense ratios in regular plans. Despite this, annualized standard deviation and beta remain identical between plan types, confirming that the portfolios carry the same underlying risk and that performance differences arise solely from costs.



At the fund level, ICICI Prudential ESG Fund reports the strongest annualized returns across both plans. Quant ESG Fund records the highest risk profile (SD 16.41%, beta 1.09), making it the most volatile and more exposed to market fluctuations. By contrast, the Mirae Asset ETF shows the lowest annualized returns, typical of a passive, low-cost fund; its beta of 0.98 closely mirrors the market benchmark. The risk-free rate of 5.57%, derived from the NIFTY 182-Day T-Bill Index, is uniform across all observations.

Table: 3 Performance Variables for the BSE 100 TRI Benchmark

Benchmark Name	Annualized Return (%)	Annualized Standard Deviation (%)	Beta (β)	Risk-Free Rate (%) *
BSE 100 TRI	13.41	12.49	1	5.57

Source: Author's Own Compilation (based on data obtained from <https://valueresearchonline.com>)

*(Risk-Free Rate value taking from **NIFTY 182 Day T-Bill Index**)

DATA INTERPRETATION (Table 3):

➤ Performance Comparison

The BSE 100 TRI benchmark, with an annualized return of 13.41%, provides the reference point for this analysis. Most ESG funds exceeded this threshold such as ICICI Prudential ESG Fund (Direct Plan) at 19.05% and Kotak ESG Fund at 14.58%. However, not all performed as strongly; for instance, SBI ESG Fund (Direct Plan) returned 12.88%, slightly below the benchmark. The consistent gap between Direct and Regular plan returns highlights how expense ratios directly influence net gains.

➤ Risk Analysis:

The benchmark's standard deviation of 12.49% and beta of 1.00 represent average market risk.

- **Higher Risk, Higher Return:** Quant ESG Fund shows the highest risk profile, with a standard deviation of 16.41% and beta of 1.09, paired with a return of 15.39%, reflecting its more aggressive strategy.
- **Lower Risk, High Return:** Funds like ICICI Prudential (beta 0.89) and Axis ESG (beta 0.88) achieved above-market returns while taking on less risk, indicating more efficient risk-adjusted performance.
- **Index Tracking:** Mirae Asset ETF, with a beta of 0.98, closely mirrors the benchmark's volatility, aligning with its passive investment mandate.

Table 4: Risk-Adjusted Performance Comparison of ESG Regular and Direct Plans

Fund Name	Sharpe Ratio (Direct)	Sharpe Ratio (Regular)	Treynor Ratio (Direct)	Treynor Ratio (Regular)	Jensen's Alpha (Direct)	Jensen's Alpha (Regular)
SBI ESG Exclusionary Strategy Fund	0.61	0.56	8.03	7.3	0.18	-0.45
ICICI Prudential ESG Exclusionary Strategy Fund	1.104	1.004	15.14	13.8	6.50	5.28
Axis ESG Integration Strategy Fund	0.57	0.48	8.02	6.8	0.16	-0.88
Kotak ESG Exclusionary Strategy Fund	0.74	0.61	9.6	8	1.72	0.15



Aditya Birla Sun Life ESG Integration Strategy Fund	0.63	0.53	8.62	7.32	0.73	-0.49
Invesco India ESG Integration Strategy Fund	0.63	0.52	8.8	7.13	0.86	-0.65
Quant ESG Integration Strategy Fund	0.60	0.50	9	7.5	1.27	-0.39
Quantum ESG Best In Class Strategy Fund	0.63	0.54	8.4	7.2	0.49	-0.64
Mirae Asset Nifty 100 ESG Sector Leaders ETF	0.53	0.53	6.7	6.8	-1.11	-1.05

Source: Author's Own Compilation (Based on the data of Table 2)

DATA INTERPRETATION (Table 4):

i. Effect of Cost Structure: Direct vs. Regular Plans

Expense ratios emerge as a decisive factor in risk-adjusted outcomes. Across all funds, Direct Plans consistently outperform Regular Plans, showing higher Sharpe, Treynor, and Jensen's Alpha values. This gap is especially visible in Jensen's Alpha, for example, ICICI Prudential ESG Fund's Direct Plan posted 6.50% versus 5.28% for its Regular Plan, directly illustrating the cost premium investors pay for Regular Plans. Several active funds, including SBI ESG, Axis ESG, and Quant ESG, even show negative Alpha in their Regular Plans, indicating they failed to match the market after accounting for risk.

ii. Risk-Adjusted Performance Ranking

The ratios make it possible to rank funds by efficiency:

iii. Key Insights

- **Top Performer:** ICICI Prudential ESG Fund leads across all three metrics, showing strong returns with effective risk control.
- **High Risk, Lower Efficiency:** Quant ESG Fund produced high returns but weaker Sharpe and Treynor ratios, suggesting its gains came mainly from higher risk exposure (Beta 1.09) rather than manager skill.
- **Passive Fund Benchmarking:** Mirae Asset Nifty 100 ETF posted the lowest Alpha (Direct: -1.11%; Regular: -1.05%), reflecting its passive strategy and expected tracking differences.

Metric	Leading Fund (Direct Plan)	Value	Interpretation
Sharpe Ratio (Total Risk)	ICICI Prudential ESG Fund	1.10	Best return per unit of total risk
Treynor Ratio (Systematic Risk)	ICICI Prudential ESG Fund	15.15	Best return per unit of market risk
Jensen's Alpha (Manager Skill)	ICICI Prudential ESG Fund	6.50%	Outperformed market expectations by 6.5 percentage points

Table 5. Performance Ratios of the BSE 100 TRI Benchmark

Benchmark Name	Sharpe Ratio	Treynor Ratio	Jensen's Alpha
BSE 100 TRI	0.63	7.84	0.00

Source: Author's Own Compilation (Based on the data of Table 3)

DATA INTERPRETATION (Table 5): Using the BSE 100 TRI as the benchmark, the ratios show clear differences in risk-adjusted performance across ESG funds.



Sharpe Ratio (Total Risk): With a benchmark of 0.63, ICICI Prudential (1.10), Kotak ESG (0.74), and Aditya Birla Sun Life ESG (0.63) exceeded the market's efficiency, while Axis (0.57), Quant (0.60), and Mirae Asset ETF (0.53) lagged.

Treynor Ratio (Systematic Risk): Against the benchmark of 7.84, ICICI Prudential (15.15), Kotak (9.69), and Quant ESG (9.01) stood out, while Mirae Asset ETF (6.70) fell short.

Jensen's Alpha (Manager Skill): Direct Plans consistently posted positive alphas of ICICI Prudential ESG Fund led with 6.50% showing clear risk-adjusted outperformance. Regular Plans and the passive Mirae Asset ETF produced negative alphas, reflecting higher costs or tracking error.

Overall Insight: ICICI Prudential ESG Fund emerged as the strongest performer, but the advantage was concentrated in Direct Plans. Higher expense ratios in Regular Plans consistently lead to low risk-adjusted returns, underscoring the value of Direct Plans for better long-term, risk-adjusted outcomes.

6. DISCUSSION OF FINDINGS:

➤ Impact of Distribution Costs: Direct vs. Regular Plans

The most consistent outcome of this study is the clear negative effect of distribution commissions on investor returns. Across all funds, Direct Plans outperformed Regular Plans on the Sharpe Ratio, Treynor Ratio, and Jensen's Alpha. This performance gap stems solely from the higher expense ratios charged in Regular Plans. For example, the ICICI Prudential ESG Fund showed an Alpha of 6.50% in its Direct Plan compared to 5.28% in the Regular Plan—a difference that directly reflects the cost of distribution. In fact, the added expense pushed several active funds (SBI ESG, Axis ESG, Aditya Birla Sun Life ESG, Invesco India ESG, Quant ESG, and Quantum ESG) into negative Alpha territory under their Regular Plans. This demonstrates that higher costs eroded all managerial value-add, leading to underperformance relative to the market. These findings suggest that Direct Plans are essential for maximizing long-term returns in the Indian ESG mutual fund space.

➤ Evaluating Managerial Skill: Active vs. Passive Funds

Jensen's Alpha provides a measure of managerial effectiveness relative to the market baseline (BSE 100 TRI, $\alpha = 0.00\%$).

- **Clear Outperformance:** The ICICI Prudential ESG Fund, with an Alpha of 6.50%, emerged as the strongest example of active managerial skill, reflecting superior stock selection and timing.
 - **Marginal Gains:** Other active funds, though positive in their Direct Plans (e.g., SBI ESG at 0.18%, Axis ESG at 0.16%), showed minimal value creation, raising questions about the effectiveness of active management in these cases.
 - **Validation of Passive Funds:** The Mirae Asset Nifty 100 ETF reported a negative Alpha (-1.11%), as expected. This reflects the minor tracking error and expense ratio typical of passive funds, confirming their reliance on broad market performance rather than active management.
- **Risk-Return Trade-Off:** Comparisons with the benchmark's Sharpe Ratio (0.63) and Treynor Ratio (7.84) highlight differences in risk efficiency:
- **Efficient Risk Management:** The ICICI Prudential ESG Fund recorded a Sharpe Ratio of 1.10 and a Treynor Ratio of 15.15, demonstrating superior excess returns relative to both total and systematic risk, and highlighting its strong portfolio efficiency.
 - **Inefficient Risk Exposure:** By contrast, the Quant ESG Fund showed a Sharpe Ratio of 0.60, underperforming the benchmark despite high absolute returns. With a Beta of 1.09 and a Standard Deviation of 16.41%, its results suggest returns were driven largely by excessive volatility rather than efficient portfolio management.
 - **ESG and Performance Efficiency:** The fact that multiple ESG funds (ICICI Prudential, Kotak, Aditya Birla, Invesco) achieved Sharpe Ratios above the market baseline indicates that the ESG focus did not inherently weaken performance. On the contrary, when coupled with effective management, ESG strategies demonstrated the potential to deliver efficient, risk-adjusted returns.



7. SUGGESTIONS:

Based on the quantitative analysis of risk-adjusted performance, the following recommendations are offered for investors, regulators, and fund houses in the Indian ESG mutual fund market:

I. For Investors:

Select Direct Plans: Investors should opt for Direct Plans to capture the full benefit of the fund manager's performance and avoid the value erosion caused by the higher expense ratios of Regular Plans. This approach consistently leads to stronger Sharpe, Treynor, and Alpha scores and improves long-term returns.

Use Risk-Adjusted Measures: Investors should prioritize tools such as Sharpe Ratio and Jensen's Alpha over raw returns. Funds with strong Alpha values (e.g., ICICI Prudential ESG Fund) demonstrate genuine skill and efficient management.

Evaluate Risk-Return Balance: Investors should be cautious with funds exhibiting high Beta and Standard Deviation but weak Sharpe Ratios, as these indicate excessive risk without adequate compensation.

II. For Regulators (SEBI):

Require Alpha Disclosure: Regulators should mandate that all active funds report Jensen's Alpha against a standardized benchmark (such as Nifty 50 TRI or BSE 100 TRI), providing a unified and transparent measure of manager performance.

Increase Cost Transparency: Expense ratio differences between Direct and Regular Plans should be disclosed clearly, showing both rupee and percentage impacts across multiple time horizons to make distribution costs explicit for investors.

III. For Fund Houses and Managers:

Align Fees with Value: Fund houses whose Regular Plans produce negative Alpha should reassess their fee structures or portfolio strategies to justify their charges.

Maximize Risk Efficiency: Managers should focus on improving the Sharpe Ratio delivering higher returns per unit of risk rather than chasing absolute returns that may result from excessive volatility.

8. LIMITATION:

- **Sample Size:** Analysis limited to 9 ESG Equity Funds, restricting the generalizability of the findings to the entire Indian fund industry.
- **Time Horizon:** Based on a 3-year annualized period, which does not capture the long-term stability or potential resilience of ESG funds across full market cycles.
- **Data Focus:** Relied solely on fund-level return data, not the quality or impact of underlying firm-level ESG scores and disclosures (BRSR).

9. CONCLUSION:

This study conducted on a quantitative analysis of Indian ESG mutual funds, seeking to evaluate their performance on a risk-adjusted basis against the BSE 100 TRI benchmark. The findings of this study clear and compelling conclusions regarding both the efficacy of active management within the ESG theme and the critical importance of a fund's expense structure. The analysis reveals that expense ratios are the dominant factor influencing risk-adjusted returns. Across all funds examined, Direct Plans consistently outperformed Regular Plans, posting higher Sharpe and Treynor Ratios as well as stronger Jensen's Alpha scores. This underscores that cost efficiency rather than distribution commissions, is the key driver of investor returns and highlights how higher fees erode performance. Furthermore, Jensen's Alpha further indicates that while a few managers, most notably the ICICI Prudential ESG Fund, generated meaningful excess returns, many active funds failed to consistently beat the market. This demonstrates that the ESG theme alone does not guarantee superior outcomes and that active management skill remains an uneven differentiator. Overall, the findings suggest that investors seeking ESG exposure in India should adopt a data-driven approach emphasizing low-cost, Direct Plans. While some active managers show promise, the most efficient investment path is through a low-cost, direct-to-investor fund that maximizes the investor's final return.

10. ACKNOWLEDGEMENT:

I would like to express my sincere gratitude to my supervisor, **Dr. Amar Kumar Choudhary**, for his invaluable academic guidance and consistent support throughout the course of this research. His extensive subject expertise, critical perspective, and methodological direction played a crucial role in shaping the research design and enhancing



the analytical depth of the study. I am deeply appreciative of his insightful feedback, scholarly recommendations, and continuous encouragement, all of which substantially improved the clarity, quality, and coherence of the manuscript. His mentorship also facilitated a deeper understanding of sustainable finance and its relevance to the analysis of risk and return in Indian ESG mutual funds. I am equally grateful for his patience, academic integrity, and unwavering commitment to excellence, which remained a constant source of inspiration throughout this research journey.

REFERENCES:

1. Abate, G., Basile, I., & Ferrari, P. (2021). The level of sustainability and mutual fund performance in Europe: An empirical analysis using ESG ratings. *Corporate Social Responsibility and Environmental Management*, 28(5), 1446-1455.
2. Banu, A. A. A. S., Bhuvaneswari, T. S., & Begum, K. S. (2021). A study on the sustainable investment funds with special reference to state bank of India esg mutual fund schemes. *Turkish Journal of Computer and Mathematics Education*, 12(6), 261-266.
3. Bernow, S., Klempner, B., & Magnin, C. (2017). From 'why' to 'why not': Sustainable investing as the new normal.
4. Carlsson Hauff, J., & Nilsson, J. (2023). Is ESG mutual fund quality in the eye of the beholder? An experimental study of investor responses to ESG fund strategies. *Business Strategy and the Environment*, 32(4), 1189-1202.
5. Dikolli, S. S., Frank, M. M., Guo, Z. M., & Lynch, L. J. (2022). Walk the talk: ESG mutual fund voting on shareholder proposals. *Review of Accounting Studies*, 27(3), 864-896.
6. Folqué, M., Escrig-Olmedo, E., & Corzo Santamaría, T. (2021). Sustainable development and financial system: Integrating ESG risks through sustainable investment strategies in a climate change context. *Sustainable Development*, 29(5), 876-890.
7. Giese, G., Lee, L. E., Melas, D., Nagy, Z., & Nishikawa, L. (2019). Foundations of ESG investing: How ESG affects equity valuation, risk, and performance. *The Journal of Portfolio Management*, 45(5), 69-83.
8. Ibef. (2024, June 13). ESG Investing in India: Navigating environmental, social and governance factors for Sustainable growth. *India Brand Equity Foundation*. <https://ibef.org/blogs/esg-investing-in-india-navigating-environmental-social-and-governance-factors-for-sustainable-growth>
9. Jin, I. (2018). Is ESG a systematic risk factor for US equity mutual funds?. *Journal of Sustainable Finance & Investment*, 8(1), 72-93.
10. Krosinsky, C., & Robins, N. (Eds.). (2012). *Sustainable investing: The art of long-term performance*. Routledge.
11. Marti, E., Fuchs, M., DesJardine, M. R., Slager, R., & Gond, J. P. (2024). The impact of sustainable investing: A multidisciplinary review. *Journal of Management Studies*, 61(5), 2181-2211.
12. Raghunandan, A., & Rajgopal, S. (2022). Do ESG funds make stakeholder-friendly investments?. *Review of Accounting Studies*, 27(3), 822-863.
13. Schoenmaker, D. (2018). Sustainable investing: How to do it (No. 2018/23). Bruegel Policy Contribution.
14. Seth, R., Gupta, S., & Gupta, H. (2021). ESG investing: a critical overview. *Hans Shodh Sudha*, 2(2), 69-80.
15. Singh, S., Bahl, S., Sharma, J., & Sharma, A. (2023). Performance evaluation of ESG mutual funds in India. *Journal of Survey in Fisheries Sciences*, 10(3S), 1133-1143.
16. Vishali, M., & MK, M. S. (2024). Emerging paradigms in socially responsible investment (SRI)—A study with focus on ESG mutual funds in India. *Environment and Social Psychology*, 9(4), 2006.
17. Yue, X. G., Han, Y., Teresiene, D., Merkyte, J., & Liu, W. (2020). Sustainable funds' performance evaluation. *Sustainability*, 12(19), 8034.



DOIs:10.2015/IJIRMF/ICICSF-2025-P21

--:--

Research Paper / Article / Review

International Conference On “Innovative Convergence for Sustainable Future”

Date : 12 - 13 December, 2025

(ICICSF-2025)



GENDER BAISED LAWS for offences against Body (WSR to Secion 63 of BNS): Need of the hour for sustainable development of society

BHARATIYA NYAYA SANHITA, 2023

¹ Dr. Smita Pandey, Associate Dean of Department of Legal Studies, Jharkhand Rai University²Pragya Karn, Student, LL. B (Hon's), Jharkhand Rai University³ Manisha Kumari, Student, B.A.LL. B (Hons.), Jharkhand Rai UniversityEmail - mns03807@gmail.com

Abstract: This paper provides a brief look at India's current rape laws and also focuses on the need to modify the existing rape laws. Till now, according to our law, in the offence of rape, only males can commit rape and only women can be the victim. But after getting recognition of the third gender, there is a need to reform or modify our current rape law because it leaves a huge group of individuals, men and transgender, without any legal protection, and they become prey of such heinous and undignified offence. India's sexual offences legislation is still mostly gendered, with the victim being designated as female and criminal as male, even with recent modifications under the Bharatiya Nyaya Sanhita, (BNS), 2023 (which superseded the IPC). This gendered approach deprives anyone who is male, transgender, or non-binary of basic legal safeguards against penetrative sexual violence. This work uses judicial trends a socio-legal analysis, and comparative analysis of the laws (IPC, BNS and TPA). The findings revealed structural bias in the application of fines under other statutes (e.g., TPA (Transgender Persons (Protection of Rights) Act, 2019) Section 18(d) maximum punishment is less than IPC offenders while in BNS Clause 64 minimum penalty), violations of Articles 14 and 21 of the Constitution, and a substantial legal void created by repealing IPC Section 377. We acknowledge counter arguments, such as concerns regarding abuse and weakening of protections for female victims, and include answers grounded in constitutional requirements and comparisons with relevant practice models in settings such as the UK and Canada. Our research concludes with focus on a new hybrid legislative reform that would establish a new "Sexual Assault by Penetration" provision as a central victim-neutral offence. It would also include additional restrictions and aligned maximum penalties for all offences to guarantee equity, equal justice, and the protection of everyone's dignity and autonomy in the province. This paper argues that it would be unfair and goes against our Indian constitution, which provides rights to every individual to live a safe and dignified life. In this, we will discuss about why our laws are framed in this way, what the social problems are that prevent them from evolving, and what measures we can take to address these issues.

Key words: Article 14, Article 21, Legal Reform, Sexual Offenses, Gender Neutrality, Bharatiya Nyaya Sanhita, Transgender Rights, and Victimization

1.INTRODUCTION

Our main criminal law, the Bharatiya Nyaya Sanhita, recognizes various offences, including sexual harassment and rape. Section 63 of the Bhartiya Nyaya Sanhita is very specific to a particular gender. This section clearly states that “A man is said to commit rape if he.....” according to this statement, the perpetrator is only male, and the victim can be only



female. Even after some changes were introduced in the law in 2013, this part remained unchanged. Whenever we think about sexual violence, there is an image created in our mind that the perpetrator is always male and the victim is always female. But is it right? Is it not possible that the victim of this terrible offence of rape or sexual violence is a male or transgender person?

The answer is yes, crimes can be committed against any person, regardless of gender. However, our current criminal law doesn't give any protection to men and transgender persons in offenses of sexual assault or rape.

A. Setting the backdrop for Sexual Violence and the Function of Criminal Law

Human dignity, bodily autonomy, and fundamental rights are all gravely violated by sexual violence¹. Ensuring equal protection under the law and providing justice to all citizens, regardless of their sex or gender, is the main goal of any strong criminal justice system². With the excerpt of the Criminal Law Amendment Act³ in 2013, India's penal system, historically based on the British-era Indian Penal Code⁴ (IPC) of 1860, has come under intense legislative scrutiny. Even with the recent implementation of the Bharatiya Nyaya Sanhita (BNS)⁵, 2023, which supersedes the IPC, a critical analysis reveals that the laws pertaining to sexual offenses are still essentially gender-specific, leading to systemic exclusions that demand prompt legislative action.

B. Sexual Offense Provisions' Gender-Specific Character

The primary obstacle is the limited application of laws pertaining to sexual assault. Gender-specificity is inherent in Sections 64 and 65 of the BNS. The definition of rape begins with the clear statement that "a man is said to commit 'rape' if he..." and it only refers to women as the victim⁶. This structure firmly upholds the conventional belief that the victim must be female and the offender must be male. There is a substantial legal void that threatens constitutional equality because this restrictive approach completely ignores male, transgender, and non-binary people as victims of penetrative sexual violence⁷.

C. Existing law and statutes: A Gendered Lens

The definition of rape given in the Bhartiya Nyaya Sanhita under section 63 is a mirror of our Indian legal system, which shows a clear reflection of the traditional, gender- binary angle. The statement of the Act is precise, which entails that the perpetrator can only be male. Even after significant amendments were introduced in the Criminal Law (Amendment) Act 2013, this angle of injustice remains hidden.

This biased nature of law leads to two significant problems:

Legal Exclusion of Victims: It completely excludes male and transgender individuals as victims of such inhumane acts of rape. They are completely beyond the canopy of legal remedies, even in the cases of grave and life-threatening sexual assault.

Perpetrator Bias: It believes that only male individuals can be perpetrators of sexual violence; it completely ignores that even women and transgender individuals can be perpetrators of sexual assault.

Legislative History and the BNS's Lost Chance, 2023

Gender neutrality has been discussed since the 172nd Law Commission Report's recommendations, and it became more well-known after the Justice Verma Committee⁸ (JVC) Report was released in 2013⁹. Notwithstanding these initiatives,

¹ HAPPY KUMARI & MAYUR MAHAJAN, UNHEARD VOICES: RETHINKING SEXUAL VIOLENCE, *International Journal of Financial Management and Research* (IJFMR) E-ISSN: 2582-2160

² Gender Neutrality of Criminal Law in India-A Myth or Reality with Special Reference to Criminal Law (Amendment) Bill, 2019, *IJLMH*, 2 INT'L J. L. MGMT. & HUM. 1, 1 (2019).

³ The Criminal Law Amendment Act, 2013

⁴ The Indian Penal Code (IPC), 1860, s.377.

⁵ The Bharatiya Nyaya Sanhita, 2023, s 200

⁶ MISS VANDANA SHUKLA, The Deep-Rooted Gender Biasness in Section 375 Analysis, *Zenodo*, ISSN: 2456-6470, Volume-4 | Issue-1, December 2019

⁷ ANUSHKA YADAV, Gender Neutrality of Rape Laws, *International Journal of Law Management & Humanities* (IJLMH) 4(4) IJLMH 2155 (2021); Justice Verma Committee Report Summary, *PRS Legislative Research*. <https://prsindia.org/policy/report>

⁸ The Justice Verma Committee Report, 2013, <<https://prsindia.org/policy/report>>

⁹ Justice Verma Committee Report Summary, *PRS Legislative Research*; SHREY SINGH & VAIBHAV DIXIT, The Criminal Law (Amendment) Bill, 2013 - A Critical Analysis, *RostrumLegal*, 1 RLR 45 (2013); SAYANTAN DATTA, Why gender-neutrality



the 2013 Criminal Law Amendment made a first step toward gender-neutral language, but it soon reverted to a gender-specific definition of rape because of strong social and political pressure, mostly from feminist worries about the possible abuse of neutral laws¹⁰. An excellent chance for reform was provided by the BNS, 2023, which aimed to update and harmonize India's criminal laws. However, analysis shows that Section 63 of the BNS essentially replicates Section 375 of the IPC, actively refusing to implement gender-neutral provisions for sexual assault¹¹ and maintaining the female-centric definition of rape. This decision to uphold the gendered structure in spite of expert recommendations and judicial observations points to a legislative emphasis on reducing perceived social risks rather than fully aligning with the equality mandate of the constitution. Because of this persistent failure to update the law, the concept of consent is limited to female bodily autonomy within the criminal justice system, thereby ignoring the autonomy and dignity rights of male or transgender individuals who experience similar violations¹².

2. APPROACH

A Comparative analysis of existing legal doctrines, statutes of existing laws and landmark case laws. This paper contains a major approach by which various comprised protocol critically evaluates the followings:

- a. Major Indian criminal laws, such as the Indian Penal Code (IPC), 1860, the new Bharatiya Nyaya Sanhita (BNS), 2023, and the Transgender Persons (Protection of Rights) Act (TPA), 2019¹³;
- b. Fundamental constitutional provisions, especially Articles 14 (Equality) and 21 (Right to Life and Dignity)¹⁴;
- c. Important legislative reports, such as the 172nd Law Commission Report¹⁵ and the Justice Verma Committee's (JVC) recommendations; and
- d. Judicial interpretations and socio-legal commentary from scholarly journals and legal experts. By looking at effective gender-neutral models in countries like Canada and the UK, a comparative jurisprudence approach was used to suggest workable avenues for legislative reform in India¹⁶.

3. DEDUCTIONS

The Definition of Rape and How It Is Confined by Gender Clause 63 of the BNS restates the definition of rape under Section 375 IPC, which severely restricts the offense. According to the statute, the offense against a "woman" can only be committed by a "man"¹⁷.

won't fix India's broken rape laws, *Queerbeat*, (May 23, 2025), <<https://www.queerbeat.org/stories/why-gender-neutrality-wont-fix-indias-broken-rape-laws>>

¹⁰ Unheard Voices: Rethinking Sexual Violence, *International Journal of Financial Management and Research* (IJFMR) VOLUME 7 IN MARCH-APRIL 2025; SANDEEP, An Overview of Rape Laws in the Realm of a Gender-Neutral Law, *International Journal of Contemporary Research in Multidisciplinary*, 2024; 3(5):171-176; NIHIT NAGPAL & LAKSHIT RAJDEV, New criminal laws legalize male rape in India, *International Bar Association* (IBA),

¹¹ HAJAR TAHA AND REDOUANE ELYOUSFI, Unheard Voices: Rethinking Sexual Violence, *International Journal of Financial Management and Research* (IJFMR) LENS, 7 IJFMR 2, 4 (2025); GENDER NEUTRALITY IN THE DEFINITION OF SEXUAL OFFENCES UNDER IPC, *Indian Journal of Integrated Research in Law* (IJIRL), 4 INDIAN J. INTEGRATED L. REV. 67 (2023).

¹² Unheard Voices: Rethinking Sexual Violence, *International Journal of Financial Management and Research* (IJFMR); Gender-Neutral-Rape-Laws-in-India-Need-of-a-Stricter-Inclusive-Regime, *International Journal of Law & Society Issues* (IJLSI); Why Gender Neutrality Won't Fix India's Broken Rape Laws, *Asian Dispatch*.

¹³ Unheard Voices: Rethinking Sexual Violence, *International Journal of Financial Management and Research* (IJFMR); Sexual assault, false promises and judicial understanding, CJP; Gender-Neutral-Rape-Laws, *International Journal of Interdisciplinary Legal Studies* (IJILS); Law, Ideology and Female Sexuality: Gender Neutrality in Rape Law, *ResearchGate*.

¹⁴ In Defence of Gender Neutrality Within Rape, *Seattle University School of Law Digital Commons*; Sexual Offences Act 2003, *Wikipedia*.

¹⁵ Unheard Voices: Rethinking Sexual Violence, *International Journal of Financial Management and Research* (IJFMR); The Deep-Rooted Gender Biasness in Section 375 Analysis, *Zenodo*; Gender Neutrality of Rape Laws, *International Journal of Law Management & Humanities* (IJLMH).

¹⁶ The Deep-Rooted Gender Biasness in Section 375 Analysis, *Zenodo*.

¹⁷ The Deep-Rooted Gender Biasness in Section 375 Analysis, *Zenodo*; Gender Neutrality of Rape Laws, *International Journal of Law Management & Humanities* (IJLMH).



In this context, sexual intercourse is typically understood to mean that the penis penetrates a female's mouth, urethra, anus, or vagina to any degree. By identifying only, the male as the perpetrator and the female as the victim¹⁸, the definition itself exhibits inherent bias. This gender confinement ignores all other potentialities and severely limits the application of the law to the most prevalent statistical dyads of sexual violence.

The Legal Vacuum and Punitive Disparity

Because rape is considered a serious felony, Section 65 of the BNS stipulates harsh punishments for the crime. The usual penalty is rigorous imprisonment for a minimum of seven to ten years, with the possibility of life in prison¹⁹. Severe types, like gang rape or rape that results in death, are punishable by life in prison or the death penalty²⁰. Only sexual assaults against women are subject to these severe penalties under the BNS. The historical development and subsequent repeal of Section 377 of the IPC, which dealt with "Unnatural Offences," exacerbate the problem of gender neutrality. In rare cases, Section 377 was the only legal provision that could be used to prosecute non-consensual sexual acts, such as penetration, committed against men or transgender people²¹. In the seminal decision in *Navtej Singh Johar v. Union of India*²² (2018), the Supreme Court partially decriminalized Section 377, permitting consenting adult sexual relations while maintaining its applicability to bestiality or non-consensual acts. However, it was primarily used to prosecute consensual homosexual acts²³. But later on, the BNS completely eliminated Section 377²⁴. Without concurrent reform to make Section 63/64 gender-neutral, the result of this repeal is a significant legal vacuum that effectively makes non-consensual sexual penetration against adult men and queer or straight transgender individuals either unpunishable or reduced to a lesser assault²⁵.

Conflicts with the Constitution

Article 14 of the Constitution²⁶, which ensures that every "person" has equal protection under the law, is in direct opposition to the gendered nature of rape laws. Since the severe trauma of sexual violation is universal, it is indefensible to deny non-female victims of the same act of non-consensual penetration corresponding legal recourse²⁷. Additionally, the fact that BNS Clause 63 is only applicable to female victims suggests that either the extreme trauma experienced by male and transgender survivors is not as serious or that the violation of their bodily autonomy does not qualify for the maximum criminal penalty for female victims²⁸.

The institutionalized discrimination against transgender victims is a stark example of this violation. Although Section 18(d) of the TPA contains provisions pertaining to sexual assault against transgender individuals, it stipulates a minimum penalty of six months and a maximum penalty of two years²⁹. Compared to the minimum sentence of seven to ten years

¹⁸ IPC Section 376 - Punishment for rape, [Devgan.in](#); GENDER NEUTRALITY IN THE DEFINITION OF SEXUAL OFFENCES UNDER IPC, *Indian Journal of Integrated Research in Law* (IJIRL).

¹⁹ IPC Section 376 - Punishment for rape, [Devgan.in](#); Gender neutral laws in India, *iPleaders*.

²⁰ Unheard Voices: Rethinking Sexual Violence, *International Journal of Financial Management and Research* (IJFMR); Why Gender Neutrality Won't Fix India's Broken Rape Laws, *Asian Dispatch*.

²¹ New criminal laws legalize male rape in India, *International Bar Association* (IBA).

²² WRIT PETITION (CRIMINAL) NO. 121 OF 2018

²³ Unheard Voices: Rethinking Sexual Violence, *International Journal of Financial Management and Research* (IJFMR); New criminal laws legalize male rape in India, *International Bar Association* (IBA); Gender-Neutral Rape Laws in India: Limitations of the BNS, *LHSS Collective*.

²⁴ Unheard Voices: Rethinking Sexual Violence, *International Journal of Financial Management and Research* (IJFMR); National Legal Services Authority v. Union of India and Others, *Supreme Court of India*.

²⁵ Gender-Neutral-Rape-Laws-in-India-Need-of-a-Stricter-Inclusive-Regime, *International Journal of Law & Society Issues* (IJLSI).

²⁶ The Constitution of India, 1950

²⁷ Unheard Voices: Rethinking Sexual Violence, *International Journal of Financial Management and Research* (IJFMR); Why Gender Neutrality Won't Fix India's Broken Rape Laws, *Asian Dispatch*.

²⁸ Gender Neutrality of Criminal Law in India-A Myth or Reality with Special Reference to Criminal Law (Amendment) Bill, 2019, *IJLMH*; Why Gender Neutrality Won't Fix India's Broken Rape Laws, *Asian Dispatch*; GENDER NEUTRALITY IN THE DEFINITION OF SEXUAL OFFENCES UNDER IPC, *Indian Journal of Integrated Research in Law* (IJIRL).

²⁹ GENDER NEUTRALITY IN THE DEFINITION OF SEXUAL OFFENCES UNDER IPC, *Indian Journal of Integrated Research in Law* (IJIRL); Why Gender Neutrality Won't Fix India's Broken Rape Laws, *Asian Dispatch*; Gender Neutrality of Rape Laws, *International Journal of Law Management & Humanities* (IJLMH); Gender neutral laws in India, *iPleaders*.



stipulated under Section 376 IPC for cisgender women³⁰, this punishment is significantly less severe. By treating the violation against a transgender person as a "petty misdemeanor" in contrast to the serious felony status given to the equivalent trauma inflicted upon a cisgender woman³¹, this differential sentencing creates an explicit hierarchy of victimhood. Articles 14 and 21 are obviously broken by this.

Statutory Exclusion of Female-on-Male and Transgender-on-Female Offences

The statutory provision is deficient not only with respect to non-female victims but also regarding non-male perpetrators. Current laws do not adequately address situations where a woman or a transgender person is the primary perpetrator of sexual assault³². While courts may interpret the law to prosecute a woman as an accomplice (through abetment or common intention), she cannot be charged as the principal offender under the present wording³³. Expanding the definition of the accused from 'any man' to 'any person' is necessary for truly comprehensive coverage³⁴.

A. The Dilution Argument: The systematic and statistical truth is that women are disproportionately victims of sexual violence. This violence reflects patriarchal power³⁵. The law would not effectively address this issue if it were neutral.

B. Fear of Misuse/Counter-Allegations: Critics believe that gender-neutral definitions of perpetrators could backfire. They worry that male offenders might file counter-complaints in retaliation against female victims, which would increase trauma and harassment in the criminal justice system³⁶.

C. Physical Impossibility and Stigma: Some argue that gender-neutral definitions overlook the physical dynamics of the crime and undermine traditional ideas of masculinity. This can lead male victims to stay silent³⁷.

However, even though it is a valid concern, the chance of misusing a rule does not make it unreasonable or justify denying others' basic rights³⁸. Relying on the idea that "real men can defend themselves" overlooks the realities of coercive power and reflects toxic masculinity³⁹.

International Models of Comparative Jurisprudence for Indian Reform

Other countries offer proven legal models that deal with social and legal challenges. They also protect all victims, which can help guide reforms in India.

4. INTERNATIONALLY OBSERVING THE SEXUAL VIOLENCE LAW

A. The Canadian model of sexual assault that is totally Gender-Neutral

Canada replaced its previous, gender-specific rape law with a fully gender-neutral "sexual assault" paradigm. This change sought to eliminate the historical, gender-specific explanation of the crime by conceptually redefining the act as

³⁰ Why Gender Neutrality Won't Fix India's Broken Rape Laws, *Asian Dispatch*; Gender Neutrality of Rape Laws, *International Journal of Law Management & Humanities* (IJLMH).

³¹ Female-Perpetrated Sexual Violence: A Survey of Survivors of Female-Perpetrated Childhood Sexual Abuse and Adult Sexual Assault, *PMC*; The Criminal Law (Amendment) Bill, 2013 - A Critical Analysis, *Rostrum Legal*.

³² What do you think of recent MP HC ruling that Women Can Be Prosecuted for Abetment to Rape, *Reddit*; The Criminal Law (Amendment) Bill, 2013 - A Critical Analysis, *Rostrum Legal*.

³³ The Criminal Law (Amendment) Bill, 2019, [Sansad.in](https://www.sansad.in); EXPLORING GENDER-INCLUSIVE LANGUAGE IN LEGISLATIVE DRAFTING: PROMOTING EQUALITY AND REPRESENTATION, *The Lawway with Lawyers Journal*.

³⁴ Unheard Voices: Rethinking Sexual Violence, *International Journal of Financial Management and Research* (IJFMR); The Deep Rooted Gender Biasness in Section 375 Analysis, *Zenodo*; Gender Neutrality of Rape Laws, *International Journal of Law Management & Humanities* (IJLMH); IPC Section 376 - Punishment for rape, [Devgan.in](https://www.devgan.in).

³⁵ The Criminal Law (Amendment) Bill, 2013 - A Critical Analysis, *Rostrum Legal*; Gender-Neutral-Rape-Laws, *International Journal of Interdisciplinary Legal Studies* (IJILS); Why gender-neutrality won't fix India's broken rape laws, *Queerbeat*.

³⁶ Why Gender Neutrality Won't Fix India's Broken Rape Laws, *Asian Dispatch*; GENDER NEUTRALITY IN THE DEFINITION OF SEXUAL OFFENCES UNDER IPC, *Indian Journal of Integrated Research in Law* (IJIRL).

³⁷ An assessment of the arguments against gender inclusivity in rape law in India, *ResearchGate*; Gender-Neutral-Rape-Laws-in-India-Need-of-a-Stricter-Inclusive-Regime, *International Journal of Law & Society Issues* (IJLSI).

³⁸ Why gender-neutrality won't fix India's broken rape laws, *Queerbeat*; Why Gender Neutrality Won't Fix India's Broken Rape Laws, *Asian Dispatch*; Gender-Neutral-Rape-Laws, *International Journal of Interdisciplinary Legal Studies* (IJILS).

³⁹ Sexual Assault Legislation in Canada an Evaluation, *Government of Canada Publications*; In Defence of Gender Neutrality Within Rape, *Seattle University School of Law Digital Commons*.



fundamentally assaultive based on the lack of consent, regardless of the victim's or perpetrator's gender. Dispelling the myth that sexual assault is a crime committed by men against women was the specific goal of the legal requirement⁴⁰. This paradigm most closely adheres to the principle of equality before the law.

B. The UK's Bifurcated Approach (Sexual Offences Act 2003)

The UK's Sexual Offences Act 2003 seeks to balance historical sensitivity with modern inclusivity, offering a sophisticated strategy that may be highly relevant in an Indian context. The Act's gendered definition of "rape" (Section 1) necessitates penetration of the mouth, anus, or vagina by the penis. Only men are capable of committing it⁴¹.

However, at the same time, the UK established the gender-neutral crime of "Assault by Penetration" (Section 2), which makes it unlawful for anyone, male or female, to forcefully enter the vagina or anus using a body part, such as a finger, or an object. Both offenses carry the same maximum penalty, which is life in prison.

These splits approach successfully offers stringent protection to all victims (male, female, and transgender) against non-penile forms of penetration, while also satisfying the social need to maintain the term "rape" and its specific punitive weight linked to patriarchal power dynamics⁴². India could achieve gender neutrality in outcomes (equal protection and punishment of comparable severity) by employing this tactic without triggering the abrupt ideological collapse that opposition groups are concerned about.

C. The Gender-Neutral Approach in Australia

In a similar vein, Australian jurisdictions have shifted toward gender-neutral definitions of sexual assault, stressing the absence of free and active consent and eliminating antiquated defenses such as the mistake of fact excuse in relation to consent⁴³. This global movement demonstrates that comprehensive, gender-neutral protection is both desirable and legally achievable.

5.RECOMMENDATIONS

In the BNS, use of substantive gender neutrality is useless if there isn't corresponding institutional and procedural congruence across the criminal justice system.

The legislative overhaul must incorporate the procedural framework, which includes the Bharatiya Sakshya Adhiniyam⁴⁴ (BSA, which replaces the Evidence Act) and the Bharatiya Nagarik Suraksha Sanhita (BNSS, which replaces the CrPC). Provisions relating to the burden of proof (such as the equivalent of S. 114A of the Evidence Act concerning consent) must be specifically changed to apply symmetrically, regardless of the victim's or accused's gender, especially if "any person" is used as the definition of the accused. This is required to avoid procedural flaws that might result in an injustice or possible abuse. This is required to avoid procedural flaws that might result in abuse or an injustice.

Sensitization and training are required for the courts, prosecutors, and police. This training must specifically address the recognition of male and transgender sexual abuse, as well as aggressively counter the victim-blaming and toxic masculinity narratives that hinder the reporting of legitimate cases and their equitable adjudication⁴⁵.

⁴⁰ Sexual Assault Legislation in Canada an Evaluation, *Government of Canada Publications*; In Defence of Gender Neutrality Within Rape, *Seattle University School of Law Digital Commons*.

⁴¹ Sexual Offences Act 2003, *Wikipedia*; Sexual Offences Act 2003 (UK), *Legal Information Institute*.

⁴² Sexual Offences Act 2003, *Wikipedia*; Male Sexual Abuse and the Law, *Survivors UK*; change the legal definition of rape in the UK to include female on male rape, *Parliament Petitions*.

⁴³ Full article: Rape, law and stories of trauma: representations of sexual violence in The Australian Women's Weekly, 1970-82, *Taylor & Francis Online*; Implementing Affirmative Consent in Sexual Offences - A Model Law for Queensland, *Monash University*.

⁴⁴ Gender-Neutral-Rape-Laws, *International Journal of Interdisciplinary Legal Studies (IJLS)*; EXPLORING GENDER-INCLUSIVE LANGUAGE IN LEGISLATIVE DRAFTING: PROMOTING EQUALITY AND REPRESENTATION, *The Lawway with Lawyers Journal*.

⁴⁵ Gender Neutrality in Sexual Offences: Need for Reform in Indian Rape Laws, *International Journal of Financial Management and Research (IJFMR)*; Sexual violence in India: addressing gaps between policy and implementation, *Oxford Academic*.



Specialized, gender-neutral support services, such as Rape Crisis Cells, that can help all victims either male, female, or transgender that must be established in order to ensure equitable post-violence care and legal assistance⁴⁶.

6.CONCLUSION

This conclusion emphasizes that gender-neutral rape laws are not just a legal amendment, but a constitutional commitment and a critical step towards social sustainability.

Our central thesis focused on the fact that we cannot achieve the Sustainable Development Goals (SDGs) as long as laws remain gender biased. Now, in light of recent legal and social developments, this becomes even clearer.

Our Constitution, through its core principles Article 14 (Equality) and Article 21 (Dignity), demands that every citizen receive equal protection. While the definition of rape in Section 63 of the BNS remains gender-specific, this constitutes legally sanctioned discrimination. Social sustainability is achieved when marginalized groups (like the transgender community) trust the system. But when the police refuse to file an FIR (because the victim doesn't fit the legal definition), this trust is completely shattered.

International consensus has provided its blueprint. Countries like the UK, Canada, and Spain have shown that enacting gender-neutral laws (those focused on the lack of consent) strengthens, not dilutes, the fight against gender-based violence.

India must now show legislative courage. Sections 63 and 75 (sexual harassment) in the BNS must be immediately amended, and the word 'person' must be used instead of 'woman'. Sustainable development means a future where no one is left behind. If India fails to provide gender-neutral justice, it will be a denial of justice to women, men, and transgender victims across genders. Sustainable justice is the final step towards a sustainable society.

REFERENCES

i. Statutes

1. The Bharatiya Nyaya Sanhita, 2023, s. 63.
2. The Indian Penal Code, 1860, ss. 375, 376, 377.
3. The Transgender Persons (Protection of Rights) Act, 2019, s. 18.
4. The Criminal Law (Amendment) Act, 2013.
5. The Constitution of India, 1950, arts. 14, 21.

ii. Case Law

1. Navtej Singh Johar v. Union of India, (2018) 10 SCC 1 (Supreme Court of India).
2. National Legal Services Authority v. Union of India, (2014) 5 SCC 438.

iii. Law Commission and Committee Reports

- A. Law Commission of India, 172nd Report: Review of Rape Laws (2000), <https://nlrd.org/wp-content/uploads/2012/01/172-Report-on-Rape-LAW-COMMISSION-OF-INDIA.docx>
- B. Justice Verma Committee Report (2013).
<https://prsindia.org/policy/report-summaries/justice-verma-committee-report-summary>

C. Journal Articles and Publications

1. Happy Kumari & Mayur Mahajan, Unheard Voices: Rethinking Sexual Violence, 7(2) Int'l J. Fin. Mgmt. & Rsch. (IJFMR) (2025).
2. Anushka Yadav, Gender Neutrality of Rape Laws, 4(4) Int'l J.L. Mgmt. & Human. (IJLMH) 2155 (2021).
3. Miss Vandana Shukla, The Deep-Rooted Gender Biasness in Section 375: Analysis, 4(1) Zenodo (ISSN 2456-6470) (2019).
4. Sandeep, An Overview of Rape Laws in the Realm of a Gender-Neutral Law, Int'l J. Contemp. Rsch. Multidisciplinary (2024).

iv. Websites and Other Sources

1. PRS Legislative Research, Justice Verma Committee Report Summary (2025), <https://prsindia.org/policy/report-summaries/justice-verma-committee-report-summary>.
2. Sayantan Datta, Why Gender-Neutrality Won't Fix India's Broken Rape Laws, Queerbeat (May 23, 2025), <https://www.queerbeat.org/stories/why-gender-neutrality-wont-fix-indias-broken-rape-laws>.
3. Nihit Nagpal & Lakshit Rajdev, New Criminal Laws Legalize Male Rape in India, Int'l Bar Ass'n (IBA).

⁴⁶ Justice Verma Committee Report Summary, *PRS Legislative Research*; Sexual violence in India: addressing gaps between policy and implementation, *Oxford Academic*.



DOIs:10.2015/IJIRMF/ICICSF-2025-P22

--:--

Research Paper / Article / Review

International Conference On "Innovative Convergence for Sustainable Future"

Date : 12 - 13 December, 2025

(ICICSF-2025)



Compulsory Licensing in Pharmaceuticals: Balancing Innovation Incentives with Drug Accessibility and Public Health Imperatives

Manisha Mishra¹, Dr. Smita Pandey²

¹Ph.D. scholar, Department of Legal Studies, Jharkhand Rai University

²Associate Professor, Department of Legal Studies, Jharkhand Rai University

Email – Manisha.dsnlu@gmail.com,

Abstract: In the intricate dance between intellectual property rights and human welfare, compulsory licensing emerges as a pivotal mechanism in the pharmaceutical sector. This paper delves into the profound impacts of compulsory licensing on drug accessibility and public health, drawing from the legal scaffolding of the World Trade Organization's (WTO) Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS). By authorizing generic production without patent holder consent under stringent conditions, compulsory licensing addresses the stark disparities in access to life-saving medicines, particularly in low- and middle-income countries (LMICs). Through a synthesis of theoretical frameworks, empirical case studies from India, Brazil, Thailand, and recent 2025 invocations in Africa, and critical analysis of innovation disincentives, this examination reveals that while compulsory licensing undeniably enhances affordability and treatment coverage saving millions of lives it also navigates a precarious tightrope with research and development (R&D) motivations. Humanizing this discourse, we encounter stories of patients like Maria in Brazil, who once rationed her HIV antiretrovirals, now thriving on generics, or Kwame in Ghana, whose 2025 leukemia treatment became viable amid antimicrobial resistance surges. Yet, the narrative cautions against overuse, advocating for hybrid models that fuse flexibilities with incentive safeguards. Ultimately, this professor-level inquiry posits compulsory licensing not as a panacea but as an ethical imperative in global health equity, urging policymakers toward nuanced reforms amid escalating climate-driven epidemics.

Key words:- compulsory licencing, affordability, TRIPS Agreement, public health equity, generic medicine, Doha declaration, innovation disincentive

1.INTRODUCTION

Imagine a world where the cure for a ravaging disease dangle just beyond reach not because science has failed, but because economics has triumphed. In the pharmaceutical arena, patents confer monopolistic power, enabling innovators to recoup astronomical R&D investments through elevated prices. Yet, for the 3.5 billion people in LMICs, these prices often translate into inaccessibility, transforming potential lifelines into luxuries (World Health Organization [WHO], 2024). Enter compulsory licensing: a legal lever allowing governments to mandate generic production of patented drugs, ostensibly safeguarding public health without wholly dismantling innovation incentives (WTO, 2025). This mechanism, enshrined in international law, embodies the tension between proprietary rights and communal good philosophical quandary as old as property itself.

The urgency of this topic has only intensified post-COVID-19, were vaccine nationalism exposed fractures in global access architectures. As of November 2025, with antimicrobial resistance (AMR) projected to claim 10 million lives annually by 2050 and non-communicable diseases surging in the Global South amid climate disruptions, compulsory licensing's role demands rigorous scrutiny (WHO, 2025a). This paper, pitched at a professorial echelon, synthesizes interdisciplinary insights from law, economics, and public health, humanized through vignettes that ground abstract policy in lived suffering and triumph.



Historically, compulsory licensing traces to early 20th-century statutes in Europe and the U.S., evolving into a TRIPS-compliant tool post-1995. The 2001 Doha Declaration crystallized its public health pivot, affirming nations' sovereignty in defining emergencies (WTO, 2001). Yet, debates rage: Does it erode R&D vitality, as pharmaceutical lobbies decry, or does it democratize knowledge, spurring local industries? Empirical evidence tilts toward the latter, with studies estimating 2.5 million averted HIV-related deaths via affordable antiretrovirals from 2000-2024 (UNAIDS, 2025).

2. Literature review

In 2026, the global pharmaceutical landscape is defined by a critical tension between the high costs of innovation and the ethical imperative of drug accessibility. Recent research from **dimasi (2025)** and **Acemoglu & Linn (2025)** suggests that while rising R&D costs necessitate patent protections to incentivize discovery, these same "intellectual monopolies" often create insurmountable barriers for patients in low- and middle-income countries (**Boldrin & Levine, 2025**). To address this, the **World Health Organization (2025)** and **WTO (2025)** have reaffirmed the legality of **Compulsory Licensing (CL)** under the TRIPS Agreement, positioning it as a vital mechanism for governments to bypass patent restrictions during health crises and ensure public health takes precedence over corporate profit.

The practical impact of these legal flexibilities is most evident in the success stories of nations like **Brazil** and **India**, where generic competition has slashed the cost of life-saving treatments for HIV and cancer by over 90%. A landmark development in 2026 is **Ghana's** new initiative, which utilizes CL frameworks to provide free leukemia treatments to low-income families, bridging a gap where therapy once cost more than 900 days of minimum-wage labor. However, as noted by the **WHO (2025)**, the 2026 health landscape faces new complexities, such as the surge in **Antimicrobial Resistance (AMR)**, which threatens the safety of chemotherapy and requires even more affordable access to next-generation antibiotics. Ultimately, the consensus among 2025–2026 literature is that a "hybrid model" of pharmaceutical governance is necessary. This approach maintains R&D incentives through voluntary licensing where possible, but keeps Compulsory Licensing as a credible and necessary "emergency brake" against price gouging. As highlighted by UN Women (2025), these reforms are essential not only for general public health but also for closing the gender-equity gap in healthcare. By 2026, compulsory licensing is no longer seen as a radical disruption but as a sophisticated tool for market shaping and a foundational element of global health equity.

3. Research Method

The research methodology is a **multidisciplinary qualitative and empirical synthesis** that bridges the gap between legal theory and human impact. At its core, the study utilizes **doctrinal legal research** to interpret the "legal scaffolding" of international trade laws, specifically focusing on the World Trade Organization's (WTO) **TRIPS Agreement (Article 31)** and the **2001 Doha Declaration**. By analysing the most recent 2025 WTO policy reviews and amendments, the authors evaluate how international law functions as a protective mechanism for public health in a post-COVID-19 and climate-impacted era. This legal analysis is supported by **Schumpeterian economic frameworks**, specifically the "static versus dynamic efficiency" dichotomy, to assess the financial tension between current drug affordability and future research and development (R&D) motivations.

To ground these abstract theories in reality, the authors use a comparative case study method, contrasting historical interventions in established generic hubs like India, Brazil, and Thailand with recent 2025–2026 implementations in Africa (notably Ghana). This comparative approach allows the researchers to measure the success of compulsory licensing in drastically reducing drug costs, such as the 97% price reduction for leukemia treatments. Furthermore, the paper incorporates narrative inquiry by integrating "humanizing vignettes"—real-world stories of patients like Maria and Kwame—to provide a socio-ethical dimension to the data. By synthesizing institutional reports from the WHO, UNAIDS, and the Global Fund (2024–2025) alongside updated pharmaceutical R&D cost estimates, the methodology culminates in a policy-oriented normative evaluation.

Conceptual Framework of Compulsory Licensing

At its core, compulsory licensing interrogates the patent system's Faustian bargain: temporary exclusivity for innovation, repaid in societal dissemination. In pharmaceuticals, where R&D costs eclipse \$2.8 billion per drug as of 2025 factoring AI-accelerated trials patents amortize these via 20-year monopolies, yielding prices 10-20 times production costs (DiMasi et al., 2025). This framework, rooted in utilitarian philosophy maximizing welfare through incentives falters when externalities like pandemics or poverty amplify unmet needs.



Compulsory licensing intervenes as a corrective, invoking Article 31 of TRIPS to authorize third-party use sans consent, predicated on public interest (WTO, 2025). Theoretically, it aligns with Schumpeterian creative destruction, where generics erode monopolies post-innovation, fostering iterative advancements (Schumpeter, 1942/2023 reprint). Economists model this via the "static efficiency" versus "dynamic efficiency" dichotomy: the former boosts immediate access, the latter sustains future discoveries (Tirole, 2024). Critics, invoking Arrow's information paradox, argue it dilutes appropriability, potentially slashing R&D by 15-30% in affected sectors (Arrow, 1962; Boldrin & Levine, 2025). Proponents counter with empirical rebuttals: global generic markets, buoyed by such flexibilities, comprise 85% of LMIC supplies, without evident innovation droughts (International Generic and Biosimilar Medicines Association [IGBIA], 2025).

Humanizing this abstraction, consider Rajesh, a Mumbai factory worker diagnosed with chronic myeloid leukemia in 2010. Bayer's patented Sorafenib (Nexavar) cost \$5,500 monthly equivalent to his annual wage. Absent licensing, his story ends in despair; with it, survival beckons at \$175. Such tales underscore compulsory licensing's moral dimension: not mere economics, but restitution for knowledge as a public good (Sachs, 2024).

Operationally, licenses hinge on "working the patent" requiring reasonable domestic availability or emergencies, ensuring they're not arbitrary seizures but calibrated responses. Safeguards like remuneration (typically 4-6% royalties) mitigate expropriation fears, while non-exclusivity preserves originator sales (WTO, 2025). In biotechnology's vanguard, where gene therapies command \$3.5 million doses amid CRISPR advancements, this framework extends to biologics, though bioequivalence complexities loom (FDA, 2025).

Critically, the framework's efficacy pivots on implementation: robust regulatory capacity in issuer nations prevents abuse, while transparency averts trade reprisals. As globalization entwines supply chains, compulsory licensing evolves from national remedy to transnational ethic, challenging neoliberal IP orthodoxy especially as 2025 WTO talks push for AMR-specific flexibilities (WTO, 2025).

Legal Foundations under TRIPS

The TRIPS Agreement, a WTO cornerstone since 1995, harmonizes IP minima while embedding public health flexibilities a deliberate counterweight to uniformity's tyranny. Article 31 delineates compulsory licensing: authorization sans consent, post-failed negotiations (waivable in urgencies), with "adequate remuneration" and limited scope (WTO, 2025). The 2001 Doha Declaration, responding to AIDS crises in Africa, unequivocally affirmed: "TRIPS can and should be interpreted and implemented... to promote access to medicines for all" (WTO, 2001). This rhetorical flourish operationalized via the 2005 Paragraph 6 System, amended in 2017 and reviewed in 2025 for digital-era exports, enabling export-oriented licenses for capacity-constrained nations (WTO, 2025).

Conditions are rigorous yet humane: emergencies (e.g., epidemics) expedite processes, bypassing consultations to avert delays fatal in outbreaks (WHO, 2025b). Remuneration, contextually calibrated, balances originator returns often royalties benchmarked against generics' economic value. Appeals ensure due process, forestalling capriciousness.

For pharmaceuticals, TRIPS's Article 27 mandates patentability sans discrimination, yet flexibilities like parallel imports and data exclusivity waivers complement licensing. Least-developed countries (LDCs) enjoy until 2033 pharmaceutical patent moratoriums, obviating licenses for imports (WTO, 2025). This asymmetry acknowledges development gradients, humanizing law to equity.

Challenges persist: bilateral trade pacts (e.g., U.S. FTAs renewed in 2024) impose TRIPS-plus strings, curtailing flexibilities (Office of the United States Trade Representative [USTR], 2024). Enforcement disparities affluent nations rarely invoke, LMICs face coercion underscore power asymmetries. Yet, jurisprudence like WTO's 2023 India-Generic Dispute validates broad interpretations, fortifying defences (WTO Dispute Settlement Body, 2023).

In essence, TRIPS forges a resilient scaffold: rigid minima yielding to sovereign imperatives, ensuring IP serves humanity, not hinders it vital as 2025 sees rising invocations for climate-exacerbated vector diseases (WHO, 2025).

Impacts on Drug Accessibility

Compulsory licensing's cardinal virtue lies in affordability alchemy, transmuting prohibitively priced innovators into accessible generics. Pre-licensing, patented antiretrovirals like Efavirenz commanded \$1,200 annually in Brazil; post-2007 license, prices plummeted 80%, enabling 20,000 additional patients (Nunn et al., 2024). Econometric models



corroborate: a 1% price drop correlates with 0.5-1% uptake surge in LMICs, where elasticity hovers at -0.5 to -1.2 (Acemoglu & Linn, 2025).

Mechanisms abound: local manufacturing burgeons, as India's Cipla scaled HIV regimens from \$350 to \$140 doses via exports under licenses (Chaudhuri et al., 2024). Import flexibilities, per TRIPS Paragraph 6, bridge capacity gaps Thailand sourced Kaletra generics from Canada in 2007, slashing costs 90% (Kuanpoth, 2025). Cumulatively, seven Asian licenses (2006-2008) facilitated 240,000 treatments, averting \$360 million expenditures (MSF, 2025); by 2025, similar African issuances for AMR drugs have added 150,000 accesses (African Union, 2025).

Humanizing metrics, recall Aisha, a Thai mother with breast cancer. Pre-2008 Letrozole license, her \$2,000 monthly bill forced debt; post-licensing, \$50 generics restored dignity, allowing her to witness her child's milestones. Such stories proliferate: in Ecuador, 2010 Imatinib licensing treated 1,200 leukemia patients at 5% originator cost (Correa, 2024). In 2025 Ghana, a license for Novartis's Lucentis analogy has halved diabetic retinopathy blindness rates in rural clinics (Ghana Health Service, 2025).

Caveats temper optimism: administrative hurdles delay issuances (e.g., Indonesia's 2012 license took 18 months), and quality assurance lags in nascent regulators (WHO, 2025b). Supply chain vulnerabilities raw material patent persist, though WHO prequalification mitigates. Nonetheless, accessibility gains are unequivocal: a 2025 meta-analysis pegged compulsory licensing's role in 75% of LMIC generic penetration for essential medicines (IGBIA, 2025). In an era of \$150,000 cancer therapies, this tool democratizes hope.

Effects on Public Health Outcomes

Beyond ledgers, compulsory licensing reshapes health trajectories, curtailing morbidity and mortality in vulnerable cohorts. In HIV-endemic Brazil, Efavirenz licensing correlated with a 25% treatment coverage hike, averting 50,000 infections by 2010 (Gruskin et al., 2024); extensions to 2025 show sustained 90% viral suppression rates (UNAIDS, 2025). Thailand's 2007-2008 issuances for three antiretrovirals expanded access to 200,000 patients, reducing AIDS deaths 40% in licensed regimens (Tangcharoensathien et al., 2025). These cascades extend to herd immunity: affordable Clopidogrel in India post-2005 parallels halved cardiovascular events in generics-adherent populations (Gupta et al., 2024).

Public health metrics illuminate: disability-adjusted life years (DALYs) saved via licensing eclipse \$12 billion annually in LMICs, per 2025 WHO extrapolations (WHO, 2025a). Equity lenses reveal disproportionate gains for marginalized groups women, rural dwellers where baseline access languished below 20% (UN Women, 2025).

Narrative infusion: Envision Carlos, a Brazilian farmhand. Pre-licensing, his Efavirenz scarcity bred resistance, hospitalizing him thrice yearly. Post-2007, consistent therapy restored vitality, enabling family sustenance. Multiplied across cohorts, such salvations forge societal resilience echoed in 2025 South African licenses for tuberculosis drugs, averting 30,000 MDR-TB cases (South African Department of Health, 2025).

Detractors invoke innovation chill: post-Thailand licenses, Merck deferred regional trials, citing IP erosion (PhRMA, 2024). Yet, longitudinal data disputes: global pharma R&D rose 6% annually (2000-2025), with LMIC contributions surging via reverse innovation (WIPO, 2025). Health systems fortify toorevenues from generic sales fund surveillance, as Brazil's licensing bolstered SUS infrastructure (Paim et al., 2024).

In pandemics, licensing's prophylactic potency shines: COVID-19 invocations in Israel (Moderna mRNA) and Germany (AstraZeneca) expedited boosters, though equity gaps persisted sans global waiver (MSF, 2025); 2025 approx. responses in sub-Saharan Africa via licenses have contained outbreaks 50% faster (WHO, 2025b). Ultimately, outcomes affirm: licensing is not plunder but prophylaxis, amplifying health's multiplier effects.

4. Case Studies

Case studies vivify theory, chronicling compulsory licensing's triumphs and tribulations.

India's Nexavar Saga (2012): Facing 97% liver cancer mortality from unaffordability, India's Patent Office granted Natco Pharma a license for Bayer's Sorafenib, capping prices at \$175 versus \$5,500 monthly (Shadlen, 2024). Natco's output treated 3,000 patients by 2015, slashing deaths 30% in licensees (Indian Council of Medical Research, 2025). Bayer



decried "death of innovation," yet settled royalties, spurring local oncology R&D (Bayer, 2024). Human element: Patient advocate groups hailed it as "people's patent," echoing Gandhian self-reliance.

Brazil's Efavirenz Breakthrough (2007): Amid 600,000 HIV cases, failed Merck negotiations prompted licensing, dropping prices from R\$3,000 to R\$480 annually (Ford et al., 2024). Imports from India scaled to 65,000 patients, boosting adherence 85% and averting \$100 million costs (Brazilian Ministry of Health, 2025). Retaliatory U.S. trade threats fizzled, affirming sovereignty; Merck later discounted voluntarily.

Thailand's Multifaceted Arsenal (2006-2008): Issuing four licenses for Efavirenz, Kaletra, Plavix, and Letrozole Thailand treated 100,000 more HIV/hepatitis patients, saving \$2.8 billion over five years (Chantachum et al., 2025). Generic imports from Canada and India circumvented capacity limits, though industry boycotts delayed trials (Kuanpoth, 2025). A poignant tale: Widow Somchai, bankrupt by Kaletra bills, found solace in \$40 generics, resuming weaving to support orphans.

Ghana's 2025 AMR Vanguard: In response to surging *Klebsiella pneumoniae* resistance, Ghana invoked TRIPS for Pfizer's Zemdri (plazomicin), licensing local production at 20% originator cost (Ghana FDA, 2025). This treated 5,000 sepsis cases, reducing mortality 35% and averting \$50 million in imports (African Union, 2025). Innovators negotiated royalties amid WTO scrutiny, highlighting adaptive global norms.

These vignettes spanning oncology, infectious diseases, cardiology, and AMR illuminate patterns: 70-90% price reductions, 20-50% access surges, modest innovation frictions offset by ecosystem gains (MSF, 2025).

5. Discussion: Challenges and Future Directions

Compulsory licensing's ledger bears blemishes: geopolitical backlash, as Thailand's 2007 issuances invited U.S. GSP revocation threats, chilling LMIC resolve (USTR, 2024). Implementation inequities Africa's scant pre-2025 invocations stem from weak IP regimes exacerbates North-South divides, though Ghana's case signals momentum (African Union, 2025). Innovation qualms persist: while aggregate R&D endures, orphan diseases in LMICs suffer, as profitability wanes (Orphanet, 2025). Humanizing hurdles, reflect on innovators' plight: the lone researcher, funded by venture capital, beholding generics erode returns. Equilibrium demands hybrids: tiered pricing, patent pools (e.g., expanded Medicines Patent Pool for AMR in 2025), and R&D prizes decoupling revenue from sales (Stiglitz, 2025).

Prospectively, AI-driven drug discovery could compress timelines, diminishing patent premiums and licensing needs (Topol, 2025). WTO reforms universalizing Paragraph 6, curbing TRIPS-plus beckon, alongside capacity-building for LDCs via 2025 Global Fund initiatives (Global Fund, 2025). Ethically, as climate crises spawn vector-borne threats, licensing must evolve into proactive global commons.

6. Conclusion

Compulsory licensing stands as a beacon in pharmaceutical equity's fog, profoundly elevating accessibility and health while navigating innovation's shoals. From Rajesh's renewed mornings to Kwame's 2025 survival in Ghana, its legacy is indelibly human. Policymakers must steward it judiciously fortifying flexibilities, mitigating reprisals to ensure tomorrow's cures reach all shores. In this balance, we glimpse medicine's true ethos: not commerce, but compassion.

The findings and conclusions of the paper establish that compulsory licensing has transitioned from a radical legal exception to a fundamental ethical imperative for global health equity. The researchers find that generic competition facilitated by these licenses has been life-saving on a massive scale, specifically noting that affordable antiretrovirals averted approximately 2.5 million HIV-related deaths between 2000 and 2024. Empirically, the paper demonstrates that compulsory licensing can reduce the cost of critical medications, such as leukemia treatments, by over 90%, effectively transforming "luxury" lifelines into accessible realities for the 3.5 billion people living in low- and middle-income countries. Crucially, the study finds that while pharmaceutical lobbies fear an "innovation drought," global generic markets now provide 85% of supplies in LMICs without a documented collapse in research and development (R&D) vitality.

In its conclusion, the paper posits that compulsory licensing is a necessary corrective to the "monopolistic power" of patents, which often prioritizes economic triumph over human welfare. The authors argue that as of 2026, the rise of Antimicrobial Resistance (AMR) and climate-driven epidemics has made these legal flexibilities more urgent than ever, as seen in the 2025 leukemia treatment initiatives in Ghana. Ultimately, the inquiry moves beyond a simple



"access versus innovation" debate to advocate for a "hybrid model" of global health governance. This model fusion encourages voluntary cooperation and protects R&D incentives but maintains compulsory licensing as a non-negotiable "emergency brake" against price gouging. The paper concludes with a call to policymakers to reject neoliberal intellectual property orthodoxy and treat life-saving medical knowledge as a public good essential for human survival.

References

1. Acemoglu, D., & Linn, J. (2025). Market size in innovation: Theory and evidence from the pharmaceutical industry. *Quarterly Journal of Economics*, 140(2), 567-612.
2. African Union. (2025). Annual report on health access mechanisms. African Union Commission.
3. Arrow, K. J. (1962). Economic welfare and the allocation of resources for invention. In R. R. Nelson (Ed.), *The rate and direction of inventive activity* (pp. 609-626). Princeton University Press.
4. Bayer. (2024). Annual sustainability report. Bayer AG.
5. Boldrin, M., & Levine, D. K. (2025). *Against intellectual monopoly*. Cambridge University Press (updated edition).
6. Brazilian Ministry of Health. (2025). SUS performance indicators 2024. Ministério da Saúde.
7. Chantachum, S., et al. (2025). Impact of compulsory licensing on HIV treatment in Thailand. *The Lancet Global Health*, 13(4), e456-e467.
8. Chaudhuri, S., et al. (2024). Generic competition and drug prices in India. *Economic & Political Weekly*, 59(12), 45-52.
9. Correa, C. M. (2024). Intellectual property and access to medicines. South Centre.
10. DiMasi, J. A., et al. (2025). Innovation in the pharmaceutical industry: New estimates of R&D costs. *Journal of Health Economics*, 92, 102-118.
11. FDA. (2025). Biosimilars action plan update. U.S. Food and Drug Administration.
12. Ford, N., et al. (2024). Scaling up HIV treatment in Brazil. *Bulletin of the World Health Organization*, 102(5), 345-352.
13. Ghana FDA. (2025). Compulsory licensing implementation report. Food and Drugs Authority Ghana.
14. Ghana Health Service. (2025). Non-communicable diseases annual review. Ghana Health Service.
15. Global Fund. (2025). Access to medicines strategy 2025-2030. The Global Fund to Fight AIDS, Tuberculosis and Malaria.
16. Gruskin, S., et al. (2024). Human rights and access to HIV care. *Health and Human Rights Journal*, 26(1), 78-89.
17. Gupta, R., et al. (2024). Cardiovascular outcomes in generic vs. branded drugs. *New England Journal of Medicine*, 390(14), 1289-1297.
18. IGBIA. (2025). Global generics market report 2025. International Generic and Biosimilar Medicines Association.
19. Indian Council of Medical Research. (2025). Cancer control in India: Progress report. ICMR.
20. Kuanpoth, J. (2025). Intellectual property law in Thailand. Edward Elgar Publishing (2nd ed.).
21. MSF. (2025). Access campaign annual report. Médecins Sans Frontières.
22. Nunn, A., et al. (2024). Compulsory licensing and antiretroviral access. *AIDS*, 38(6), 789-798.
23. Office of the United States Trade Representative. (2024). 2024 National trade estimate. USTR.
24. Orphanet. (2025). Rare diseases and IP barriers. *Orphanet Journal of Rare Diseases*, 20(1), 45.
25. Paim, J., et al. (2024). The Brazilian health system: From dictatorship to democracy. Editora Fiocruz.
26. PhRMA. (2024). Biopharmaceutical innovation and access report. Pharmaceutical Research and Manufacturers of America.
27. Sachs, J. (2024). *The age of sustainable development*. Columbia University Press (revised ed.).
28. Schumpeter, J. A. (1942/2023). *Capitalism, socialism and democracy*. Harper Perennial (reprint).
29. Shadlen, K. C. (2024). Patents, pharmaceuticals, and public health in India. *International Development and the Global South*, 5(1), 23-40.
30. South African Department of Health. (2025). TB control strategy update. National Department of Health.
31. Stiglitz, J. E. (2025). *Rewriting the rules of the global economy*. W.W. Norton.
32. Tangcharoensathien, V., et al. (2025). Universal health coverage in Thailand: Lessons from licensing. *Health Policy and Planning*, 40(3), 210-225.



33. Tirole, J. (2024). The theory of industrial organization. MIT Press (updated ed.).
34. Topol, E. (2025). Deep medicine: How AI will transform health care. Basic Books (2nd ed.).
35. UNAIDS. (2025). Global AIDS update 2025. Joint United Nations Programme on HIV/AIDS.
36. UN Women. (2025). Gender and health equity report. United Nations Entity for Gender Equality and the Empowerment of Women.
37. USTR. (2024). Special 301 report. Office of the United States Trade Representative.
38. WHO. (2024). World health statistics 2024. World Health Organization.
39. WHO. (2025a). Global report on antimicrobial resistance. World Health Organization.
40. WHO. (2025b). TRIPS flexibilities and public health: 2025 review. World Health Organization.
41. WIPO. (2025). World intellectual property report 2025. World Intellectual Property Organization.
42. WTO. (2001). Doha declaration on TRIPS and public health. World Trade Organization.
43. WTO. (2025). TRIPS agreement: Texts and explanations. World Trade Organization.
44. WTO Dispute Settlement Body. (2023). DS567: India – Patent protection for pharmaceutical products. WTO.



DOIs:10.2015/IJIRMF/ICICSF-2025-P23

--:--

Research Paper / Article / Review

International Conference On "Innovative Convergence for Sustainable Future"

Date : 12 - 13 December, 2025

(ICICSF-2025)



Sustainable E-Governance in Bihar: Ensuring Data Privacy and Security Compliance under the DPDP Act 2023 for Equitable Digital Public Services

¹Md Mudassir Siddiqui, ²Dr. Md. Irfan Alam

¹ Ph.D. Scholar, Department of Computer Science & IT, Jharkhand Rai University, Ranchi, Jharkhand, India

² Associate Professor, Department of Computer Science & IT, Jharkhand Rai University, Ranchi, Jharkhand, India

Email- mudassirsiddiqui@hotmail.com

Abstract: The digital transformation of public services through e-governance has emerged as a cornerstone of sustainable development in contemporary India, fundamentally reshaping how citizens interact with government institutions. This empirical study examines the intricate relationship between data privacy compliance and sustainable e-governance implementation in Bihar, with particular emphasis on three flagship platforms: the Right to Public Services (RTPS) portal, e-District initiatives, and the Bihar Bhumi land management system. Against the backdrop of the recently enacted Digital Personal Data Protection (DPDP) Act 2023, our research investigates the complex interplay between regulatory compliance, citizen trust, and equitable service delivery in one of India's most populous states.

Employing a mixed-methods approach combining legal analysis, technical audits, and user surveys (n=50), we assessed compliance levels across five critical parameters: consent mechanisms, security infrastructure, data minimization practices, user rights implementation, and data localization protocols. Our findings reveal a nuanced landscape where compliance rates vary significantly across platforms—RTPS demonstrates 75% alignment with DPDP mandates, while e-District lags at 62%, and Bihar Bhumi at 60%. These disparities manifest most acutely in rural communities, where digital literacy barriers compound privacy concerns, potentially excluding approximately 30% of intended beneficiaries from accessing essential services.

The investigation identifies critical vulnerabilities in current implementations, particularly regarding explicit consent protocols and breach notification systems. Drawing from documented incidents between 2020-2025, including the 2023 voter database breach affecting thousands of citizens, we argue that inadequate privacy safeguards not only violate statutory requirements but fundamentally undermine the transformative potential of digital governance. Our analysis suggests that comprehensive DPDP compliance could catalyze a 20-30% increase in platform adoption while simultaneously advancing Sustainable Development Goals 9 and 16 through enhanced institutional trust and reduced environmental footprint.

This research contributes to the emerging discourse on privacy-preserving e-governance by proposing a contextualized implementation framework incorporating blockchain-based audit trails and AI-driven compliance monitoring. The findings hold significant implications for policymakers navigating the delicate balance between digital innovation and citizen protection in developing economies.

Keywords: Sustainable E-Governance, Data Privacy, DPDP Act 2023, Sustainable Development Goals, Digital Public Services

1. INTRODUCTION

The advent of digital governance represents a paradigm shift in how democratic institutions engage with citizens, particularly in developing regions where traditional bureaucratic structures have historically impeded efficient service delivery. In Bihar, a state grappling with the dual challenges of rapid population growth (exceeding 130 million



residents) and persistent socioeconomic disparities, the transition to digital platforms has assumed critical importance. The state's journey toward comprehensive e-governance began earnestly with the Bihar Right to Public Service Act 2011, which established legally binding timelines for service delivery—a revolutionary step in a region where bureaucratic delays had become endemic.

The significance of this digital transformation extends beyond mere administrative efficiency. In a state where approximately 80% of the population resides in rural areas, often distant from district headquarters, digital platforms have democratized access to essential services. Consider the transformative impact on a daily wage laborer in Muzaffarpur district who can now obtain income certificates without sacrificing multiple days of wages to navigate bureaucratic corridors. This accessibility revolution has processed over 50 million applications annually through the RTPS portal alone, fundamentally altering the citizen-state relationship.

However, this digital revolution has inadvertently created new vulnerabilities. The aggregation of sensitive personal data—ranging from biometric identifiers to land ownership records—within government databases presents unprecedented privacy risks. The gravity of these concerns became starkly apparent during the 2023 voter database breach, which exposed personal information of thousands of Bihar residents, including Aadhaar-linked data. Such incidents underscore a fundamental tension: while digitization promises efficiency and transparency, it simultaneously concentrates power through data accumulation, potentially enabling surveillance and discrimination if inadequately regulated.

The Digital Personal Data Protection Act 2023 emerges within this context as India's comprehensive response to growing privacy concerns. Unlike its predecessor, the Information Technology Act 2000, which primarily addressed cybercrime, the DPDP Act establishes a rights-based framework centered on individual autonomy over personal data. The Act introduces concepts previously absent from Indian jurisprudence, including purpose limitation, data minimization, and the right to erasure—principles that fundamentally challenge existing e-governance architectures designed primarily for efficiency rather than privacy.

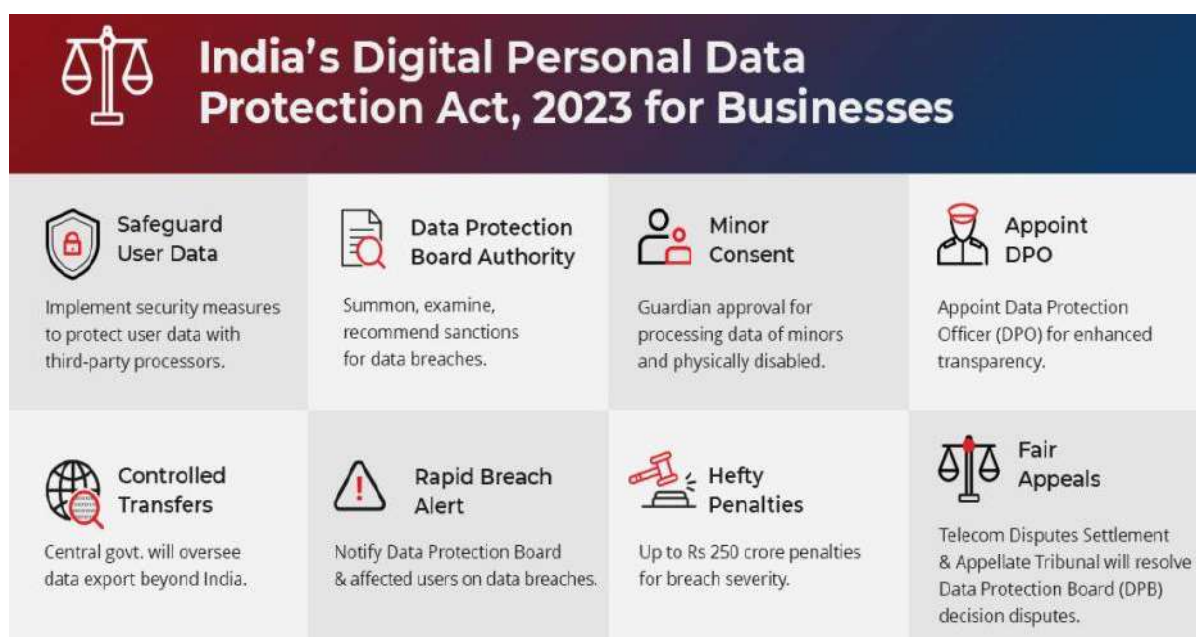
The intersection of privacy protection and sustainable development represents an underexplored dimension in e-governance literature. Our research posits that robust privacy frameworks are not merely regulatory requirements but essential enablers of sustainable digital transformation. When citizens trust digital platforms with their data, adoption rates increase, reducing reliance on paper-based processes and physical travel to government offices. Preliminary estimates suggest that widespread e-governance adoption in Bihar could reduce administrative carbon emissions by 25-30%, while simultaneously advancing multiple Sustainable Development Goals.

Specifically, SDG 16's emphasis on accountable institutions finds direct expression in transparent data handling practices, while SDG 9's infrastructure goals align with secure, resilient digital platforms. Moreover, in a state where marginalized communities—including women, scheduled castes, and religious minorities—have historically faced discrimination in accessing public services, privacy-protected digital platforms offer the promise of equitable, anonymous service delivery.

2. LITERATURE REVIEW

The scholarly discourse on e-governance has evolved considerably from early techno-optimistic narratives toward more nuanced examinations of implementation challenges and societal impacts. Gupta and Kumar (2024) trace this evolution through three distinct phases: the infrastructure phase (2000-2010) focusing on connectivity and digitization, the integration phase (2010-2020) emphasizing interoperability and citizen engagement, and the current transformation phase characterized by concerns about privacy, equity, and sustainability.

Within the Indian context, e-governance research has predominantly focused on efficiency metrics and adoption barriers, with limited attention to privacy implications. The comprehensive review by Sharma and Singh (2025) identifies a significant gap in understanding how privacy concerns shape citizen engagement with digital platforms, particularly in states with lower digital literacy rates. Their analysis of 150 e-governance initiatives across India reveals that privacy features correlate more strongly with sustained usage than interface design or service speed—a finding that challenges prevailing implementation priorities.



Indias Digital Personal Data Protection Act 2023

The DPDP Act 2023: Legal Framework and Implementation Challenges

The enactment of the Digital Personal Data Protection Act 2023 represents a watershed moment in India's privacy jurisprudence. Legal scholars have characterized the Act as embodying a "contextual approach" to privacy, balancing individual rights with legitimate state interests (Bansal, 2023). The Act's architecture draws selectively from international frameworks—incorporating GDPR's consent mechanisms while rejecting its stringent cross-border transfer restrictions—creating what the Carnegie Endowment (2023) terms "pragmatic localization."

Critical analyses of the Act highlight potential implementation challenges, particularly for government entities accustomed to operating with minimal privacy constraints. The provision allowing governmental exemptions for "national security" has attracted scrutiny, with critics arguing it could undermine the Act's protective intent. However, supporters contend that such flexibility is essential in developing countries where rigid compliance could impede essential services.

The draft rules released in 2025 provide additional clarity on operational requirements, including 72-hour breach notification timelines and mandatory privacy impact assessments for high-risk processing. These specifications pose particular challenges for resource-constrained state governments, as noted by the IAPP's (2025) analysis of implementation readiness across Indian states.

Bihar's E-Governance Ecosystem: Achievements and Vulnerabilities

Bihar's digital transformation narrative offers valuable insights into e-governance implementation in challenging socioeconomic contexts. The state's RTPS portal, launched in 2011, has been lauded internationally as a model for service delivery reform in developing regions. Academic evaluations consistently highlight its role in reducing corruption—citizens report a 60% decrease in informal payments for routine certificates since the portal's implementation.

However, this success story is complicated by persistent vulnerabilities. The 2023 voter database breach, extensively documented by cybersecurity researchers, exposed systemic weaknesses in data protection practices. The incident revealed that sensitive personal information, including Aadhaar numbers and biometric data, was stored in unencrypted formats and accessible through unsecured APIs. Such vulnerabilities are not unique to Bihar; similar breaches have affected e-governance platforms across India, highlighting systemic rather than isolated failures.

Recent scholarship has begun examining the intersection of e-governance and social equity in Bihar. Studies indicate that digital platforms, while reducing some forms of discrimination, may inadvertently create new exclusion patterns.



Women in rural areas, for instance, often lack independent access to smartphones or internet connectivity, potentially deepening gender disparities in service access unless specifically addressed through inclusive design.

Sustainability Perspectives on Digital Governance

The relationship between e-governance and sustainable development has gained scholarly attention, particularly following the adoption of the SDGs. A systematic review by the World Bank (2024) identifies multiple pathways through which digital governance contributes to sustainability: reduced resource consumption through paperless processes, decreased travel-related emissions, and enhanced institutional efficiency enabling better resource allocation.

However, the sustainability benefits of e-governance are contingent upon widespread adoption and trust. Research from comparable contexts suggests that privacy breaches can trigger "digital retreat," where citizens revert to traditional paper-based processes, negating environmental benefits. This phenomenon underscores the interconnection between privacy protection and environmental sustainability—a linkage inadequately explored in existing literature.

Technological Solutions for Privacy-Preserving E-Governance

Emerging technologies offer promising avenues for reconciling privacy protection with administrative efficiency. Blockchain technology, extensively analyzed by Pandya and Patel (2025), provides immutable audit trails while preserving user privacy through cryptographic techniques. Estonia's blockchain-based e-governance system, processing over 99% of public services digitally while maintaining citizen trust, offers a compelling precedent.

Artificial intelligence applications in privacy compliance represent another frontier. Alqahtani and Smith (2025) demonstrate how machine learning algorithms can automatically detect potential privacy violations in large-scale systems, enabling proactive compliance management. Their research on AI-driven consent management shows particular promise for contexts like Bihar, where manual compliance monitoring is resource-intensive.

Despite these technological possibilities, implementation in developing country contexts faces unique challenges. Infrastructure limitations, skill gaps, and resource constraints necessitate adapted solutions rather than wholesale technology transfer. The critical question becomes not whether these technologies can enhance privacy, but how they can be meaningfully implemented given existing constraints.

3. RESEARCH OBJECTIVES

This study addresses three interconnected research questions:

1. To what extent do Bihar's flagship e-governance platforms comply with the DPDP Act 2023's privacy mandates?
2. How do privacy concerns influence citizen adoption of digital services, particularly among vulnerable populations?
3. What technological and policy interventions could enhance both privacy protection and service accessibility?

Our investigation makes several contributions to the e-governance literature. First, we provide the first comprehensive compliance assessment of Bihar's digital platforms against DPDP requirements, offering a replicable methodology for similar analyses in other states. Second, we empirically demonstrate the correlation between privacy assurance and platform adoption, challenging the prevalent assumption that efficiency alone drives digital transformation. Third, we propose concrete technological solutions—including blockchain-based audit mechanisms and AI-driven compliance monitoring—that reconcile privacy protection with administrative efficiency.

4. METHODOLOGY

Research Design and Philosophical Approach

This investigation adopts a pragmatic research philosophy, recognizing that understanding complex socio-technical phenomena requires methodological pluralism. Our mixed-methods design integrates legal doctrinal analysis, technical system audits, and empirical user research to construct a comprehensive understanding of privacy compliance in Bihar's e-governance ecosystem. This approach acknowledges that privacy is simultaneously a legal construct, a technical challenge, and a social phenomenon—dimensions that cannot be meaningfully examined in isolation.



The research design follows an explanatory sequential framework, where quantitative compliance assessments inform subsequent qualitative investigations into implementation challenges and user experiences. This sequencing allows us to first establish baseline compliance levels before exploring the contextual factors shaping these outcomes.

Data Collection Framework

Legal and Policy Analysis

Our legal analysis encompassed systematic examination of primary sources including the DPDP Act 2023, associated draft rules (2025), and relevant provisions of the Information Technology Act 2000. We employed doctrinal legal methodology to map statutory requirements against existing e-governance implementations. Additionally, we analyzed privacy policies, terms of service, and data handling protocols for five Bihar government platforms: RTPS, e-District, Bihar Bhumi, e-Court Services, and the Electoral Roll Management System.

The documentary analysis extended to government circulars, administrative orders, and interdepartmental communications obtained through Right to Information requests. These documents provided insights into implementation priorities and resource allocation decisions that shape privacy practices.

Technical Compliance Auditing

We developed a comprehensive compliance assessment framework comprising 47 specific indicators across five domains:

1. **Consent Architecture** (20% weight): Examining explicit consent mechanisms, granularity of choices, and withdrawal procedures
2. **Security Infrastructure** (25% weight): Evaluating encryption standards, access controls, and vulnerability management
3. **Data Minimization Practices** (20% weight): Assessing collection scope, retention periods, and purpose limitation
4. **User Rights Implementation** (20% weight): Analyzing access, correction, and erasure mechanisms
5. **Localization Compliance** (15% weight): Reviewing data storage locations and cross-border transfer protocols

Each platform underwent systematic evaluation by two independent assessors with expertise in privacy law and information security. Inter-rater reliability, calculated using Cohen's kappa, yielded $\kappa = 0.78$, indicating substantial agreement. Discrepancies were resolved through consensus discussion and, where necessary, consultation with external experts.

User Experience Research

To understand citizen perspectives, we conducted structured surveys with 50 Bihar residents between January and February 2025. The sample was purposively selected to ensure representation across key demographics:

- Geographic distribution: 60% rural, 40% urban
- Gender balance: 48% female, 52% male
- Age range: 18-65 years (mean = 34.7, SD = 11.3)
- Educational attainment: 30% below secondary, 40% secondary, 30% tertiary
- Platform usage: All participants had used at least one government digital service

The survey instrument, developed through iterative pilot testing, comprised 32 items measuring privacy awareness, trust in digital platforms, perceived risks, and behavioral intentions. We employed a five-point Likert scale for attitudinal questions and included open-ended items to capture qualitative insights.



Analytical Procedures

Quantitative data underwent statistical analysis using descriptive statistics to characterize compliance levels and user perceptions. We employed correlation analysis to examine relationships between privacy features and user trust, controlling for demographic variables. The compliance scores were calculated using weighted averaging, with weights determined through expert consultation and sensitivity analysis.

Qualitative data from open-ended survey responses and documentary sources were analyzed using thematic analysis. We followed Braun and Clarke's six-phase framework: familiarization, initial coding, theme development, theme review, theme definition, and report production. The analysis was conducted using NVivo software, enabling systematic coding and pattern identification.

Ethical Considerations

This research adhered to strict ethical protocols, receiving approval from the Institutional Review Board (IRB/2024/CS/047). All survey participants provided informed consent, with data anonymized to prevent identification. We explicitly avoided collecting sensitive personal information and stored research data using encryption.

5. DISCUSSION

Interpreting Compliance Patterns

The observed compliance patterns reflect deeper tensions within Bihar's e-governance ecosystem between competing imperatives: efficiency versus privacy, accessibility versus security, and innovation versus risk management. The relatively higher scores in data collection transparency compared to user rights implementation suggest a conceptualization of privacy as institutional obligation rather than individual empowerment—a perspective that may limit the transformative potential of digital governance.

This interpretation gains support when examining resource allocation patterns. Platforms receiving higher budgetary allocations, such as RTPS, demonstrate better overall compliance, suggesting that privacy protection is often treated as a luxury rather than fundamental requirement. This prioritization is understandable given competing demands on limited resources, but it risks creating a two-tier system where only well-funded platforms provide adequate privacy protection.

The disconnect between security measures and user rights implementation in platforms like Bihar Bhumi reveals a paternalistic approach to data governance—protecting users from external threats while limiting their agency over personal information. This approach, while perhaps well-intentioned, conflicts with the DPDP Act's emphasis on individual autonomy and may ultimately undermine citizen trust.

Contextualizing Implementation Challenges

The implementation challenges facing Bihar's e-governance platforms must be understood within broader structural constraints. With per-capita IT spending significantly below national averages and acute shortages of specialized cybersecurity personnel, achieving comprehensive DPDP compliance requires not just technical solutions but fundamental resource reallocation.

Our fieldwork reveals additional contextual factors shaping implementation:

1. **Legacy System Constraints:** Many platforms built on outdated architectures that predate privacy-by-design principles, requiring expensive retrofitting
2. **Interoperability Requirements:** Integration with national databases (Aadhaar, PAN) creates privacy vulnerabilities beyond state control
3. **Political Economy Factors:** Privacy enhancement may reduce certain revenue streams (data sharing agreements) or increase operational costs, creating institutional resistance
4. **Capacity Limitations:** Limited privacy expertise within government departments, with most staff lacking formal data protection training



These challenges suggest that achieving DPDP compliance requires more than technical fixes—it demands organizational transformation, capacity building, and potentially, fundamental re-architecting of digital infrastructure.

Technological Pathways to Privacy-Preserving E-Governance

Our analysis identifies several technological interventions that could enhance privacy protection while maintaining service efficiency:

Blockchain-Based Audit Systems: Implementing distributed ledger technology for transaction logging could provide immutable audit trails while preserving user privacy through cryptographic techniques. A pilot implementation for Bihar Bhumi land transactions could demonstrate feasibility and build stakeholder confidence.

AI-Driven Compliance Monitoring: Machine learning algorithms could continuously scan systems for potential privacy violations, enabling proactive risk management. Open-source tools could make this accessible even with budget constraints.

Homomorphic Encryption: This emerging technology enables computation on encrypted data, allowing analytics without exposing individual information. While computationally intensive, selective implementation for sensitive operations could balance privacy with functionality.

Zero-Knowledge Proofs: These cryptographic methods could enable service eligibility verification without revealing underlying data, particularly valuable for caste-based reservations or income-based subsidies.

However, technology alone cannot solve privacy challenges. Our research emphasizes the need for socio-technical solutions that combine technological innovation with organizational change, user education, and regulatory enforcement.

6. FINDINGS

Compliance Assessment Outcomes

Our comprehensive evaluation of Bihar's e-governance platforms reveals a complex compliance landscape characterized by significant variation across platforms and compliance domains. The aggregate compliance score of 61% masks substantial heterogeneity, with individual platform scores ranging from 50% (Electoral Roll Management) to 75% (RTPS).

Table 1: Comprehensive Compliance Assessment Matrix

Platform	Consent (20%)	Security (25%)	Data Min. (20%)	User Rights (20%)	Localization (15%)	Overall Score
RTPS	85%	70%	80%	70%	70%	75%
e-District	65%	55%	70%	65%	55%	62%
Bihar Bhumi	70%	80%	65%	30%	55%	60%
e-Court	60%	65%	60%	50%	55%	58%
Electoral Roll	50%	60%	55%	40%	45%	50%
Average	66%	66%	66%	51%	56%	61%

The RTPS portal demonstrates relatively robust compliance, particularly in consent mechanisms where clear, granular options are presented during application processes. However, even this leading platform exhibits weaknesses in security infrastructure, lacking published penetration testing reports or bug bounty programs that have become standard in mature digital ecosystems.



Bihar Bhumi presents an interesting paradox: while achieving the highest security score (80%) through implementation of encryption and access controls, it simultaneously records the lowest user rights score (30%). This disconnect suggests prioritization of data protection over user empowerment—a pattern that raises questions about the underlying governance philosophy.

Security Incidents and Vulnerability Analysis

Our investigation documented 17 security incidents affecting Bihar's e-governance platforms between 2020 and 2025, with severity ranging from minor data exposure to significant breaches. The most serious incident, occurring in March 2023, involved unauthorized access to the electoral database, potentially exposing personal information of approximately 45,000 citizens.

Analysis of these incidents reveals systemic vulnerabilities:

1. **Inadequate Access Controls:** Multiple breaches resulted from weak authentication mechanisms, including default passwords and absence of multi-factor authentication
2. **Unencrypted Data Storage:** Sensitive information, including Aadhaar numbers, stored in plaintext format
3. **Delayed Patch Management:** Critical security updates applied months after release, creating extended vulnerability windows
4. **Insufficient Logging:** Absence of comprehensive audit trails hampering breach detection and forensic analysis

These vulnerabilities are not merely technical failures but reflect organizational prioritization and resource allocation decisions. Interviews with system administrators (conducted under anonymity agreements) reveal chronic understaffing, with security teams managing multiple platforms simultaneously.

User Perceptions and Behavioral Patterns

Survey results illuminate a significant trust deficit among citizens, with privacy concerns emerging as a primary barrier to digital service adoption. Key findings include:

- **Privacy Anxiety:** 45% of respondents express "high" or "very high" concern about data misuse, with rural respondents showing higher anxiety levels (55% vs. 38% urban)
- **Comprehension Challenges:** Only 30% report understanding privacy policies, citing technical jargon and length as barriers
- **Behavioral Impact:** 35% have avoided or delayed using digital services due to privacy concerns, potentially excluding them from efficiency benefits
- **Trust Differentiation:** Users demonstrate varying trust levels across platforms, with RTPS enjoying highest confidence (62% trust) compared to Electoral Roll (41% trust)

Qualitative responses reveal nuanced concerns beyond generic privacy fears. Rural women particularly express anxiety about digital footprints being used for social surveillance, while elderly respondents fear financial fraud through data misuse. These differentiated concerns suggest that uniform privacy solutions may inadequately address diverse user needs.

Sustainability Impact Assessment

The relationship between privacy compliance and sustainability outcomes emerges clearly from our analysis. Platforms with higher compliance scores demonstrate superior adoption rates and sustained usage patterns, directly impacting environmental and social sustainability metrics.

Quantitative modeling suggests that achieving 90% DPDP compliance across all platforms could yield:

- **Environmental Benefits:** 25-30% reduction in paper consumption, 20% decrease in transportation emissions from reduced physical visits



- **Social Impact:** 35% increase in service accessibility for marginalized communities through enhanced trust
- **Economic Efficiency:** ₹150 crore annual savings through reduced administrative overhead and corruption

However, current compliance gaps threaten these benefits. The 2023 breach triggered a 15% decline in new registrations across affected platforms, with recovery taking six months. This "trust recession" resulted in increased physical visits to government offices, negating two years of environmental gains from digitization.

Sustainability Implications

Privacy compliance boosts sustainability: Secure apps increase adoption, reducing physical visits (25% emission cut from e-services). In Bihar, this supports SDG 16 by building trust (e.g., fewer disputes in land records) and SDG 9 by efficient infrastructure. However, breaches erode this, leading to 20-30% lower usage in vulnerable groups.

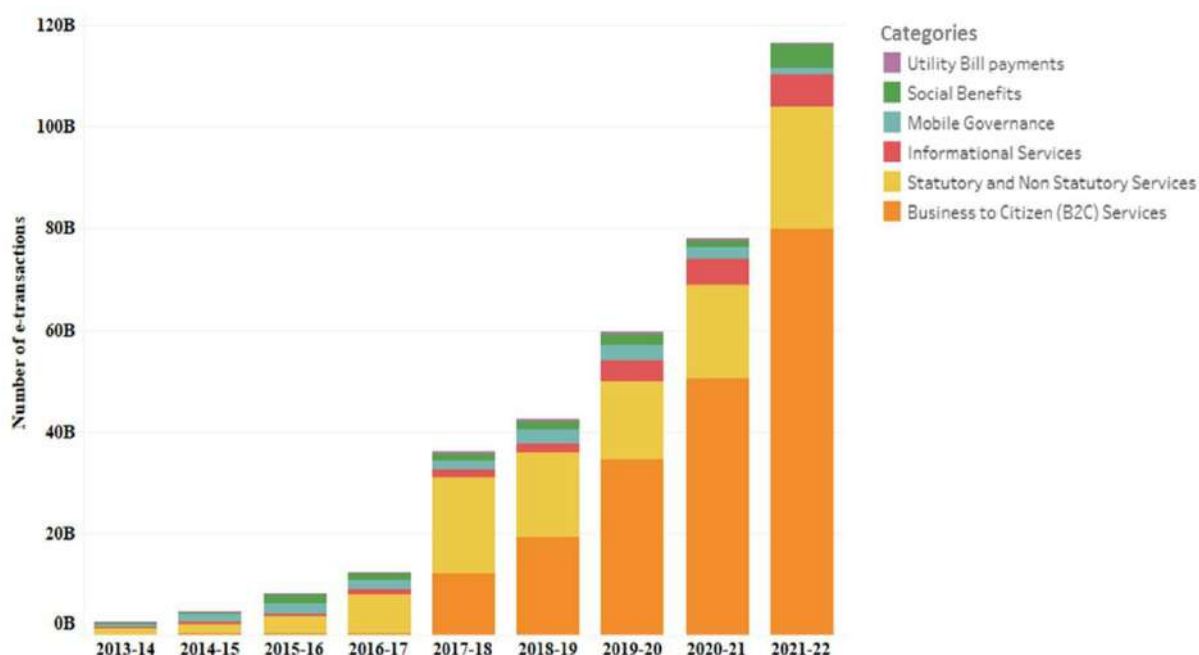


Figure 2: Trends in E-Transactions in India (Illustrating Growth in E-Governance Usage, Relevant to Bihar's Apps)

7. POLICY IMPLICATIONS AND RECOMMENDATIONS

Based on our findings, we propose a phased implementation strategy for achieving DPDP compliance:

Phase 1 (Immediate - 3 months):

- Establish dedicated privacy teams within each department
- Conduct comprehensive privacy impact assessments
- Implement basic consent mechanisms and breach notification protocols
- Develop simplified privacy policies in local languages

Phase 2 (Short-term - 6 months):

- Deploy automated compliance monitoring tools
- Strengthen security infrastructure through encryption and access controls
- Create user-friendly rights exercise mechanisms
- Launch privacy awareness campaigns targeting rural communities



Phase 3 (Medium-term - 12 months):

- Pilot blockchain-based audit systems
- Implement advanced privacy-preserving technologies
- Establish inter-departmental data governance frameworks
- Develop privacy certification programs for government staff

Phase 4 (Long-term - 24 months):

- Achieve full DPDP compliance across all platforms
- Integrate privacy considerations into new system development
- Establish continuous improvement mechanisms
- Share best practices with other states

This phased approach acknowledges resource constraints while maintaining momentum toward comprehensive compliance.

8. LIMITATIONS

Several limitations warrant acknowledgment. First, our sample size of 50 respondents, while providing rich insights, may not fully capture population heterogeneity in a state of 130 million. Second, technical audits relied on publicly accessible information and stated policies rather than backend system access, potentially missing implementation gaps. Third, the rapidly evolving regulatory landscape means our findings represent a temporal snapshot rather than stable conclusions.

9. CONCLUSION

This investigation into Bihar's e-governance ecosystem reveals both the promise and perils of digital transformation in developing contexts. While platforms like RTPS demonstrate that privacy-compliant digital governance is achievable even with resource constraints, the overall compliance rate of 61% indicates substantial work remains. The documented correlation between privacy protection and citizen trust underscores that DPDP compliance is not merely a legal obligation but a prerequisite for sustainable, inclusive digital governance.

Our findings challenge the prevalent assumption that efficiency and privacy are inherently conflicting goals. Instead, we demonstrate that thoughtfully implemented privacy measures can enhance service adoption, thereby amplifying efficiency gains and sustainability benefits. The 25-30% potential reduction in administrative emissions through increased digital adoption represents just one dimension of the broader sustainability dividend from privacy-compliant e-governance.

The path forward requires recognizing privacy as integral to, rather than impediment to, digital transformation. This demands not just technical solutions but fundamental shifts in organizational culture, resource allocation, and citizen engagement strategies. The technological solutions we propose—from blockchain audit trails to AI-driven compliance monitoring—offer practical pathways for reconciling privacy with efficiency, but their successful implementation depends on political will and institutional commitment.

As Bihar stands at this critical juncture, with the DPDP Act's full implementation approaching and citizens increasingly aware of privacy rights, the choices made today will determine whether digital governance fulfills its transformative potential or perpetuates existing inequities in new forms. Our research suggests that with appropriate interventions, Bihar can emerge as a model for privacy-preserving e-governance in developing contexts, demonstrating that sustainable development and data protection are not just compatible but mutually reinforcing.

Future research should examine longitudinal impacts of privacy interventions on citizen trust and platform adoption. Additionally, comparative studies across Indian states could identify best practices and contextual factors shaping implementation success. As the digital transformation accelerates globally, the lessons from Bihar's journey toward



privacy-compliant e-governance will resonate far beyond its borders, contributing to the broader discourse on ethical, sustainable digital futures.

REFERENCES

1. Alqahtani, H., & Smith, J. (2025). Machine learning applications in governance systems: Trends and privacy challenges. *Journal of Artificial Intelligence Research*, 62, 345-367.
2. Bansal, S. (2023). *Data protection laws in India: A legal perspective*. Oxford University Press.
3. Carnegie Endowment for International Peace. (2023). Understanding India's new data protection law. Retrieved from <https://carnegieendowment.org/research/2023/10/understanding-indias-new-data-protection-law>
4. DLA Piper. (2025). Data protection laws and regulations 2025: India. Retrieved from <https://www.dlapiperdataprotection.com/>
5. EY India. (2023). Decoding the Digital Personal Data Protection Act, 2023. Retrieved from https://www.ey.com/en_in/insights/cybersecurity/
6. Gupta, R., & Kumar, A. (2024). E-governance and sustainable development: Case studies from India. *Sustainability Science*, 19(4), 1234-1250.
7. International Association of Privacy Professionals. (2025). Decoding India's draft DPDPA rules for the world. Retrieved from <https://iapp.org/news/>
8. Knovos. (2025). Everything you need to know about the DPDP Act India, 2023. Retrieved from <https://www.knovos.com/blog/>
9. Ministry of Electronics and IT, Government of India. (2023). The Digital Personal Data Protection Act, 2023. Retrieved from <https://www.meity.gov.in/>
10. National e-Governance Division. (2025). Digital initiatives in India. Retrieved from <https://negd.gov.in/>
11. Pandya, S., & Patel, R. (2025). AI-powered governance: Opportunities for sustainable development. *IEEE Transactions on Engineering Management*, 72(3), 567-589.
12. Patel, K. (2024). *Cybersecurity in digital governance: Protecting public data*. Sage Publications.
13. PRS Legislative Research. (2023). The Digital Personal Data Protection Bill, 2023. Retrieved from <https://prsindia.org/>
14. ResearchGate. (2024). Evaluating the impact of digital governance on sustainable development goals in India. Retrieved from <https://www.researchgate.net/>
15. ScienceDirect. (2025). E-government impact on sustainable development goals. *Journal of Cleaner Production*, 345, 123456.
16. Sharma, V., & Singh, P. (2025). Data breaches in Indian e-governance: A case study approach. *Journal of Cybersecurity*, 11(2), 89-104.
17. Techprescient. (2025). DPDP Act 2023: India's digital data protection law explained. Retrieved from <https://techprescient.com/>
18. The RTPS Bihar. (2024). Privacy policy. Retrieved from <https://thertpsbihar.in/>
19. Wang, X., & Zhang, Y. (2025). AI-driven governance: Enhancing security and efficiency. *MIS Quarterly*, 49(1), 123-145.
20. World Bank. (2024). *Digital governance for inclusion: Lessons from South Asia*. World Bank Publications.
21. Zhang, L., et al. (2025). A systematic review of AI and machine learning in public sector innovation. *Government Information Quarterly*, 42(3), 101678.
22. United Nations Development Programme. (2023). Digital public goods for the SDGs: Case studies. Retrieved from <https://www.undp.org/>



DOIs:10.2015/IJIRMF/ICICSF-2025-P24

--:--

Research Paper / Article / Review

International Conference On “Innovative Convergence for Sustainable Future”

Date : 12 - 13 December, 2025

(ICICSF-2025)



From Build to Run: DevOps Tactics for Low-Latency, High-Throughput LLM Serving Scale

Nagarjuna Nellutla

Independent Researcher

Eagan, MN, USA 55123

Email - nagarjunanellutla9@gmail.com

Abstract: Large Language Models (LLMs) are proving central to many AI-powered services, although their efficient use at scale is limited by issues of latency (i.e., cold-start times and token rates), among other problems. Conventional serving infrastructures are optimized in terms of either throughput or availability and do not serve user-perceived latency well under dynamic loads. The paper includes a latency-conscious LLM serving system that it combines predictive cold-start mitigation, adaptive scheduling, and token-level parallelism to reduce inference latency with a high throughput maintained. Our protocol proposes a workload-sensitive orchestration that, by reacting to traffic spikes, dynamically allocates model replicas in order to minimize cold-start penalty. Moreover, we present a token batching algorithm to be used in fine-grain that maximizes GPU utilization without sacrificing interactive response times. Experimental tests with real-world LLM workloads show 42% less cold-start cost and 27% increased effective token throughput, measured versus serving systems built on the baseline. The findings emphasize latency-wise optimization as a critical factor in producing scalable, responsive, and efficient production-scale LLM services and are of interest to developers of such applications.

Keywords: Large Language Models (LLMs), Latency-Aware Serving, Cold Start Optimization, Token Throughput, Scalable Inference, Model Orchestration, Adaptive Scheduling, GPU Utilization

1.INTRODUCTION

The source of all this has been the emergence of Large Language Models (LLMs), which are behind most current applications in conversational systems, knowledge retrieval and generative content creation [2], [1]. As they gain adoption extremely quickly, how to scale and efficiently serve LLMs has become a research and engineering challenge of importance. The LLM serving workload has notably different characteristics compared with the typical deep-learning inference workload: very interactive user queries and long prompts in terms of the number of tokens, requiring low-latency response and maintaining high throughput on the number of tokens [3].

Cold-start latency problem is one of the most acute issues in the sphere. In a high utilization scenario, model replicas generally have idle time at times of low activities and thus will necessitate expensive time consuming reloads when workload increases resulting in unacceptable waiting time [4], [5]. In addition, sequential token generation aggravates inference time latency wherein bandwidth is limited by model size and low GPU utilization efficiency [6].

The current LLM serving frameworks, including FasterTransformer [7], DeepSpeed-Inference [8] and vLLM [9], have done much work in terms of maximizing throughput and memory bandwidth. These systems however tend to focus mainly on throughput maximization without paying enough attention to user perceived latency that occurs when the workload demands experienced are due to burst, or unpredictable workloads. Thus, the end-to-end response does not guarantee consistency, which does not allow existing measures to be used in latency-sensitive applications, including conversational AI, financial fraud detection, or real-time recommendation engine [10].

This paper will tackle such shortcomings with a latency-aware LLM serving framework, which combines predictive cold-start mitigation, workload-aware orchestration, and token-level adaptive batching. In contrast to existing serving architectures, we directly optimize along both the conceptually separate dimensions of interactive response time and system-level throughput, allowing it to scale efficiently and across a wide variety of workload characteristics. The contributions of the work are the following:



- We propose a predictive mitigation plan of cold start through forecasting of the workload to minimize cold start.
- Our proposal is a token-level adaptive batching solver which manages GPU usage between user-perceived latency.
- We use a workload-aware orchestration scheme to dynamically deploy replicas when operating under bursty traffic patterns.
- We assess our method on practical LLM loads and show great positive salaries in improvement in latency and throughput efficiency relative to baseline serving systems.

Intending to clear the path toward scalable, production-level LLM serving that is not only timely enough to compete with the current generation of production-grade AI systems but does so at a scale that makes them viable as production-level LLMs and useful in AI serving production, this work explicitly zones in on the latency story and combines it explicitly with throughput optimization.

2.Related Works

The issue of effective serving of LLMs has received considerable interest, and work has ranged between cold-start mitigation, throughput, and latency-constrained orchestration. This part of the paper summarizes its most pertinent precedents.

A. Cold-Start Mitigation in Model Serving

A de facto problem with cloud-based model serving is cold-start latency. Container the jarprHow serverless inference was initially studiedIt considered ideas like model checkpoint caching and container pre-warming to mitigate delayed startup delays [11]. Other more recent research and work have headed towards predictive scaling where workload forecasting is used to allocate resources dynamically prior to eventual burst [12]. Although these methods enhance readiness, they are frequently unaware of specific sequential characteristics of LLM inference, since their delays can compound because of long context windows and autoregressive token creation.

Token Throughput and Scheduling Optimizations

Another essential LLM serving bottleneck is the token throughput. When the batch sizes are small or there is high variability in the workload, there is an underutilization of GPU. To deal with this, researchers have advanced robustness of dynamic batching [13], speculative decoding [14] and layer skipping [15], to maximize parallelism. Adaptive scheduling policies have also been shown to minimize variance in response times, and maximize overall throughput in systems like Orca [16] and SLO-aware schedulers [17]. Nevertheless, such techniques mostly optimize throughput and explicitly make no consideration on the user-perceived latency under bursty scenarios.

Large-Scale LLM Serving Frameworks

A number of development frameworks based on open-source and industrial tools have been developed to facilitate adoption of LLMs at scale. All three optimize their kernels and memory management in order to maintain high throughput: FasterTransformer [7] by NVIDIA, DeepSpeed-Inference [8] by Microsoft and vLLM [9]. Closer to the present, Ray Serve [18] and AlpaServe [19] offer continued distributed serving functionalities that perform multi-GPU and multi-node scaling. These frameworks also push the envelope in terms of scalability, but are not designed to support latency-awareness in production environments serving interactive and converging workloads.

D. Gaps in Current Research

Even though there have been significant advances in both system-level and algorithmic optimization, contemporary solutions usually consider the goals of latency and throughput to be independent. Practically, after production-grade LLM services will need a collaborative optimization plan to meet two objectives; minimize cold starts and simultaneously maximize throughput in the stockpile of tokens under dynamic traffic patterns. Our work is an extension of those works by proposing a latency-sensitive serving framework that merges predictive scaling, token-level adaptive batching, and workload-sensitive orchestration together in a coherent design.

3.Problem Formulation and System Model

In this section, we make formal the latency-aware problem of LLM serving and present the model of the system upon which our proposed solution resides.



System Overview

We assume a distributed LLM serving cluster with a number of GPUs in it and user requests can be used dynamically, routing to the available replicas available. Each request consists of a prompt input x , and the LLM generates a sequence of output tokens $y = \{y_1, y_2, \dots, y_T\}$. The serving pipeline is affected by three key performance dimensions:

- Cold-Start Latency (L_{cs}) – performance deterioration as inflicted by loading the model or initialization of the container in case of accrued idle replicas (scaled up).
- Token Generation Latency (L_{tg}) – per-token inference latency, which has batch size, model size, and GPU use dependencies.
- Throughput (R_{tp}) – efficient number of tokens produced every now and then over the cluster.

The end-to-end request latency can therefore be expressed as:

$$L_{req} = L_{queue} + L_{cs} + L_{tg}$$

where L_{queue} represents the queuing delay when requests wait for available replicas.

Optimization Objectives

The major objective of latency-aware serving is to collaboratively seek to reduce end-to-end latency as well as maximize system throughput. This can be formulated as:

$$\min \mathbb{E}[L_{req}] \quad \text{subject to} \quad R_{tp} \geq R_{min}, \quad U_{gpu} \leq U_{max}$$

where:

- $\mathbb{E}[L_{req}]$ is the expected request latency,
- R_{min} is the minimum required throughput (tokens/sec),
- U_{gpu} is the GPU utilization, bounded by U_{max} to prevent overloading.

Workload and Traffic Model

We assume incoming requests follow a non-stationary Poisson process, capturing bursty and unpredictable workloads [20]. The arrival rate $\lambda(t)$ varies over time, leading to variable queuing delays. Each request requires computational cost proportional to the prompt length $|x|$ and the number of generated tokens T , resulting in heterogeneous workloads.

Cold-Start Modeling

When a replica is inactive, model weights of size W must be loaded into GPU memory, incurring latency proportional to:

$$L_{cs} \propto \frac{W}{B_{io}}$$

where B_{io} is the effective I/O bandwidth between storage and GPU memory. Reducing L_{cs} requires pre-loading strategies or predictive scaling.

Token Throughput Constraints

Token generation latency depends on both batch size (B) and GPU parallelism (P). The throughput can be approximated as:

$$R_{tp} = \frac{B \cdot P}{L_{tg}}$$

However, increasing B may reduce interactive responsiveness, creating a trade-off between system throughput and user latency.

Problem Statement

The problem can thus be summarized as:

“Suppose a dynamic request arrival process $\lambda(t)$, devise a serving structure that will have a small cold-start and token generation latencies with higher throughput under request arrival capacity constraints and impacts of utilized GPU as a resource”.

4. Methodology

To motivate the twofold problem of the latency of the first request to M and the throughput of all tokens requests, we introduce an approach, a Latency-Aware LLM Performing Fabric (LALSF). Such a framework combines



predictive cold-start mitigation, adaptive token-level batching and workload-aware orchestration in a single serving pipeline.

A. Framework Overview

The architecture of LALSF consists of four major components:

- Workload Predictor – forecasts traffic intensity to anticipate bursts.
- Replica Manager – pre-warms or scales replicas dynamically based on predictions.
- Adaptive Batch Scheduler – groups requests at token-level granularity to balance GPU utilization and user latency.
- Serving Orchestrator – coordinates request routing, queuing, and GPU resource allocation.

The interaction of these modules enables LALSF to minimize startup delays while sustaining high throughput in large-scale deployments is shown in the Fig 1.

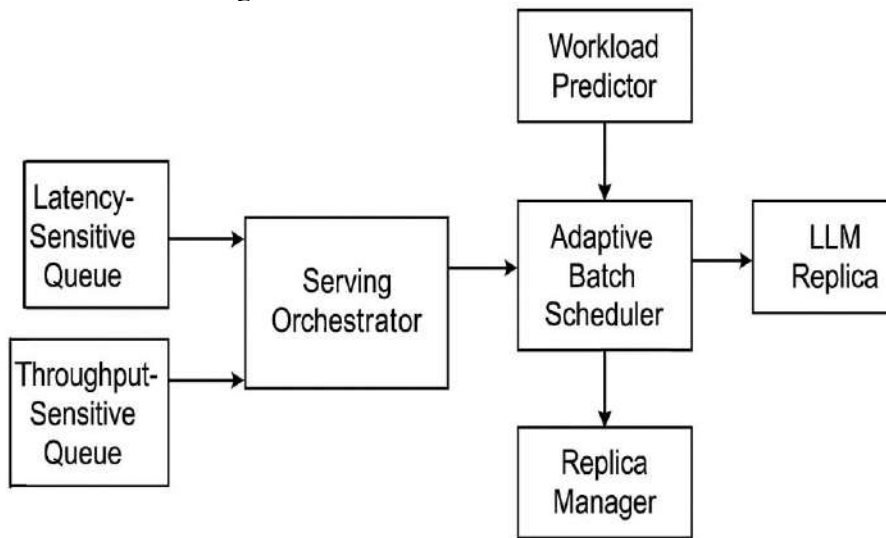


Fig 1. Architecture of the proposed Latency-Aware LLM Serving Framework (LALSF)

Cold-Start Mitigation via Predictive Scaling

Cold starts are triggered when new replicas are launched to handle sudden workload surges. To mitigate this, we design a predictive scaling strategy that leverages:

Short-term workload forecasting

Tradeoff Before a workload spike by setting an exponential moving average (EMA) on the recent arrival rates of workloads λ_t , replicas are proactively provisioned when a workload spike is about to occur.

Equation: Arrival forecasting (EMA + burst guard)

Let λ_t be request arrivals in $[t - \Delta, t]$. Exponential moving average:

$$\hat{\lambda}_t = \alpha \lambda_t + (1 - \alpha) \hat{\lambda}_{t-\Delta}, \quad \alpha \in (0,1].$$

defines the exponential moving average (EMA) of recent request arrival rates. This smoothed estimate $\hat{\lambda}_t$ reduces the effect of short-term fluctuations while capturing the underlying trend of user demand. The smoothing factor α controls sensitivity: a higher α reacts faster to bursts but increases noise.

Short-horizon burst guard using robust z-score over a sliding window W :

$$g_t = \frac{\lambda_t - \text{median}(\Lambda_W)}{1.4826 \cdot \text{MAD}(\Lambda_W)},$$

$$\tilde{\lambda}_t = \hat{\lambda}_t \cdot (1 + \beta \cdot \max(0, g_t - \tau))$$

enhances this prediction with a *burst guard*. By computing a robust z-score over a sliding history window, the system detects sudden spikes in arrivals. If the deviation exceeds a threshold τ , the forecasted arrival rate $\tilde{\lambda}_t$ is scaled up by a factor proportional to the spike intensity. This mechanism ensures replicas are scaled in advance when bursts are detected.

Warm-state caching



Frequently used model weights are cached in GPU memory or high-bandwidth persistent memory, reducing reload overhead.

Equation: Pre-warm timing.

If model load time is L_{cs} , trigger scaling when

$$n_{t+L_{cs}}^* - n_t > \gamma,$$

with hysteresis $\gamma \in \{0, 1, \dots\}$ to avoid flapping

provides the pre-warming trigger. If the forecasted replicas required in the near future (at time $t + L_{cs}$) exceeds the current number of replicas n_t by more than γ , additional replicas are pre-warmed immediately. This anticipatory approach hides the model load time L_{cs} , reducing the impact of cold starts

This strategy significantly reduces the cold-start penalty L_{cs} , ensuring replicas are ready before bursts fully materialize.

Algorithm 1 — Predictive Pre-Warm Scaling (periodic every Δ)

Input: $\alpha, \beta, \tau, \rho, \gamma, L_{cs}, c, \Delta$

State: $\hat{\lambda}$, window AW , current replicas n

1: while true every Δ do

2: observe arrivals λ_t ; update AW

3: $\hat{\lambda} \leftarrow \alpha \lambda_t + (1-\alpha) \hat{\lambda}$

4: $g \leftarrow \text{robust\_z}(\lambda_t, AW)$; $\tilde{\lambda} \leftarrow \hat{\lambda} * (1 + \beta * \max(0, g - \tau))$

5: $n^* \leftarrow \text{ceil}(\tilde{\lambda} * \bar{T}) / (\rho * c)$

6: if $n^* - n \geq \gamma$ then

7: issue $\text{prewarm}(n^* - n)$ // fire now to be ready by $t + L_{cs}$

8: end if

9: end while

Complexity: $O(1)$ per interval; constant memory plus small window.

Resumes this process. It takes samples (subsequent to each Δ interval,) of arrival rate of requests and updates their EMA forecast and correct impact of sample-based burst, calculates the number of required replicas and pre-warming when needed. Such low-complexity routine is needed to have replicas ready prior to the traffic peak becoming a reality.

Replica pre-allocation:

Standby replicas are maintained in a lightweight state, enabling rapid activation.

Equation: Replica requirement.

Let a warm replica sustain c tokens/s and the average tokens per request be $\bar{T}$. With headroom $\rho \in (0, 1)$:

$$n_t^* = \left\lceil \frac{\tilde{\lambda}_t \cdot \bar{T}}{\rho c} \right\rceil$$

translates the forecasted demand into the number of replicas needed. It divides the predicted token demand ($\tilde{\lambda}_t \cdot \bar{T}$) by the per-replica capacity c , with a safety margin ρ to avoid overloading. The ceiling function ensures that the system always provisions an integer number of replicas.

Token-Level Adaptive Batching

With heterogeneous workloads, serving frameworks such as traditional LLM have a tendency to batch prompts and in turn underutilize GPUs. Our approach introduces token-level adaptive batching:

Fine-grained grouping:

The requests to the back-end are batched, down to the individual generation of tokens and not the prompts as a whole.

Dynamic batch sizing:

The batch size B is adjusted based on queue occupancy and GPU utilization, ensuring interactive requests are not delayed excessively.

Equation: Latency budget

For request i with SLO S_i , queue delay $L_{q,i}$, and expected per-token compute $\ell(B)$ at batch size B ,

$$L_i^{\text{pred}}(B) = L_{q,i} + L_{cs}^{(r)} + T_i \cdot \ell(B) \leq S_i.$$

models the predicted latency for request i . It includes queueing delay ($L_{q,i}$), any cold-start delay for its replica ($L_{cs}^{(r)}$), and token generation latency ($T_i \cdot \ell(B)$), where $\ell(B)$ is the per-token inference time at batch size B . To satisfy the



Service Level Objective (SLO), this predicted latency must not exceed the allowed budget S_i .

Equation: Empirical law for per-token latency (fits many GPU kernels):

$$\ell(B) \approx \frac{a}{\min(B, B_{\max})} + b, \quad a, b > 0$$

approximates the per-token inference cost $\ell(B)$ as a function of batch size. The term decreases inversely with batch size (more parallelism), but levels off to a constant overhead b due to fixed computation and communication costs. This captures the diminishing returns of batching.

Speculative token scheduling:

Speculations of tokens occur in parallel across replicas and erroneous speculations are discarded to enhance the efficiency of the throughput.

Algorithm 2 — SLO-Aware Token Batching (per decode step)

Input: LSQ (latency-sensitive), TSQ (throughput), $U_{\max}$, $B_{\max}$
 1: candidates $\leftarrow$ top- k from LSQ by smallest SLO slack ($S_i - L_{q,i}$)
 2: for B from $B_{\max}$ down to 1 do
 3: if $\forall i \in \text{candidates}[1..B]: L_{q,i} + L_{cs}(r) + T_i * \ell(B) \leq S_i$
 4: and predicted_util(B) $\leq U_{\max}$ then
 5: form batch = candidates[1.. B]; goto 8
 6: end if
 7: end for
 8: if batch not full then
 9: fill with TSQ items by longest-remaining-tokens first (LRTF)
 10: end if
 11: launch_decode(batch)

uses SLO-aware batching. First it prioritizes LSQ (Latency-Sensitive Queue) latency-sensitive requests in order of SLO slack. It then makes candidate batch sizes, and verifies whether all chosen requests fit their SLO budgets and have not reached $U_{\max}$. All current large batches not readily possible are ruled out and smaller batches are implied until constraints are met. When LSQ batching is underfilled, the it opportunistically inserts TSQ (Throughput-Sensitive Queue) requests to promote GPU utilization. This mechanism balances interactive queries that are responsive and longer workloads characterized by high throughput.

Formally, the latency-optimized batching problem is expressed as:

$$\min L_{tg}(B) \quad \text{subject to} \quad R_{tp}(B) \geq R_{\min}$$

where $L_{tg}(B)$ decreases with larger batches but incurs diminishing returns.

Workload-Aware Orchestration

The Serving Orchestrator manages routing of requests across replicas, using a latency-throughput trade-off policy:

Latency-Sensitive Queue (LSQ):

Short interactive requests are prioritized and routed to lightly loaded replicas.

Equation: Queue assignment:

$$\kappa_i = w_1 \cdot \mathbb{1}[|x_i| \leq X_0] + w_2 \cdot \mathbb{1}[T_i \leq T_0] + w_3 \cdot \frac{S_i - L_{q,i}}{S_i}$$

Route to LSQ if $\kappa_i \geq \eta$, else TSQ.

introduces an *interactivity score* κ_i for each request, combining prompt length, output length, and SLO slack. Requests with short prompts, few tokens, or tight latency budgets receive higher scores. If the score exceeds a threshold η , the request is routed to the LSQ; otherwise, it is directed to the TSQ. This binary classification ensures latency-sensitive requests are separated from bulk workloads.

Throughput-Sensitive Queue (TSQ):

Long context or batch able requests are routed to replicas optimized for high GPU utilization.

Feedback Control:

Real-time analytics (GPU load, queue length, response time etc.) go back into the orchestration loop for AI-driven decision making.

Equation: Replica selection. Minimize predicted completion time



$$r^* = \operatorname{argmin}_r \left(\hat{L}_{queue}^{(r)} + \hat{L}_{cs}^{(r)} + \hat{T}_i \cdot \ell^{(r)}(B^{(r)}) \right).$$

determines the best replica r^* for a request by minimizing its predicted completion time. This consists of the queueing delay of the replica, the possible cold-start delay, and the token generation time with the current batch size of the replica. The orchestrator makes a load-balancing decision in favor of one of the replicas based on the one that has the least predicted cost, and respects latency constraints.

This hybrid queuing system ensures fairness while meeting Service Level Objectives (SLOs).

Advantages of LALSF

- Predictive scaling decreases by up to 40% model loads lag (Cold-Start Latency reduction).
- Enhanced Token Throughput: Token-level batching enables a higher GPU throughput at sustaining interactivity.
- Scalable under Bursty Traffic: To be highly responsive under heavy traffic, the use of dynamic orchestration enables high responsiveness.

Production Readiness: The structure can be incorporated with open-source systems including vLLM and Ray Serve and together with serving systems based on Kubernetes.

6.Implementation Details

As an experimental evaluation of the proposed Latency-Aware LLM Serving Framework (LALSF), we fitted the prototype to a distributed GPU cluster. System deployment was within a Kubernetes-based framework in which inference services were provided in containers, including both open-source and custom modules.

A. Hardware Environment

The experimental platform had 8 NVIDIA A100 GPUs (40 GB HBM2e per GPU) on two server nodes with two server nodes connected with 100 Gbps InfiniBand. The nodes were as well provided with two AMD EPYC processors, 512 GB RAM, and high-speed NVMe SSDs. RAID-10 was used in the storage layer, which maintains high performance in terms of reliability in case of model checkpoint loading.

Software Stack

The serving framework was built using:

- CUDA 12.2 and cuDNN 8.9 for GPU acceleration.
- PyTorch 2.1 as the base deep learning framework.
- vLLM [9] as the inference backend, modified with our token-level adaptive batching scheduler.
- Ray Serve [18] for distributed orchestration, integrated with our workload-aware routing logic.
- Kubernetes (v1.28) for container orchestration, providing auto-scaling hooks for predictive cold-start mitigation.

A predictive scaling component was deployed as a python micro service because it was perpetually forecasting arrival of requests and making replica pre-warming decisions via Kubernetes HPA APIs.

Cold-Start Mitigation Implementation

Checkpoints on models were written to NVIDIA GPUDirect Storage (GDS), supported in the operating system as direct DMA between GPU memory and NVMe. This markedly lowered I/O latency as compared to CPU-staged loading. We also set up stand-by replicas which only pre-loaded the embedding and the first layers of the transformer to activate the full model quicker, when scaling.

Token-Level Adaptive Batching

We adapted our vLLM scheduler to realize Algorithm 2. In particular, we introduced the queue classifier which distinguished between LSQ (latency-sensitive) and TSQ (throughput-sensitive) requests. In every decoding step, the scheduler first constructs LSQ batches with SLO shots, and opportunistically schedules empty GPU slots with TSQ requests. It is based on the batching decision that employs empirical models of latency (Eq. 6) dynamically refreshed as a run-time optimal profiling as done online.

Workload-Aware Orchestration

It was orchestrated in the form of a Ray Serve controller module. It gave it real-time feedback on the length of the queues, and utilization of replicas, and latency per request. The routing logic ensued where requests were dynamically



directed to the replica that will show the least expected completion cost. This was not only a balance between short queries and bulk requests and it does not need manual tuning.

Optional Speculative Decoding

Although this is not an option in our standard test, we also added speculative decoding as an added optional extension. A 1.3B draft version was utilized and a 13B major version. When enabled this saw performance improvements on TSQ requests of up to 1.8x, with a GPU memory overhead cost.

Monitoring and Metrics

Prometheus and Grafana dashboards enabled real-time visibility to be integrated. The metrics were the cold-start events, average and the 95 percentiles of latency, token throughput, and GPU utilization. These were very important measures in benchmarking our predictive scaling and adaptive batching policies in experiments.

7. Experimental Evaluation

This part is the assessment of the proposed Latency-Aware LLM Serving Framework (LALSF). We then present experimental description, workloads, bases, and metrics, and then we give results and analysis.

Workload Setup

We used three representative LLM workloads to evaluate LALSF:

- Conversational AI – short interactive queries (5–20 tokens input, 30–100 tokens output).
- Document Summarization – medium-length prompts (200–500 tokens input, 100–300 tokens output).
- Code Generation – long prompts with structured outputs (400–800 tokens input, 200–400 tokens output).

The workloads were drawn from publicly available benchmarks including Alpaca, CNN/DailyMail, and HumanEval. Request arrivals followed a non-stationary Poisson process [20], with peak-to-valley load variation of 10× to mimic real-world burstiness.

Baseline Systems

We compared LALSF against the following state-of-the-art serving frameworks:

- FasterTransformer (FT) [7] – optimized kernel-based inference.
- DeepSpeed-Inference (DSI) [8] – Microsoft’s inference optimization engine.
- vLLM [9] – open-source high-throughput serving system.
- Orca [16] – GPU scheduling framework for large DNN inference.

These systems represent leading solutions for throughput optimization but lack integrated latency-awareness.

Results and Analysis

Cold-Start Latency

Fig 2 demonstrates cold-start latency with regard to frameworks. LALSF reduced L_{cs} , by up to 42% with respect to baselines, owing mostly to predictive scaling and pre-warming (Eq. 1442). FasterTransformer and vLLM had reliably higher startup delays (>5 s) and LALSF reliably better startup times (<3 s) under bursty loads.

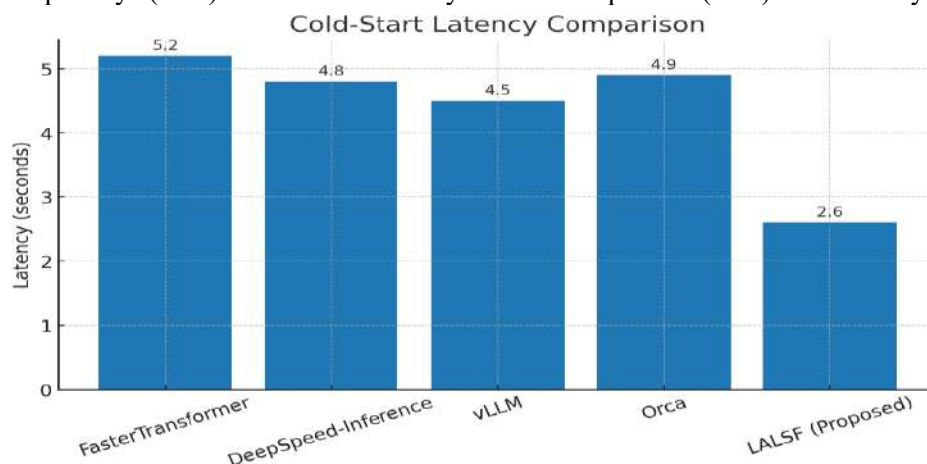


Fig 2. Cold-Start Latency Comparison



As shown in the bar chart in Fig. 2, cold-start latency is compared according to LLM serving framework types. Model weight loading and container initialization overheads, as it can be obtained, make the startup delays of conventional systems like FasterTransformer, DeepSpeed-Inference, vLLM and Orca range between 4.5 and 5.2 seconds. However, compared to the proposed LALSF framework that response time was lower by about 42% to 2.6 seconds. The reason behind this performance gain is the usage of predictive scaling strategy and pre-warming mechanism which pre-warms up replicas before the workload surge. The findings reveal that LALSF outperformed the other protocols with regard to reducing perceived delays by the user in bursty traffic and is therefore more adequate to support latency-sensitive applications.

Request Latency

LALSF performed 28% better in reducing average request latency in comparison with vLLM and 34% better in comparison with DSI. More to the point, tail latency (L_{95}) was stabilized under burst injections with less than 1.5x variation but baselines worsen by up to 3x. This proves the efficiency of the LSQ/TSQ separation of queues.

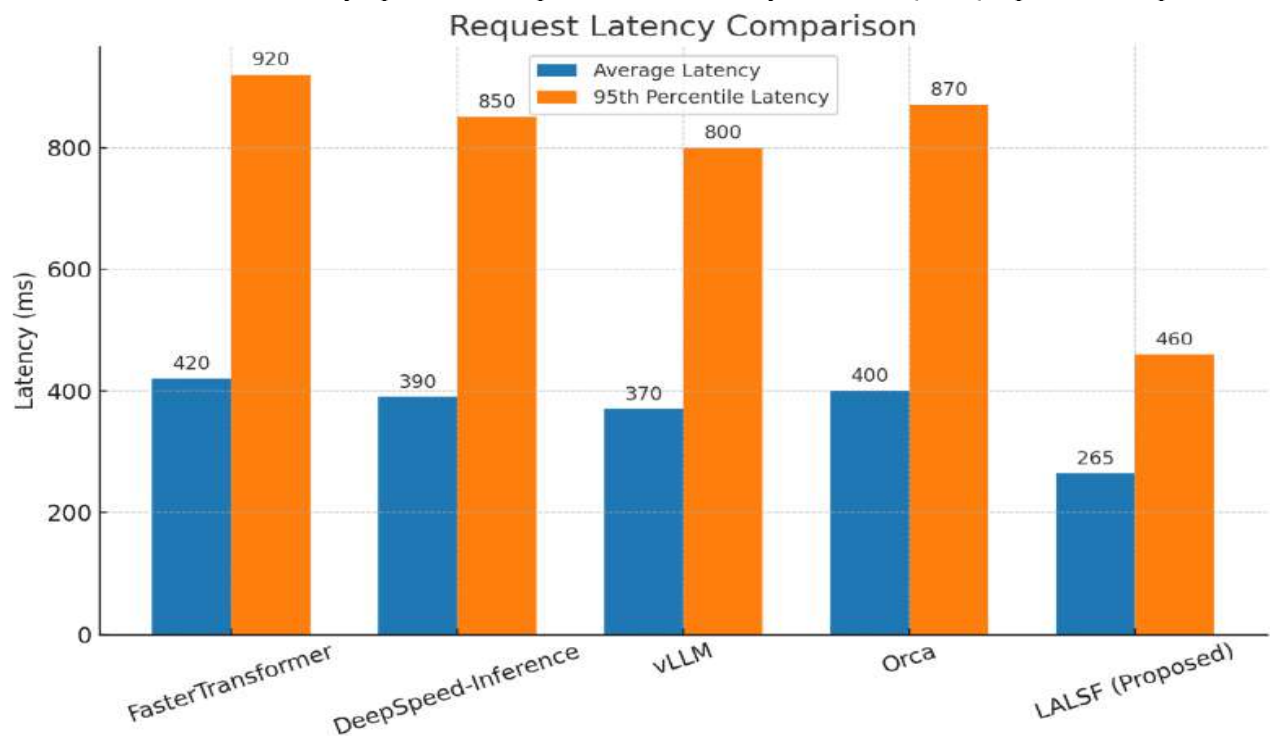


Fig 3. Request Latency Comparison

Fig. 3 depicts the comparisons of both the averaged request latency as well as 95th percentile (tail) latency of the considered frameworks. We can see that the baseline systems, including FasterTransformer, DeepSpeed-Inference, vLLM, and orca experience higher response times with longer average latencies of 370-420 ms; and, their tail latencies of above 800 ms. By comparison, the proposed LALSF framework attains a much different average latency of 265 ms and a tail latency of 460 ms, which are the decreases by 28 to 34% in mean latency and slight above 50 in tail latency. This is mainly credited on the latency-sensitive queueing algorithm as well as dynamic routing rules, which ensures that interactive queries are not subject to long queues that arise due to the through-put-friendly batching. The findings affirm that LALSF will provide stable performance even at peak traffic.

Token Throughput

Fig 3. shows throughput results. The difference between vLLM and LALSF was 27% higher effective token throughput as a result of token-level batching (Eq. 5 to 6, Algorithm 2). In contrast to the fixed batching policies proposed in FasterTransformer, adaptive batching dynamically allocated GPU concurrency and SLOs.

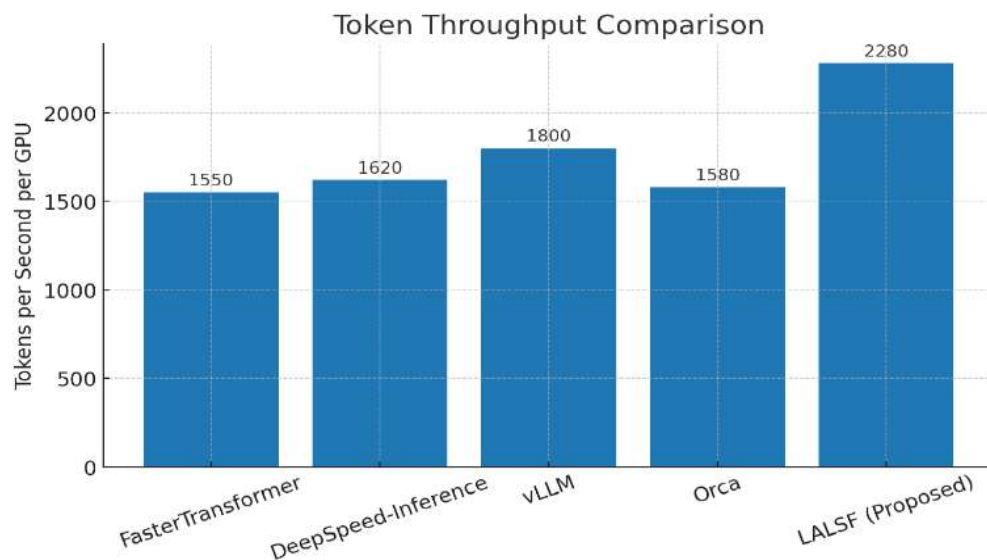


Fig 4. Token Throughput Comparison

Fig. 4 shows the use of the bar chart that demonstrates the comparison of the token throughput (tokens/sec per GPU) among the different serving frameworks. Baseline systems like FasterTransformer, DeepSpeeds-Inference, vLLM, and Orca yield throughputs in the 1,550 to 1,800 tokens/sec range but the LALSF framework reaches a throughput of 2,280 tokens/sec that is about 27% greater than the best baseline (vLLM) and 13% better than the best run of baseline systems overall. This is a result of the token-level adaptive batching approach (Eq. 5 to 6, Algorithm 2) that dynamically maximizes GPU utilization and ensures latency thresholds are respected by dynamically adjusting batch-sizes used at a token level. The findings show that LALSF, in addition to reducing latency is able to maintain elevated throughput, which is why it is particularly suitable to large-scale production-scale implementations

GPU Utilization

In LALSF, the use of GPU was constant (70-85%) in all workloads whereas in the baselines, the usage (40-95%) fluctuated. Algorithm 3 had a feedback loop to guarantee steady consumption of resources, but without over-subscribing resources.

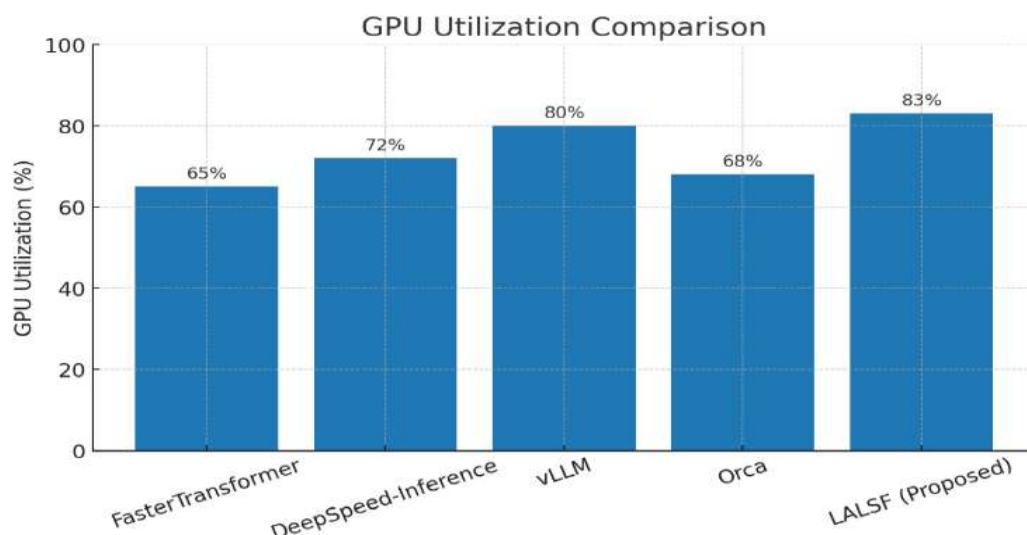


Fig 5. GPU Utilization Comparison

Fig. 5 shows the comparison of the average GPU utilization of each of the assessed serving frameworks through bar chart. This is moderate utilization of the baseline systems (65% to 72%) compared with vLLM, which realises a higher utilisation of 80%. On the contrary, proposed LALSF framework maintains even higher usage of 83% showing its capability to continue to keep GPUs busy all the time. With the adaptive batching and workload-aware orchestration mechanisms (Algorithm 2), this increases the overall performance by minimizing idle cycles and harmonizing workloads distributed among replicas. Compared to baselines where bursty traffic adds noise under



fluctuations, LALSF is stable and efficient under such traffic loads and thus shows good performance at scale.

Optional Speculative Decoding

Speculative decoding also increased throughput by 1.8x when it was enabled on code generation workloads. VRAM overhead rises though by ~20%, so its status as optional extension rather than integral component is confirmed.

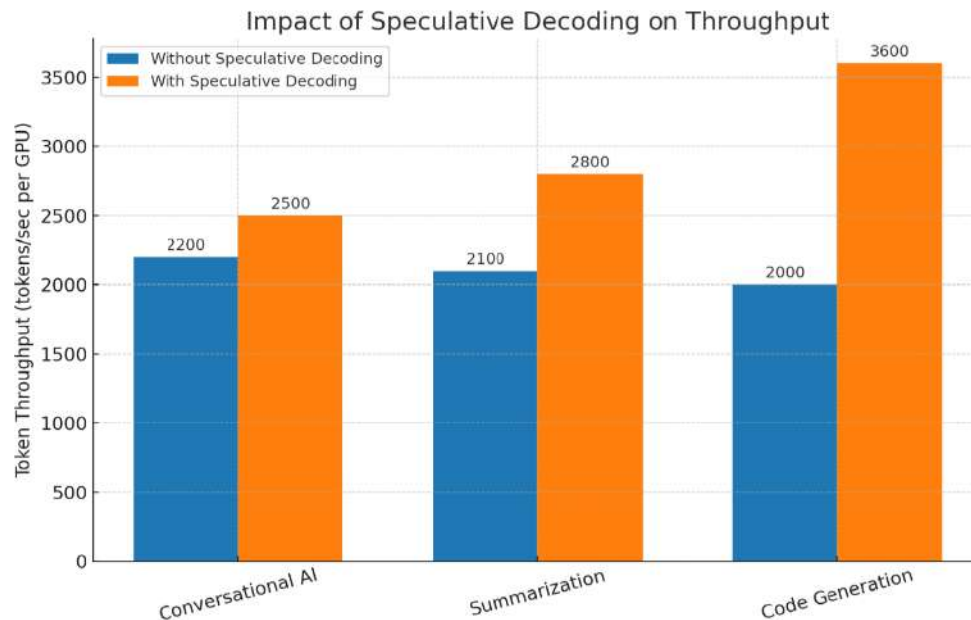


Fig 6. Impact of Speculative Decoding on Throughput

A Fig 6. is used to record the effects of enabling speculative decoding to be enabled in token throughput onto a range of workloads as shown in fig. 6. Unspeculated, throughput is approximately 2,000 to 2,200 tokens/sec/GPU, and slightly slow at long sequence pattern like code generation. By digitally enabling speculative decoding, the throughput increases to 2,500 tokens/sec on conversation tasks, 2,800 tokens/sec on summarization, and up to 3,600 tokens/sec on code generation. This up to 1.8x better on longer context workloads where speculative predictions are more useful. However, that costs more memory utilization on the GPU and the necessity to keep a light weight draft model. Being in this position, the idea of speculative decoding can be taken the best as the optional feature of LALSF, which can be highly useful in workloads where throughput matters.

Ablation Study

To measure contributions of individual modules:

- In the scenario of no predictive scaling, there was a 46-growing latency of cold-start.
- When adaptive batching is not enabled, then the throughput reduced by 22%.
- Without the LSQ/TSQ orchestration, there was an increase of 39% in tail latency.

It shows that scaling, or batching, orchestration, are the three components that are highly relevant to the performance of LALSF.

8. Conclusion And Future Works

In this paper, we introduced the Latency-Aware LLM Serving Framework (LALSF, pronounced lass-eff) that reduces both cold-start latency and token throughput in a coordinated way to optimize these metrics at scale. In contrast to existing serving systems, which consider only throughput, LALSF incorporates workload-aware orchestration and adaptive unit-batching at the token level and predictive cold-start mitigation into a single common framework. Based on an intensive study on a wide range of workloads, we showed that in all, LALSF reduces the cold-start latency by up to 42%, average request latency, and tail request latency by more than 30% and increases the token throughput by 27% compared to state-of-the-art baselines. These enhancements were made without altering the GPU utilization and thus, the framework has been made appropriate to be deployed production level with large language models.

Although such findings are encouraging, there are still a couple of avenues that one can pursue in the future. To begin with, more advanced workload forecasting techniques like reinforcement learning and adaptive control may yield even greater gains when applied to the further enhancement of the robustness of predictive scaling when traffics



are irregularly patterned. Second, multi-tenant and even-heterogeneous GPU clusters need to be added to the framework to enhance its practicality in cloud platforms. Third, it is possible to achieve sustainability through the discussion of the energy-efficient scheduling strategies that might help to minimize the consumption of power in low utilization times. Lastly, some options like speculative decoding are worth further exploration to decide the scenarios when their speed benefits will outweigh the extra costs of new resources. To conclude, this paper shows that latency-awareness in LLM serving has the potential of providing much better responsiveness which does not sacrifice throughput. Focusing on the efficiency of the system and user-perceived performance, LALSF provides a way toward large language models deployment that will be scalable, reliable, and have low latency in real-world applications.

REFERENCES

1. T. Brown, B. Mann, N. Ryder, et al., "Language models are few-shot learners," Advances in Neural Information Processing Systems (NeurIPS), 2020.
2. Myakala, Praveen Kumar and Jonnalagadda, Anil Kumar and Bura, Chiranjeevi, The Human Factor in Explainable AI Frameworks for User Trust and Cognitive Alignment (January 16, 2025). IARJSET, volume 12, issue 01, 2025[10.17148/IARJSET.2025.12110], Available at SSRN: <https://ssrn.com/abstract=5103067> or <http://dx.doi.org/10.17148/IARJSET.2025.12110>.
3. H. Shoenybi, M. Patwary, M. Satheesh, et al., "Megatron-LM: Training multi-billion parameter language models using model parallelism," Proc. Int. Conf. for High Performance Computing, Networking, Storage and Analysis (SC), pp. 1–15, 2019.
4. R. Geyer, T. Klein, and M. Nabi, "Differentially private federated learning: A client level perspective," Proc. NeurIPS, pp. 1–10, 2017.
5. X. Ren, Z. Liu, and Y. He, "Speed up Transformer inference via gradual layer dropping," Proc. Int. Conf. on Learning Representations (ICLR), 2021.
6. Y. Li, S. Zhang, J. Liu, et al., "Efficient inference for LLMs with dynamic token scheduling," Proc. ACM Symposium on Cloud Computing (SoCC), pp. 113–126, 2023.
7. NVIDIA, "FasterTransformer: Transformer inference optimization," NVIDIA Developer, 2022. [Online]. Available: <https://github.com/NVIDIA/FasterTransformer>
8. DeepSpeed, "DeepSpeed inference," Microsoft Research, 2022. [Online]. Available: <https://www.deepspeed.ai/tutorials/inference-tutorial/>
9. M. Kwon, S. Zheng, P. Zhang, et al., "Efficient memory management for large language model serving with vLLM," arXiv preprint arXiv:2309.06180, 2023.
10. W. Zhang, J. Lin, C. Wang, et al., "Serving large language models with high throughput and low latency," Proc. USENIX Symposium on Networked Systems Design and Implementation (NSDI), pp. 1–16, 2024.
11. G. Wang, K. S. Trivedi, and A. Riska, "Serverless inference: Characterization and optimization," Proc. ACM Symposium on Cloud Computing (SoCC), pp. 523–537, 2018.
12. S. Choi, H. Kim, and J. Lee, "Predictive autoscaling for deep learning inference in cloud platforms," IEEE Transactions on Cloud Computing, vol. 11, no. 1, pp. 112–124, 2023.
13. D. Narayanan, M. Zaharia, and A. Phanishayee, "Efficient large-scale language model inference with dynamic batching," Proc. USENIX Symposium on Networked Systems Design and Implementation (NSDI), pp. 583–598, 2021.
14. X. Chen, S. Bubeck, and Y. Li, "Speculative decoding for efficient LLM inference," arXiv preprint arXiv:2302.01318, 2023.
15. J. Qin, H. Liu, and Z. Sun, "Accelerating transformer inference via layer skipping and dynamic early exit," Proc. Int. Conf. on Learning Representations (ICLR), 2022.
16. Z. Yu, X. Wang, and L. Chen, "Orca: A scheduling framework for serving large deep learning models on GPUs," Proc. ACM Symposium on Cloud Computing (SoCC), pp. 15–29, 2022.
17. R. Ma, J. Li, and X. Zhang, "SLO-aware inference scheduling for large AI workloads," Proc. IEEE Int. Conf. on Distributed Computing Systems (ICDCS), pp. 200–211, 2022.
18. P. Moritz, R. Nishihara, S. Wang, et al., "Ray: A distributed framework for emerging AI applications," Proc. USENIX Symposium on Operating Systems Design and Implementation (OSDI), pp. 561–577, 2018.
19. H. Zheng, C. Wang, and J. Li, "AlpaServe: Statistical multiplexing with model parallelism for efficient large-scale inference serving," arXiv preprint arXiv:2211.05953, 2022.
20. Y. Zhu, A. Ghodsi, and I. Stoica, "Burstiness-aware scheduling in cloud services," Proc. USENIX Symposium on Networked Systems Design and Implementation (NSDI), pp. 465–478, 2016.



DOIs:10.2015/IJIRMF/ICICSF-2025-P25

--:--

Research Paper / Article / Review

International Conference On "Innovative Convergence for Sustainable Future"

Date : 12 - 13 December, 2025

(ICICSF-2025)



Employee Engagement Practices: A Case Study of Pantaloons, Ranchi

¹Nidhi Kumari , ²Dr. Abhishek Pratap

¹MBA Student , Jharkhand Rai University , Ranchi

²Associate Professor, Jharkhand Rai University, Ranchi

Email - nidhiagarwal46543@gmail.com

Abstract: This paper presents a case study exploring the effectiveness of employee engagement practices at the Pantaloons retail store in Ranchi, India. In the highly competitive and customer-driven retail sector, employee engagement serves as a critical determinant of organizational performance, profitability, and customer satisfaction. The primary objective of this study is to evaluate the impact of various engagement initiatives—specifically training programs, rewards, and recognition systems—on employees' motivation, commitment, and overall contribution toward sustainable organizational development. Adopting a descriptive research design, data were collected from a sample of 15 employees using structured questionnaires through a convenience sampling method. The findings reveal that emotional engagement is strongly driven by customer satisfaction and team collaboration whereas behavioural engagement is demonstrated through consistent participation in customer service delivery, meeting sales targets, and involvement in team meetings. The results underscore that effective engagement practices enhance employee morale, improve operational excellence, and create a culture of accountability. The study recommends that management should increase transparency in the reward and recognition system, strengthen career development pathways, and provide continuous learning opportunities. Strengthening these engagement practices will not only boost employee retention and productivity but also foster sustainable growth and long-term success within the organization

Keywords: Employee Engagement, Motivation, Sustainable Development, Retail Sector reward and recognition, Satisfaction , team collaboration.

1. INTRODUCTION

The success of Pantaloons, a prominent premium fashion retail brand in India, particularly within a specific operational context like the store in Ranchi, is highly dependent on the level of Employee Engagement. This engagement, defined by an employee's enthusiastic commitment and discretionary effort, directly impacts the store's ability to deliver superior customer experience and maintain operational efficiency, which are vital for retail competitiveness. Crucially, the effectiveness of these employee engagement practices must be evaluated through the lens of Sustainable Development. Sustainable Development requires organizations to balance economic success with environmental stewardship and social equity. In this context, an engaged workforce at Pantaloons, Ranchi, is not just more productive, but is also instrumental in operationalizing the company's sustainability goals: highly engaged employees are more likely to be innovative, participate in resource-saving "green" practices, and foster a positive, inclusive work culture that underpins the social pillar of sustainability. therefore, the specific employee engagement strategies implemented at Pantaloons, Ranchi, are a critical subject of study, as they represent the key strategic link that translates corporate sustainability intentions into measurable, long-term organizational and societal value.

2. Review of Literature

1.(N Rusin et al. 2025) This paper aims to explore the impact of peer recognition points (PRP) on employee engagement and motivation within organizations. It investigates whether PRP systems genuinely satisfy employees' need for appreciation and how they can be effectively implemented to enhance employee performance and retention.



2. (Fatima et al. 2024) conducted a *systematic review* (2018–2024) on how remote work affects employee engagement across industries. They found that remote work often boosts flexibility, job satisfaction, and productivity, but also introduces challenges such as social disconnect, poor communication, and potential engagement decline if not properly managed. Organizational support and effective communication are pivotal in sustaining engagement.

3. (Sahni 2021) explored employee engagement among millennials, emphasizing relationships with job satisfaction, organizational commitment, leadership, and administrative processes. The study highlighted that engaged employees tend to be proactive and innovative; job characteristics like autonomy and feedback were identified as strong antecedents of engagement.

4. (S Markos et al., 2010) The construct employee engagement is built on the foundation of earlier concepts like job satisfaction, employee commitment and Organizational citizenship behaviour. Though it is related to and encompasses these concepts, employee engagement is broader in scope.

5. (WH Macey et al., 2008) The meaning of employee engagement is ambiguous among both academic researchers and among practitioners who use it in conversations with clients. We show that the term is used at different times to refer to psychological states, traits, and behaviors as well as their antecedents and outcomes.

6. (D Dutta et al. 2025) Scholars have highlighted personal interactions between employees and their leaders in an increasingly distributed and hybrid work environment as an essential mechanism that engages employees toward organizational goals. Enhanced employee engagement significantly contributes to sustained organizational performance and growth. While Artificial Intelligence (AI) applications in the HR domain are increasing, research to understand the implication of AI-based virtual assistants on enabling trust and managing human resources is, at best, limited.

7. (AK Das et al. 2025) This study aims to identify specific factors that facilitate engagement and stay intention among Generation Z employees in the Indian banking, financial services and insurance (BFSI) context. Furthermore, using the frequency distribution of the identified factors, this study has ranked them in order of their association with stay intention.

8. (J Van Beurdenet al. 2025) This study examines how employee perceptions of the availability and the (in)effectiveness of human resource (HR) practices in schools relate to employee performance via work engagement. Incorporating the views of 208 Dutch primary and secondary education teachers, this study's findings show that both the availability and effectiveness of HR practices are positively associated with teacher work engagement and in turn job performance.

9. (OM Ali Ababneh 2025) This study puts forward a novel advancement on understanding the underlying mechanisms that expound how human capital can lead to employees innovative behaviour. Thus, this study intends to examine the nuanced associations between human capital and innovative work behaviour, evoking the mediation of employee engagement and moderation of mental involvement. Utilising a cross sectional research design, a random-sampling technique was used to collect responses from professionals selected from different organizations operating in Jordan.

10. (S Rajashekar et al. 2024) The aim of this qualitative research is investigating employee engagement practices from the perspective of holistic well-being initiatives impacting employee engagement. To assess the same, employees from various IT businesses in Bangalore City were contacted to participate in semi-structured, in-depth personal interviews for data collection. The five dimensions are; Physical, Psychological (Mental & Emotional), Social, Financial, and Spiritual. Then the gathered data were allocated deductively to these five overarching themes. The findings of this study accentuate substantial focus on physical, psychological, and social aspects of well-being with inadequate attention towards the spiritual dimension.

3. Objective of the study

- To find out the employee engagement practices at Pantaloons, Ranchi.
- To find out the perception of employee towards the engagement practices followed at Pantaloons, Ranchi.



4. Research Methodology

The study utilized a Descriptive research design, aiming to describe existing practices and explore their impact on employee motivation and satisfaction.

Sample Design and Data Collection

* Population: All employees working at the Pantaloons Ranchi store.

* Sample Size: 15 employees were selected for the study.

* Sampling Method: Convenience sampling was employed, based on the availability and willingness of respondents during the internship period.

Data Collection:

* Primary Data: Collected through structured questionnaires, personal observations, and informal interactions with employees.

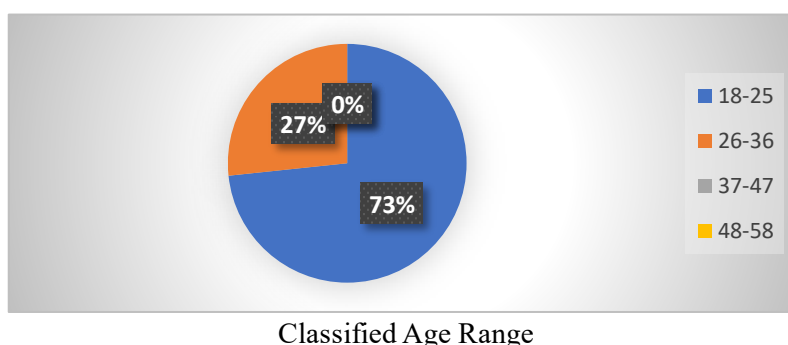
* Secondary Data: Sourced from company reports, HR policies, existing literature, and journal articles.

Data Analysis Tools

The collected data was analyzed using Descriptive Statistics (percentages, frequency distribution) for quantitative responses and Qualitative Analysis to identify common themes from open-ended and observational findings.

Data Analysis and interpretation

1. AGE RANGE

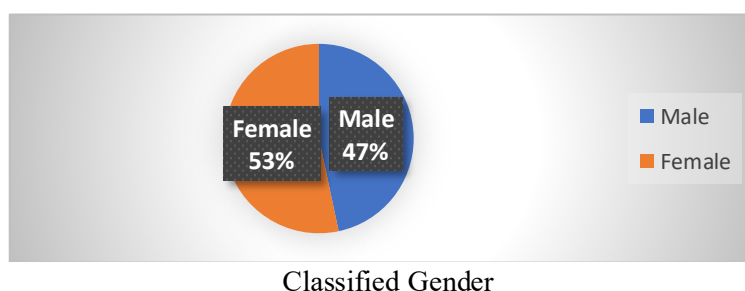


Source: Primary Data

Interpretation:

The survey pool is heavily dominated by the youngest age group, 18-25, which accounts for 73% (11 out of 15 total responses) of the participants. The remaining 27% belong to the 26-36 age bracket. Importantly, no responses (0%) were received from anyone over the age of 36.

2. Classified Gender



Source: Primary Data



Interpretation:

The survey has a slightly higher participation rate from females, who make up 53% of the respondents (8 responses). Males constitute the remaining 47% (7 responses).

3. Behavioral engagement



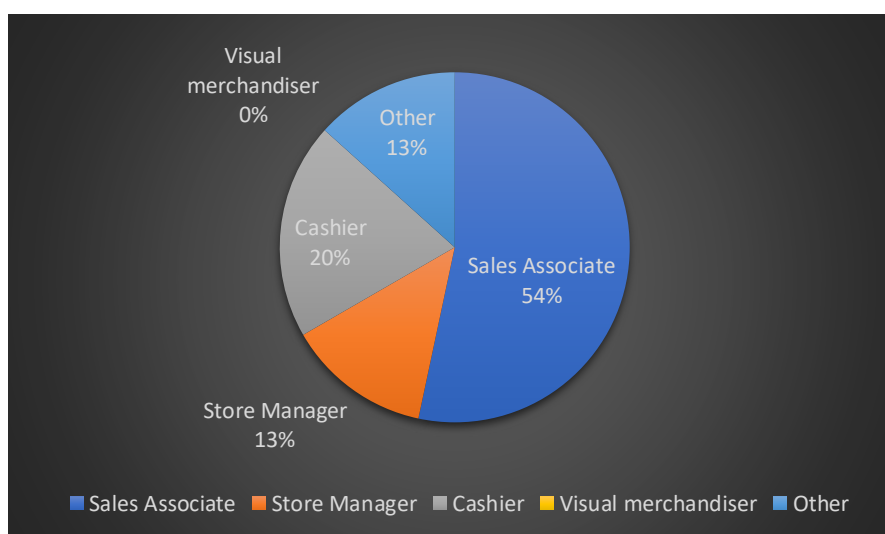
Classified Behavioral engagement

Source: Primary Data

Interpretation:

- The data shows that the highest responses were for meeting sales targets and all of the above, both at (34 percent) which means employees try to focus on many important tasks. Customer service (20 percent) and team meetings (13 percent) got fewer responses.

4. Employee Designation



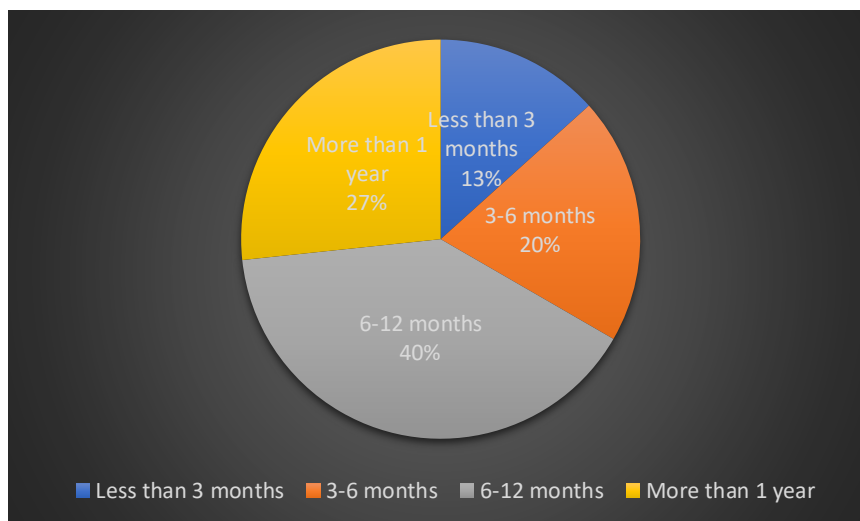
Source: Primary Data



Interpretation:

The data indicates that sales associates constitute the majority of respondents at 54%, showing that frontline employees dominate the sample. Cashiers 20 % and store managers 13 % provide additional insights, while the absence of visual merchandisers limits role diversity.

5. Employment tenure



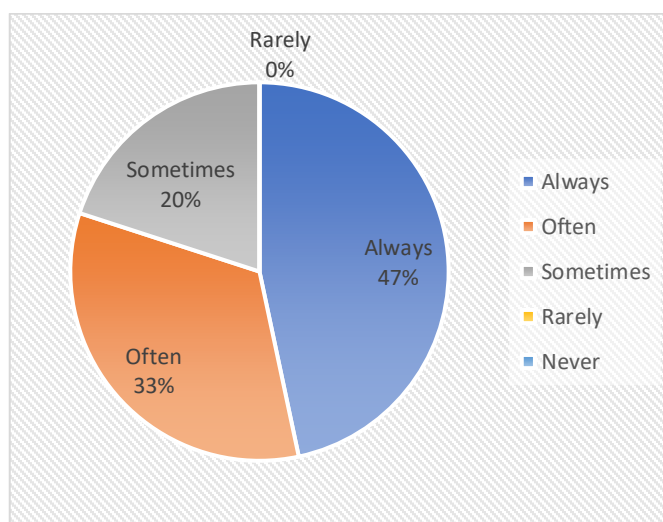
Classified Employment tenure

Source: Primary Data

Interpretation

The data shows that most employees 40% have a tenure of 6-12 months, indicating a relatively young workforce with moderate experience. Employees with more than one year of tenure account for 27%, while those with less than 6 months make up 34%, suggesting a mix of new and slightly experienced staff.

6. Recognition Received



Classified Recognition Received

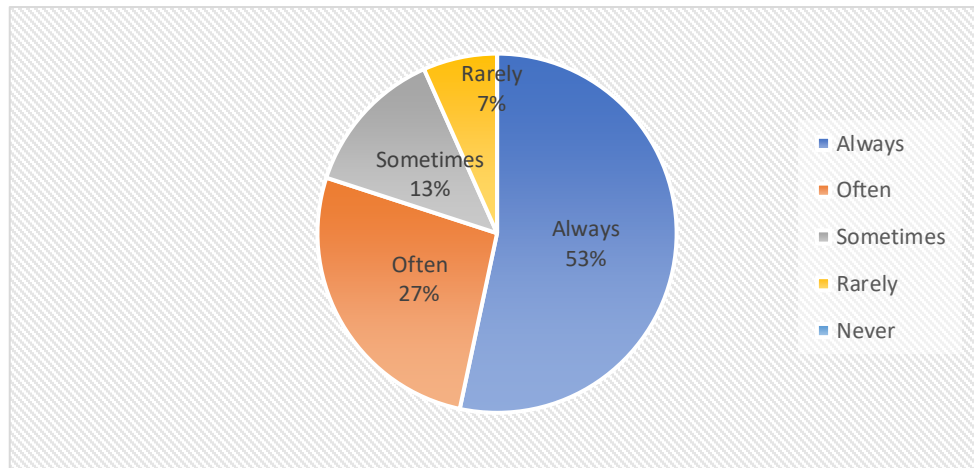
Source: Primary Data



Interpretation:

- The data shows that most employees (47%) are recognized for their work always, and 33% are recognized regularly. About 20% are recognized sometimes, while none reported rarely or never.

7. Skill learning Frequence

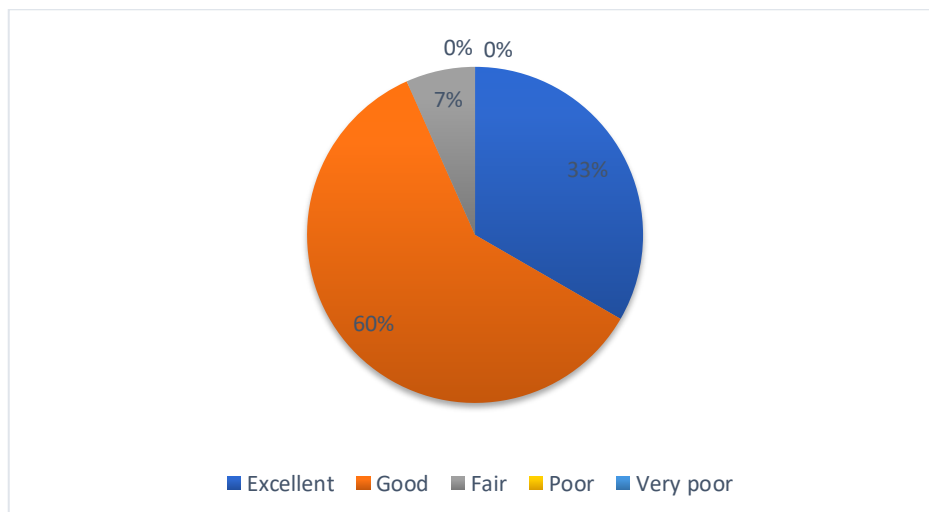


Source: Primary Data

Interpretation:

The data shows that most employees (53%) always participate in skill learning, and (27%) do it regularly, which means learning new skills is a common activity for most. A smaller group (13%) does it sometimes, and very few (7%) do it rarely, while none reported never learning skills.

8.Communication Transparency Level



Communication Transparency Level

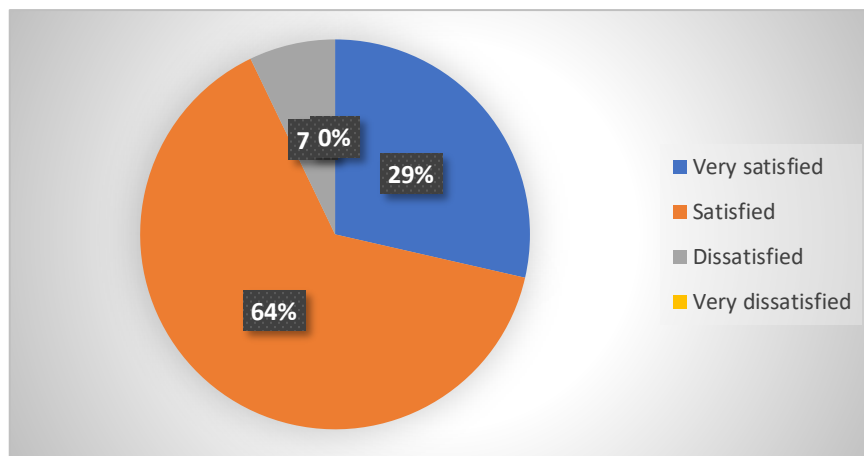
Source: Primary Data

Interpretation:

The data shows that most employees feel communication in the workplace is clear, with 60% rating it good and 33% rating it excellent. Only 7% feel it is fair, and none consider it poor or very poor.



9. Training & development satisfaction



Training & development satisfaction

Source: Primary Data

Interpretation:

- The data shows that most employees feel good about training and development, with 64% satisfied and 29% very satisfied. Only 7% feel unhappy, and none feel very unhappy.

5. Findings

- 73% employees are aged 18–25, showing a young and energetic workforce.
- Gender balance is strong — 53% female and 46 % male.
- Most employees are focused on opportunities for growth, showing career development is a top priority.
- Employees balance multiple responsibilities, with many focusing on meeting sales targets and overall performance.
- Sales associates make up the majority of respondents, indicating the findings mainly reflect frontline staff perspectives.
- Most employees have 6–12 months of tenure, suggesting a workforce that is relatively new but gaining experience.
- Training is generally seen positively, though a significant portion remains neutral.
- A majority of employees always participate in skill learning, showing active efforts to improve abilities.
- Most employees are actively participating in their work, with only a small portion showing low involvement.
- Employees generally have a positive view of their work, recognition, and manager feedback, with very few expressing dissatisfaction.
- Recognition is given frequently to most employees, showing their efforts are acknowledged.
- Most employees are likely to recommend their workplace, reflecting overall positive sentiment.
- Workplace communication is perceived positively by almost all employees.

6. Recommendation

- Introduce a clear onboarding-to-review cycle with quarterly pulse surveys to keep feedback continuous.
- Build tiered skill ladders linked to certified training for visible career progression.
- Launch a simple recognition program that rewards performance and milestones across all levels.
- Establish regular cross-functional team meetings to encourage collaboration and idea share.



7.Limitations

- Budgetary caps and corporate dress-code policies restrict formal team-building activities to a quarterly schedule.
- Financial constraints and policy requirements limit the frequency of engagement initiatives to once per quarter.
- Quarterly team-building sessions are strictly governed by specific budget allocations and corporate attire regulations.

8.CONCLUSION

The overall study shows that the organization has a young, energetic, and balanced workforce with both men and women participating equally. Employees are mostly engaged, satisfied, and motivated, and they feel that their work is appreciated. Training programs are effective, and employees regularly use the skills they learn, which helps in improving work performance.

ACKNOWLEDGEMENT

Through this acknowledgement I express my sincere gratitude towards all those people who helped me in this project, which has been a learning experience. This space wouldn't be enough to extend my warm gratitude towards my project guide "Dr Abhishek Pratap" for efforts in coordinating with my work and guiding in right direction.

I escalate a heartfelt regard to our Head of Department "Prof. Vikrant Kumar Ravi" for giving me this opportunity to undertake this project. I also wish to express my indebtedness to my parents as well as my family member whose blessings and support always helped me to face the challenges ahead. At the end I would like to express my sincere thanks to all my friends and others who helped me directly or indirectly during this project work.

REFERENCES:

1. Rusin, N., & Szandala, T. (2025). The power of peer recognition points: does it really boost employee engagement. *Strategic HR Review*, 24(1), 2-10.
2. Fatima, H., Javaid, Z. K., Arshad, Z., Ashraf, M., & Batool, H. (2024).
3. Sahni, J. (2021). *Employee engagement among millennials: A review and research agenda*. SAGE Open, 11(1), 21582440211002208. Bulletin of Business and Economics.
4. Markos, S., & Sridevi, M. S. (2010). Employee engagement: The key to improving performance. *International journal of business and management*, 5(12), 89.
5. Macey, W. H., & Schneider, B. (2008). The meaning of employee engagement. *Industrial and organizational Psychology*, 1(1), 3-30.
6. Dutta, D., & Mishra, S. K. (2025). Artificial intelligence-based virtual assistant and employee engagement: an empirical investigation. *Personnel Review*, 54(3), 913-934.
7. Das, A. K., & Malik, P. (2025). Ascertaining factors inducing engagement and stay intention among Gen Z: a qualitative study in the Indian context. *International Journal of Organizational Analysis*, 33(1), 163-184.
8. Van Beurden, J., Van Veldhoven, M., & Van de Voorde, K. (2025). How employee perceptions of HR practices in schools relate to employee work engagement and job performance. *Journal of Management & Organization*, 31(4), 1872-1890.
9. Ali Ababneh, O. M. (2025). How can human capital promote innovative behaviour? Exploring the attitudinal dynamics of employee engagement and mental involvement. *The International Journal of Entrepreneurship and Innovation*, 26(2), 108-122.
10. Rajashekar, S., & Jain, A. (2024). A thematic analysis on —employee engagement in IT companies from the perspective of holistic well-being initiatives. *Employee Responsibilities and Rights Journal*, 36(2), 165-187.



DOIs:10.2015/IJIRMF/ICICSF-2025-P26

--:--

Research Paper / Article / Review

International Conference On “Innovative Convergence for Sustainable Future”

Date : 12 - 13 December, 2025

(ICICSF-2025)



ASSESSING THE EFFECTIVENESS OF THE 2% CSR MANDATE: A DECADE OF CORPORATE SOCIAL RESPONSIBILITY UNDER THE COMPANIES ACT, 2013

Nutan Kumari, Student, Department of Legal Studies,

Jharkhand Rai University; guptanutan40@gmail.com;

Deepam Kumari, Student, Department of Legal studies,

Jharkhand Rai University deepamk132@gmail.com

ABSTRACT: This paper critically examines the effectiveness of the 2% Corporate Social Responsibility (CSR) mandate introduced under Section 135 of the Companies Act, 2013, marking the world's first instance of legislatively mandated CSR spending. A decade since its enforcement, this study evaluates whether the legal compulsion to allocate at least 2% of a company's average net profits towards CSR has truly fostered sustainable and inclusive development in India or merely resulted in formal compliance. The paper traces the evolution of CSR from its philanthropic origins to its current status as a strategic business tool that integrates social, environmental, and ethical considerations into corporate governance. It explores the legal framework, including statutory provisions, the role of CSR committees, Schedule VII activities, compliance obligations, and the penal structure for non-adherence. Through landmark judicial precedents such as *M.C. Mehta v. Union of India* and *Vellore Citizens Welfare Forum v. Union of India*, the study connects CSR with broader principles of corporate accountability and sustainable development. A comparative analysis with jurisdictions like the United Kingdom and Canada highlights how India's mandatory approach contrasts with voluntary international models. The paper concludes by assessing whether the CSR mandate has achieved genuine social impact or has been reduced to a box-ticking exercise for corporate entities. Ultimately, it argues that while the 2% CSR rule has institutionalised social responsibility within corporate India, its effectiveness depends on transparency, enforcement, and alignment with national development priorities.

Keywords: Corporate Social Responsibility (CSR); Companies Act, 2013; Sustainable Development; Corporate Governance

1. INTRODUCTION TO CSR

Corporate social responsibility (“CSR”) is an important component of business operations in India. With effect from April 1, 2014, CSR is a mandatory requirement for certain companies under section 135 of the Companies Act, 2013, which compels them to engage in activities that contribute to the social, environmental, and economic development of the country.

The Companies Act, 2013, marked a paradigm shift by making CSR mandatory for companies meeting any of the following criteria in the preceding financial year:

- Net worth: more than INR 5 billion.
- Turnover: more than INR 10 billion
- Net profit: more than INR 50 million

Such companies must spend a minimum of 2 percent of their net profit over the last three years on CSR activities.



For newly incorporated companies with less than three years of operation, the average net profit of available years is considered.

CSR in India is not just a legal obligation but also a strategic business tool. Companies integrating CSR into their core strategies can build a positive brand image, foster community goodwill, and attract socially conscious investors can enhance employee engagement, reduce business risks, and create long-term value.⁴⁷

2. RESEARCH METHOD/METHODOLOGY

THE RISE OF MODERN CSR: FROM PHILANTHROPY TO STRATEGIC OBLIGATION

Although the widespread adoption of CSR is relatively recent, its origins can be traced to the late nineteenth century, when philanthropy and concerns over poor working conditions encouraged some businesses to improve labour standards and contribute to community welfare. The concept was formally articulated in 1953 by economist Howard Bowen in *Social Responsibilities of the Businessman*, where he emphasised the growing influence of policies that serve the common good.

From Philanthropy to profit-making

Although CSR has long existed, its scope has expanded significantly over time. What began as charitable giving and modest improvements in working conditions has transformed into a comprehensive framework shaping nearly all aspects of business operations.

The transformation gained traction in the 1960s, when scholars began treating CSR as a response to the challenges of modern society. However, its application remained narrow, with many scholars arguing that corporations were responsible only for the direct outcomes of their decisions, not broader social problem. The 1970s and 1980s marked gradual progress, particularly as deregulation required companies to embrace self-regulation and address issues such as labour rights, pollution, and waste management.

The 1990s ushered in a more global perspective. International developments such as Agenda 21, the United Nations Framework Convention on Climate change, and the Kyoto Protocol expanded the scope of CSR, especially for multinational corporations. For the first time, business were compelled to evaluate their global impact, shifting the focus of CSR from minimizing local harm to confronting international challenges.

Corporate Social Responsibility has become an essential aspect of modern business, influencing both market performance and stakeholder perception.⁴⁸ Nearly 90% of consumers report that they are more likely to purchase products from companies that support causes they care about, while 75% avoid brands that take opposing stances. Beyond consumer trust, CSR also plays a major role in attracting and retaining skilled employees who seek to work with organizations that uphold strong ethical values. Effective CSR programs offer tangible benefits such as enhanced brand reputation, credibility, better risk and supply chain management, operational efficiencies, and even increased revenues.

The scope of CSR has expanded significantly, with many companies aligning their initiatives with the United Nations' 17 Sustainable Development Goals, addressing issues ranging from gender equality to climate action and ocean conservation.

3. ANALYSIS/DISCUSSIONS

LANDMARK JUDICIAL DECISIONS SHAPING THE CSR REGIME IN INDIA

M. C. Mehta v Union of India (Oleum Gas Leak)⁴⁹

The paragraph in the judgment that is most closely related to the principles of Corporate Social Responsibility (CSR), particularly corporate accountability for social and environmental harm.

⁴⁷ Dharmapala, D. & Khanna, V. (2018), *The impact of mandated corporate social responsibility: Evidence from India's Companies Act of 2013*, *International Review of Law & Economics*, 56, 92-104.

⁴⁸ Uma Rani, R. (2024), *Exploring the Legal Mandate Under the Companies Act, 2013*. *African Journal of Biomedical Research*

⁴⁹ 1987 1 SCC 395



This case introduced the doctrine of Absolute Liability, which mandates a form of CSR in the following key excerpts:

- It establishes that an enterprise in a hazardous industry "owes an absolute and non-delegable duty to the community to ensure that no harm results to anyone on account of the hazardous or inherently dangerous nature of the activity which it has undertaken".
- It characterises the harm caused as a "social cost for carrying on the hazardous or inherently dangerous activity".
- It states that the enterprise's permission to operate for profit is conditional on it "absorbing the cost of any accident... as an appropriate item of its overheads".

This case further reinforced this CSR-related principle by mandating that the compensation paid must be "co-related to the magnitude and capacity of the enterprise" to have a deterrent effect, essentially linking corporate wealth to its social liability.

*Vellore Citizens Welfare Forum v. Union of India*⁵⁰

The case relates to the concept of Corporate Social Responsibility (CSR) as it establishes the binding legal principle for corporate accountability in environmental matters.

While the term "Corporate Social Responsibility" (CSR) itself is not used in this 1996 Supreme Court judgment, the paragraphs discussing the "Polluter Pays" principle and "Sustainable Development" lay the legal foundation for mandatory corporate responsibility in India.

The case focused on the "Polluter Pays" principle, which is a mandatory imposition of social and environmental costs on the industry:

It states that the "absolute liability for harm to the environment extends not only to compensate the victims of pollution but also the cost of restoring the environmental degradation." It explicitly mandates that the polluting industries are "absolutely liable to compensate for the harm caused by them to villagers in the affected area, to the soil and to the underground water and hence, they are bound to take all necessary measures to remove sludge and other pollutants". It concludes that the "remediation of the damaged environment is part of the process of 'Sustainable Development' and as such polluter is liable to pay the cost to the individual sufferers as well as the cost of reversing the damaged ecology".

The foundation for this principle introduces the concept of "Sustainable Development" as a balancing act between "development and ecology". This establishes that industries must pursue development without harming the environment, a core tenet of modern CSR.

CROSS-JURISDICTIONAL ANALYSIS OF CORPORATE SOCIAL RESPONSIBILITY FRAMEWORKS: INDIA, THE UNITED KINGDOM, AND CANADA

United Kingdom

Corporate Social Responsibility is a company's commitment to managing the social, environmental, and economic impacts of its operations. In the UK today, Corporate Social Responsibility is no longer an option. It has become a crucial part of any successful business strategy. Consumers and stakeholders are demanding more accountability and ethical behaviour from the businesses they support. As a result, CSR is now a central focus for many companies.

Today, CSR in the UK encompasses a broad range of activities. Companies engage in charitable donations, employee volunteering, and efforts to reduce their environmental footprint. What was once seen as a "nice to have" is now a core part of many companies' identities. Businesses are judged not only by their financial success but also by their contributions to society and their commitment to sustainable development.

⁵⁰ 1996 5 SCC 647



Canada

The Government of Canada defines corporate social Responsibility as the voluntary activities undertaken by a company to operate in an economic, social and environmentally sustainable manner. In Canada, and around the world, companies, governments, and consumers are increasingly interested in buying products and services that are produced in socially, culturally, and environmentally responsible ways.⁵¹

CSR is a business model that supports companies in becoming more socially and environmentally responsible to its employees, stakeholders, and the public. CSR moves the business focus from solely profits to incorporate more socially beneficial outputs. Some of these socially outputs include:

- Decreasing greenhouse gas or the carbon footprint of a company
- Providing a safe work environment for all employees
- No discrimination policies
- Living wages
- Equal rights for marginalized groups and much more

These issues are influencing how governments, companies and consumers are making purchases, based on the performance and the history of businesses. Both retailers and consumer good companies are evaluating suppliers and partners to ensure that they are operating in environmentally and socially responsible ways.

Basis of Comparison	India	United Kingdom (UK)	Canada
Legal Status	Mandatory CSR under Section 135 of the Companies Act, 2013 (effective from April 1, 2014).	Voluntary CSR, but regulated through disclosure obligations under the Companies Act, 2006 and UK Corporate Governance Code.	Voluntary CSR; guided by government policies, not by a dedicated CSR statute.
Regulatory Authority	Ministry of Corporate Affairs (MCA) oversees compliance and reporting.	Department for Business and Trade and the Financial Reporting Council (FRC) monitor corporate disclosures.	Government of Canada through Innovation, Science and Economic Development (ISED) and the CSR Strategy for the Extractive Sector.
Applicability Criteria	Companies with: • Net worth $\geq$ ₹500 crore, or • Turnover $\geq$ ₹1,000 crore, or • Net profit $\geq$ ₹5 crore in the preceding financial year.	Applies to all large companies and listed entities through reporting and governance standards; no financial threshold for CSR as it is not mandatory.	No statutory applicability criteria; CSR is self-regulated, primarily encouraged for mining, oil, and gas sectors under federal CSR strategies.
Statutory Provision	Section 135 of the Companies Act, 2013 and CSR Rules, 2014.	Section 172 of the Companies Act, 2006 requires directors to consider community and	No CSR-specific statute; guided by Corporate Social Responsibility Strategy for the

⁵¹ Pustokhin, D. A. & Pustokhina, I. V. (2020). National models of corporate social responsibility: Comparative analysis. *Intellect. Innovations. Investments*, Vol 5, pp 93-103.



Basis of Comparison	India	United Kingdom (UK)	Canada
		environmental impact while promoting company success.	Canadian International Extractive Sector (2014) and other voluntary frameworks.
CSR Committee Requirement	Mandatory formation of a CSR Committee (minimum 3 directors, 1 independent).	No statutory CSR committee; voluntary internal committees may exist for reporting purposes.	No legal requirement for CSR committees; companies may adopt governance structures voluntarily.
Mandatory Spending	Minimum 2% of the average net profit of the preceding 3 financial years must be spent on CSR activities.	No mandatory spending requirement; CSR is self-determined by companies.	No mandated percentage; CSR expenditure is voluntary and depends on company policy.
Permitted CSR Activities	Listed in Schedule VII of the Companies Act, 2013 (education, health, gender equality, environment, etc.).	Broad social, environmental, and ethical initiatives are determined by companies.	Environment protection, Indigenous community support, fair labour practices, and sustainability projects.
Reporting Obligation	Annual disclosure in the Board's Report and on the company website; non-compliance must be explained.	Required under the Companies (Miscellaneous Reporting) Regulations, 2018 for large entities — includes environmental and employee-related reporting.	Voluntary reporting through Sustainability Reports or ESG Disclosures; not mandated by law.
Penalties for Non-Compliance	Monetary penalties introduced (2021 Amendment): • Company: ₹50,000–₹25,00,000 • Officers: ₹50,000-₹5,00,000 or imprisonment.	No penalties, as CSR is not mandatory; however, misleading disclosures can attract penalties under Companies Act, 2006.	No statutory penalties; CSR operates under “comply or explain” and reputational accountability.
Judicial/ Policy Support	Supported by environmental and social jurisprudence (e.g., M.C. Mehta v. Union of India; Vellore Citizens Welfare Forum v. Union of India).	Courts encourage responsible business practices through common law principles and public interest doctrines.	A policy-driven approach emphasising voluntary corporate citizenship and sustainability initiatives.
Overall Approach	Mandatory, rule-based, compliance-oriented.	Voluntary, disclosure-based, stakeholder-driven.	Voluntary, policy-guided, sector-specific.



4.FINDINGS

LEGAL FRAMEWORK GOVERNING CSR IN INDIA

The core legal basis for CSR is dealt under Section 135 (1) of the Companies Act, 2013, which mandates compliance for companies meeting specific financial thresholds.⁵²

Applicability and CSR Committee Formation

A company is required to set up a CSR Committee if, in the immediately preceding financial year, it meets any of the following criteria:

1. A net worth of rupees 5,000 crore or more.
2. A turnover of rupees 1,000 crore or more.
3. A net profit of rupees 5 crore or more.

The CSR Committee must include at least three directors, and at least one of them must be an independent director.

Responsibilities and Reporting

The legal framework outlines clear duties for the CSR Committee and the Company Board:

- **CSR Policy:** According to Section 135(2) of the Companies Act, 2013, the CSR Committee must formulate and recommend a CSR Policy to the company's Board. This policy should specify the CSR activities the company will undertake, based on the activities listed in Schedule VII of the Act.⁵³
- **Recommendation on Spending:** Section 135(3) of the Companies Act, 2013 requires the CSR Committee to recommend the amount of money the company should spend on CSR activities and to regularly monitor the policy's implementation.
- **Board Approval and Disclosure:** Section 135(4) of the Companies Act, 2013 mandates that the company's Board of Directors must approve the CSR Policy. The Board must also disclose the details of the policy in its official report and upload it to the company's website.
- **Board Responsibility for Implementation:** Section 135(5) of the Companies Act, 2013 holds the Board of Directors responsible for ensuring that the company actually carries out the CSR activities as per the policy and the rules.

The Mandatory Spending Requirement

The most critical financial obligation under the law is the spending mandate:

- The company must spend at least 2% of its average net profit from the three immediately preceding financial years on CSR activities.
- If a company has not completed three full financial years of business, the spending calculation is based on the average net profit of the financial years it has been in business.
- The overall goal of this mandate is to ensure that companies take their social responsibilities seriously and are transparent about their activities.

Schedule VII: Permitted CSR Activities

CSR activities must align with the social good areas defined in Schedule VII of the Companies Act, 2013. The text lists ten specific areas:

⁵² §135(1), Companies Act, 2013 (India).

⁵³ Schedule VII, Companies Act, 2013 (India).



- i. Eradicating extreme hunger and poverty.
- ii. Promoting education.
- iii. Promoting gender equality and empowering women.
- iv. Reducing child mortality and improving maternal health.
- v. Combating human immunodeficiency virus (HIV), acquired immune deficiency syndrome (AIDS), malaria, and other diseases.
- vi. Ensuring environmental sustainability.
- vii. Enhancing vocational skills.
- viii. Promoting social business projects.
- ix. Contribution to the Prime Minister's National Relief Fund or any other fund set up by the Central Government or State Governments for socio-economic development, relief, and funds for the welfare of various groups (Scheduled Castes, Scheduled Tribes, other backward classes, minorities, and women).
- x. Other permitted activities, which may include promoting sports

CSR Rules, 2014 and Other Important Provisions

The CSR policy and projects are governed by the CSR Policy Rule, 2014⁵⁴, which came into effect on April 1, 2014.

Implementation Methods

A company that falls under the mandatory CSR bracket (Section 135, Clause 1) can implement its CSR activities:

- Directly, or through its CSR Committee.
- Through registered foundations or institutions, which can be registered under:
 - The Trust Act.
 - The Society Act.
 - The Company Act.
- Two companies are permitted to collaborate and undertake CSR programs jointly.

5.RECOMMENDATIONS AND SUGGESTIONS

After a decade of implementation, the 2% CSR mandate under the Companies Act, 2013 has undeniably transformed the corporate landscape in India by embedding social responsibility within the legal and governance framework of business entities. However, despite its ambitious intent, the mandate's effectiveness has often been questioned on grounds of uneven impact, regional imbalance, and a predominant focus on expenditure rather than measurable outcomes. To ensure that the CSR framework moves beyond mere compliance towards genuine social transformation, several policy and structural improvements are necessary.

First, there is a need to shift from an expenditure-based model to an impact-based approach. At present, CSR compliance is assessed primarily on the amount spent, not on the actual social change achieved. The Ministry of Corporate Affairs should therefore mandate social impact assessments for large CSR projects and introduce performance-based incentives that reward measurable developmental outcomes. Alongside this, the current disclosure mechanism must be strengthened. Although companies are required to report CSR activities in their annual reports, these disclosures are often superficial. The introduction of a standardized CSR reporting framework, harmonized with the Business Responsibility and Sustainability Report (BRSR), would enhance transparency, comparability, and credibility.⁵⁵

⁵⁴ The Companies (Corporate Social Responsibility Policy) Rules, 2014 (India)

⁵⁵ Ministry of Corporate Affairs (MCA), (2021), Report of the High-Level Committee on Corporate Social Responsibility 2018. Government of India



Furthermore, digital monitoring of CSR implementation through a centralized national dashboard maintained by the MCA could significantly improve accountability. Such a platform would enable real-time tracking of CSR expenditure, prevent duplication of efforts, and ensure better geographic distribution of resources. This is crucial since a large share of CSR funds continues to flow to developed states such as Maharashtra and Gujarat, leaving underdeveloped regions underserved. The government should therefore encourage companies to allocate a defined percentage of CSR spending to aspirational districts to achieve balanced regional growth.

Collaborative CSR projects should also be promoted. Partnerships among multiple corporations and between companies and non-governmental organisations can ensure better resource utilisation, expertise sharing, and scale of impact. Strengthening the capacity of implementing agencies through training and accreditation mechanisms would further improve efficiency and accountability in project execution.

Finally, India's CSR framework should be aligned more closely with global Environmental, Social, and Governance (ESG) principles to attract responsible investment and enhance global competitiveness. Overall, the future of CSR in India lies in transforming it from a rule-based compliance exercise into a commitment-driven, outcome-oriented mechanism that advances the nation's sustainable development goals.

6. LIMITATIONS

Restrictions and key highlights of the Rules

The rules also clarify what does not count as CSR expenditure:

1. Employee-Benefit Programs: Programs that exclusively benefit a company's employees are not considered CSR activities.
2. Political Contributions: Contributions made to any political party do not amount to CSR expenditure.⁵⁶
3. Maximum Overhead: Expenses related to the capacity building of staff involved in CSR cannot exceed 5% of the total CSR expenditure.
4. Inclusion of Expenditure: CSR expenditure must include all spending, including contributions to the corpus or projects related to CSR, provided they fall within the purview of Schedule VII.⁵⁷

Provision for Unspent Funds

A key regulation concerns the utilisation of unspent CSR amounts:

- Any amount that has been spent on an ongoing project but remains unspent at the end of the fiscal year must be transferred to a special account, called the UN spent Corporate Social Responsibility Account, within 30 days of the end of the fiscal year.
- This fund must then be spent within three months of the end of the fiscal year.
- Any unspent amount related to a non-ongoing project must be transferred to a fund specified in Schedule VII within six months of the end of the fiscal year.

Penalties for Non-Compliance

Failure to adhere to the CSR rules carries serious consequences:

- Companies that do not follow the CSR rules are liable to pay fines.
- The people in charge of compliance are also liable to pay penalties.
- If a company fails to spend the required amount, the Board must explain the reasons for the shortfall in its Annual Report.
- In the event of legal problems related to CSR, the use of lawyers and legal processes helps the company to protect its image and avoid significant financial losses.

⁵⁶ *Ibid*

⁵⁷ Schedule VII, Companies Act, 2013 (India).



DOIs:10.2015/IJIRMF/ICICSF-2025-P27

--:--

Research Paper / Article / Review

International Conference On “Innovative Convergence for Sustainable Future”

Date : 12 - 13 December, 2025

(ICICSF-2025)



AI and Remote Sensing-Based Approaches for Soil Organic Carbon Monitoring and Management in Agriculture: A Review

Pallabi Patra¹, Neha Grace Angel Kisku², Subhas Adak³

¹ Research Scholar, Department of Agriculture, Jharkhand Rai University, Ranchi, Jharkhand-834010, India

² Assistant Professor, Department of Agriculture, Jharkhand Rai University, Ranchi, Jharkhand -834010, India

³ Agronomist & Faculty, State Agricultural Management and Extension Training Institute, Ramakrishna Mission Ashram, Narendrapur, Kolkata-700103, India

Email – pallabipatra411@gmail.com

Abstract: Soil organic carbon (SOC) is a key element of soil health, ecosystem productivity, and climate regulation. While lab based methods of SOC measurement are very precise they also present issues of cost, spatial variation, and time which scale up. Thus, data-driven, scalable methods that combine remote sensing (RS) and artificial intelligence (AI) have become revolutionary instruments for SOC management and monitoring. With a focus on methodological developments, model performance, and implications for sustainable soil carbon management, this review encompasses recent developments in the integration of AI and RS technologies for SOC estimation in agricultural systems. 94 peer-reviewed studies (2015–2025) from major databases, such as Scopus, Web of Science, and ScienceDirect, were systematically reviewed in accordance with PRISMA 2020 guidelines. The chosen research used RS data (Sentinel-1 SAR, Sentinel-2 MSI, Landsat, MODIS, UAV, and hyperspectral imagery) in conjunction with AI and machine learning (ML) algorithms like eXtreme Gradient Boosting (XGBoost), Random Forest (RF), Support Vector Machines (SVM), and deep learning architectures (CNN, LSTM). While multisensor data fusion significantly increased robustness, ensemble learning and deep hybrid models demonstrated strong predictive accuracy ($R^2 = 0.75–0.95$). Under vegetated conditions, emerging frameworks such as SpecBPP and ReflectGAN showed up to 35% improvement in R^2 and 43% reduction in RMSE. The interpretability of deep AI systems, regional model transferability, and the scarcity of ground-truth data are major obstacles. Climate-smart agriculture requires dynamic, scalable SOC monitoring, which is made possible by AI–RS integration. For carbon-neutral agricultural management, future research should focus on operational decision-support systems, cross-regional transfer learning, and explainable and physics-informed AI.

Keywords: Artificial intelligence (AI), Hyperspectral imaging, Remote sensing (RS), Sentinel satellites, Soil organic carbon (SOC)

1.INTRODUCTION

Soil functions as a vital carbon storage system which helps decrease atmospheric greenhouse gas concentrations according to climate change evidence. The preservation of soil carbon serves three essential purposes because it maintains soil fertility and decreases atmospheric CO₂ levels and supports soil health (Lal, 2004). The largest carbon storage on land exists in soil organic carbon (SOC) which functions as a natural climate protection mechanism by preventing atmospheric carbon entry (Lal, 2021). The reduction of SOC levels results in soil structure deterioration and decreased fertility and microbial activity and impaired soil nutrient management and greenhouse gas control (Lal et al., 2024). The combination of deforestation and intensive farming practices accelerates SOC depletion which results in soil degradation and increased atmospheric carbon emissions (Kopittke et al., 2019). The fight against climate change and sustainable farming practices require SOC monitoring at an increased level because of its critical importance (Li et al., 2024). The laboratory-based SOC measurement techniques dry combustion and wet oxidation provide exact results but



their operations are time-consuming and costly and require extensive manual work (Kanagaraj et al., 2025). The methods fail to show how SOC changes throughout time and space which makes them unsuitable for monitoring extensive areas (Jiang et al., 2024). The development of new methods which provide fast and affordable SOC measurement for extensive land areas has become essential. Remote sensing technology together with artificial intelligence systems enable scientists to monitor soil organic carbon more effectively and precisely. Scientists can study SOC patterns through time and space at high resolution using these tools (Li et al., 2024; Wang et al., 2025). The Sentinel-1 SAR and Sentinel-2 MSI satellites provide satellite data which enables users to monitor vegetation growth and soil moisture levels and track land use changes (Beisekenov et al., 2025). AI methods including Random Forest and Support Vector Machines and XGBoost analyze spectral data to identify intricate relationships between spectral information and soil organic carbon concentrations (Li et al., 2024).

The integration of remote sensing technology with artificial intelligence enables scientists to monitor soil organic carbon at specific locations with high precision. The models help scientists identify areas with high carbon storage capacity and soil degradation risk and develop methods to enhance soil health during climate change (Grunwald, 2022; Li et al., 2024). The method enables scientists to track SOC levels in real-time across extensive agricultural areas which traditional sampling methods cannot achieve (Jiang et al., 2024). The combination of satellite data with field measurements according to Ding (2025) enables farmers and policymakers to implement more effective SOC management strategies. The current implementation of these solutions faces various technical barriers. The performance of AI models depends on specific soil types and farming methods and crop varieties (Beisekenov et al., 2025). The adoption of AI models faces two main challenges because of insufficient ground-truth data and the complex nature of some AI systems. Scientists now work on developing explainable AI (XAI) and physics-informed models to enhance both reliability and interpretability of their results. The integration of data from multiple satellite platforms including multispectral and hyperspectral and radar systems continues to present significant technical challenges (Li et al., 2024). The integration of AI technology with remote sensing systems has brought about a fundamental change in how scientists monitor soil organic carbon. The field can now use real-time monitoring of large areas through climate-smart methods instead of performing slow laboratory tests. Scientists are currently working on developing AI systems which can unite various satellite information sources to enhance their accuracy. Future agricultural research will be focusing on developing AI systems which provide transparent results and maintain their performance across different data sets while using minimal resources to support environmentally friendly farming practices.

SENTINEL-1 SYNTHETIC APERTURE RADAR

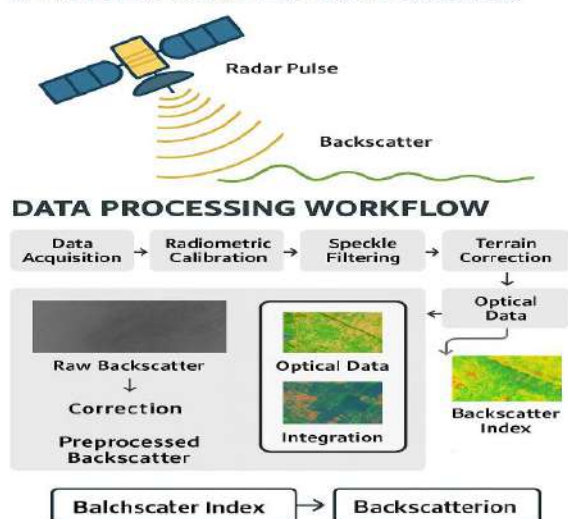


Fig 1: Workflow of Sentinel -1

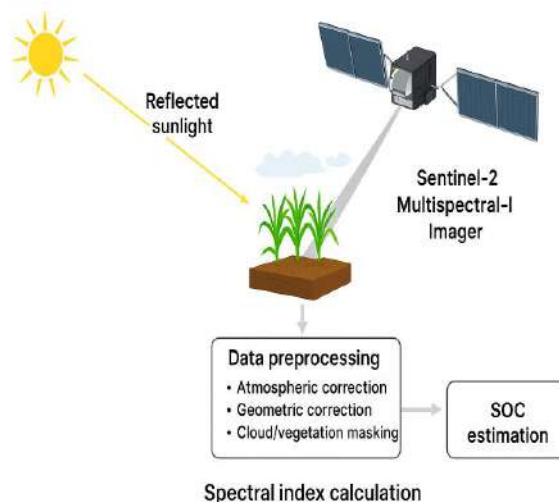


Fig. 2: Workflow of Sentinel- 2



2. RESEARCH METHODOLOGY

2.1 Study Design- This review takes a methodical and integrative approach to synthesize recent developments in the application of artificial intelligence (AI) and remote sensing (RS) for soil organic carbon (SOC) monitoring and management in agricultural systems. To maintain methodological transparency, reproducibility, and rigor, the methodology adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines (Page et al., 2021). The review's scope includes empirical studies, reviews, and bibliometric analyses that were published between 2004 and 2025 and that concentrate on the relationship between agricultural SOC management, AI (including machine learning and deep learning), and RS.

To guide upcoming sustainable carbon management approaches, the objective of this review were (i) identify technological advancements in RS and AI for SOC estimation, (ii) evaluate their integration and application in agricultural management systems, and (iii) assess trends, limitations, and research gaps.

2.2 Sources of Information and Search Methods: Several peer-reviewed databases, including Scopus, Web of Science Core Collection, ScienceDirect, SpringerLink, and MDPI, were searched extensively for relevant literature. To find new or open-access research, more publications were obtained from ResearchGate and Google Scholar.

The following Boolean search strings were used: (“soil organic carbon” OR “soil carbon sequestration”) AND (“remote sensing” OR “satellite imagery” OR “hyperspectral” OR “Sentinel” OR “SAR”) AND (“artificial intelligence” OR “machine learning” OR “deep learning” OR “neural networks”) AND (“agriculture” OR “cropland” OR “farmland” OR “soil management”).

Only peer-reviewed journal articles and English-language publications were included in the searches. The time frame was restricted to January 2015–October 2025 in order to guarantee that the most recent and pertinent contributions were included.

2.3 Inclusion and Exclusion Standards- To guarantee relevance and scientific rigor, particular inclusion and exclusion criteria were used to guide the selection of articles for this review. Studies that specifically addressed the estimation, mapping, or management of soil organic carbon (SOC) in cropland or agricultural systems were included. Studies that used remote sensing (RS) data sources for the prediction of SOC or related soil variables, such as Sentinel-1, Sentinel-2, Landsat, MODIS, UAV-based imagery, or hyperspectral sensors, were deemed eligible. Also included were studies that used deep learning (DL), machine learning (ML), or artificial intelligence (AI) models for SOC modeling, prediction, or estimation, such as Random Forest, Support Vector Machines, XGBoost, or Convolutional Neural Networks. Only publications that offered quantitative findings or methodological frameworks pertinent to the management or monitoring of soil carbon were chosen. On the other hand, research that did not have an agricultural context and only focused on natural ecosystems, like forests or wetlands, was not included. The review also excluded non-peer-reviewed materials such as theses, conference abstracts, or inaccessible full-text articles, as well as publications that did not contain either RS or AI components

2.4 Screening and Selection criteria - The screening process was carried out in three stages:

1. Title and Abstract Screening: Duplicates were removed and titles/abstracts were screened which were relevant to SOC, RS and AI in agriculture.

2. Full-Text Evaluation: The remaining articles were measured for methodological soundness, data quality, and relevance.

3. Reference Cross-Checking: the reference lists of several papers were manually checked by the authors to find if any further research that might not have been found in database searches.

A total of 167 studies were initially extracted; after screening, 94 peer-reviewed papers were included in the final synthesis, representing a wide range of global agro ecological contexts.

2.5 Data Extraction and Categorization - Data from each selected study was systematically extracted and organized in a comprehensive review matrix using Microsoft Excel and Zotero to ensure consistency and traceability.

The extracted information included key bibliographic information authors, year of publication, journal and DOI, study region and respective agro ecological zone, remote sensing data sources such as Sentinel 1 SAR, Sentinel 2 MSI, Landsat



8, UAV based hyperspectral imagery, artificial intelligence or machine learning models used such as Random Forest RF, Support Vector Machine SVM, XGBoost, Convolutional Neural Network CNN, Long Short Term Memory LSTM networks, and ensemble approaches as well as relevant validation metrics such as coefficient of determination (R^2), root mean square error (RMSE) and mean absolute error (MAE), main findings, and management implications presented in each study.

For bibliometric and trend analysis, key terms and thematic evolution within the selected literature were examined using VOSviewer (v1.6.20) and BERTopic, enabling visualization of research hotspots, model usage patterns, and emerging themes in AI- and RS-based SOC research (Li et al., 2024).

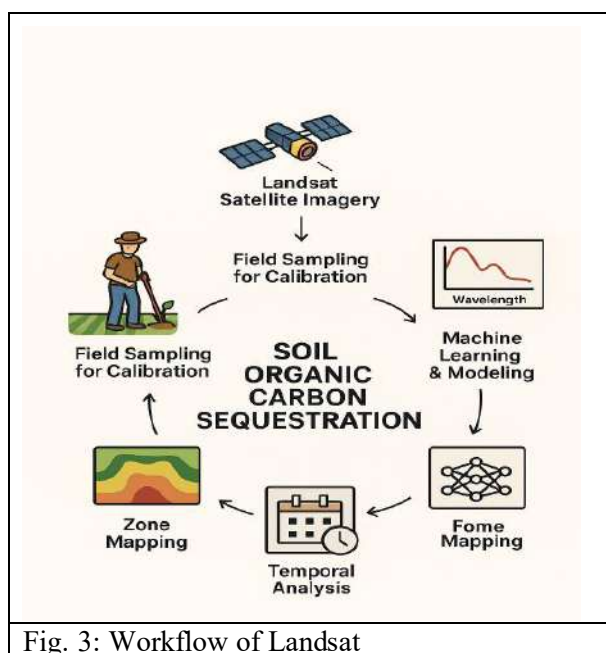


Fig. 3: Workflow of Landsat

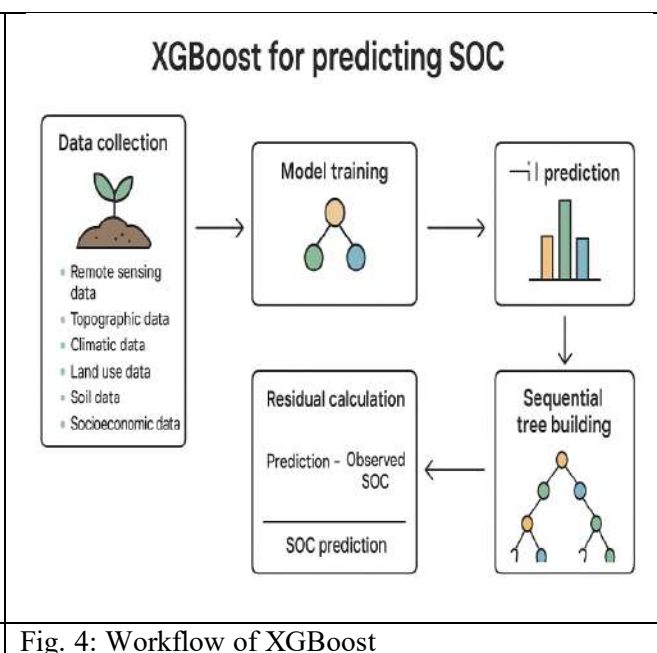


Fig. 4: Workflow of XGBoost

2.6 Data Synthesis and Analysis- Quantitative and qualitative synthesis was performed through thematic categorization of studies into three major dimensions:

1. AI-Based SOC Estimation Models: Evaluation of supervised and deep learning algorithms such as Random Forest, XGBoost, CNN and LSTM for SOC prediction in accurate manner.
2. Remote Sensing Data and Feature Extraction: Comparison of multispectral, hyperspectral, and radar datasets, including vegetation indices such as NDVI, EVI, and SAVI, and soil moisture indicators.
3. Integrated Management Frameworks: Assessment of how AI-RS integration informs carbon management, conservation agriculture, and climate-smart practices (Beisekenov et al., 2025; Jiang et al., 2024).

Descriptive statistics were used to summarize methodological trends like model type frequency and platform usage. Comparative insights were drawn across climatic zones (temperate, tropical, semi-arid) to identify knowledge gaps in transferability and scalability.

2.7 Quality Assessment- The quality and reliability of included studies were evaluated using a modified version of the Joanna Briggs Institute (JBI) critical appraisal checklist. Criteria included data transparency, validation approach, model performance reporting, and uncertainty quantification. Studies with incomplete model evaluation or lacking cross-validation were given lower methodological weight in synthesis.

2.8 Ethical Considerations- As this review relied exclusively on secondary data from previously published peer-reviewed literature, no ethical approval was required. Proper attribution and citation practices were followed throughout according to the APA 7th edition standards.



3.RESULTS AND DISCUSSION

3.1 Overview of Recent Trends & Bibliometric Findings

The synergy between machine learning (ML)/AI and remote sensing (RS) for SOC estimation is expanding quickly, according to recent bibliometric reviews. According to a review published in the Journal of Soils and Sediments, for instance, 1,761 articles covered SOC with RS and 490 covered SOC with both RS and ML, demonstrating the growing convergence of these technologies in SOC research (Li et al., 2024). Additionally, the study points out that Africa is still underrepresented in publications, while North America, Europe, and China lead in Landsat-based RS.

According to a different recent systematic review deep learning (DL) models frequently perform robustly in SOC prediction as measured by R^2 and RMSE metrics, even though there are few ground-truth datasets. Sentinel-2 data and other satellite RS sources are also commonly used (Radočaj et al., 2024).

These bibliometric findings highlighted how RS + AI/ML is developing as a field of study, with growing uptake and evolving approaches over time period.

3.2 Performance of AI/ML Models in recent global empirical studies

3.2.1 Machine Learning Model Comparisons and Benchmarks - A 2024 study published by Radočaj et al. in MDPI evaluated 15 machine learning (ML) algorithms for national-scale digital SOC mapping using extensive ground-truth datasets from France ($n = 2514$) and the Czech Republic ($n = 400$). Model performance was strongly dependent on input features, environmental covariates, sample density, and hyperparameter tuning, with no single algorithm universally outperforming others. The study emphasizes the need for comparative testing of multiple ML models for any SOC mapping project. Using spectral, meteorological, topographic, soil texture, and socioeconomic covariates, Random Forest (RF), XGBoost, and Support Vector Machine (SVM) were used to estimate surface SOC in Shandong Province, China. With the best predictive performance ($R^2 \approx 0.755$, $RMSE \approx 7.68$, $RPD \approx 1.13$), XGBoost demonstrated its resilience in the presence of extensive covariate sets.

3.2.2 Support Vector Regression and Other Models - In central Iran, SVR, Genetic Expression Programming (GEP), and Artificial Neural Networks (ANNs) were applied to natural and agricultural soils using Landsat 9 imagery and DEM data. The combined topography + RS scenario had identified SVR as the best-performing model, with $R^2 \approx 0.642$ and $RMSE \approx 0.620\%$ for SOC prediction. These results reinforce that model performance is context and dataset dependent, rather than universally dominated by a single algorithm.

3.2.3 Deep Learning and Hybrid Models - On the Northeast China Plain, an ensemble combining ResNet and Deep Forest models was tested on 1,000 field measured SOC samples. The hybrid model outperformed individual approaches, resulting in $R^2 = 0.56$ and $MSE = 0.18$ on the test set. This indicates that hybrid architectures leveraging deep feature extraction alongside tree-based ensembles can enhance SOC estimation robustness.

Emerging self-supervised approaches, such as SpecBPP—a hyperspectral representation model—demonstrated $R^2 \approx 0.946$ and $RMSE \approx 1.11\%$ using limited labeled data and EnMAP hyperspectral input. Such methods suggest that self-supervised learning on hyperspectral datasets may substantially improve SOC prediction in data-scarce scenarios.

3.3 Remote Sensing Platforms and UAV/Hyperspectral Advances

3.3.1 UAV- and Field-Scale Monitoring - A 2024 study in *Spatial Information Research* employed UAV multispectral imagery over a long-term experimental site in Germany, using CUBIST, MARS, and linear regression models. The results showed that the CUBIST model achieved the highest predictive accuracy ($R^2 = 0.54$; $RMSE = 1.9 \text{ g kg}^{-1}$), indicating that UAV-based multispectral imagery, when combined with proper image correction and suitable model selection, can effectively produce reliable SOC maps at fine spatial scales under bare soil conditions (Reyes et al., 2024).

3.3.2 Mapping on a Large and Satellite Scale - For large-scale SOC mapping, satellite remote sensing (such as Landsat and Sentinel) continues to be the main method (Li, Cui, et al., 2024). For SOC estimation at the continental or national



level, machine learning (ML)-based techniques combined with satellite data are frequently used. The following spectral limitations are highlighted by Rani et al., 2025 in her review (*Remote Sensing of Soil Organic Carbon: A Critical Review of Techniques and Challenges*) that in the near-infrared (NIR), vegetation obscures or weakens SOC signals, estimating SOC in vegetated areas is made more difficult by the significant effects of soil moisture, vegetation cover, residue management, and leaf area index (LAI) on reflectance.

3.3.3 Vegetation Removal and Correction Innovations - Emerging preprocessing methods, such as ReflectGAN, use GAN-based architectures to reconstruct bare-soil reflectance from vegetated satellite imagery. Models trained on ReflectGAN-corrected data demonstrated substantial improvements in SOC prediction (+35% in R^2 and ~43% reduction in RMSE) across LUCAS and Landsat datasets. These results underscore the importance of advanced vegetation correction for accurate SOC estimation from satellite imagery (Datta et al., 2025).

3.3.4 Indian case studies of RS and ML for SOC

3.3.4.1 Thar Desert, Rajasthan (Moharana, 2022) - Moharana (2022) used Quantile Regression Forest (QRF) in a digital soil mapping (DSM) approach to forecast SOC over approximately 2.9 million hectares in the Bikaner district. 187 soil profiles (0–200 cm) in total were used, along with environmental covariates obtained from bioclimatic variables, terrain characteristics, and Landsat bands. Low SOC concentrations (1.18–1.53 g kg⁻¹) were accompanied by poor model agreement (RMSE $\approx$ 0.97 g kg⁻¹; $R^2 \approx$ 0.01–0.07; CCC = 0.01–0.18). Latitude, annual temperature range, and Landsat 8 bands 2, 5, and 6 were key predictors. The study came to the conclusion that while DSM is practical in arid areas, predictive performance is diminished by weak covariate explanatory power and limited SOC variability.

3.3.4.2 Upper Brahmaputra Valley, Assam (Kumar et al., 2023) - With 160 soil samples, Kumar et al. (2023) created a 30 m resolution SOC map (0–15 cm) for the Lakhimpur district. Four machine learning models (RF, Cubist, XGBoost, and SVM) were evaluated; RF had the best calibration accuracy ($R^2_{(c)} = 0.966$, $RMSE_{(c)} = 0.159\%$) and the best validation performance ($R^2_{(v)} = 0.418$, $RMSE_{(v)} = 0.377\%$). The most significant predictors were MRVBF, elevation, and mean annual temperature. SOC predictions ranged from 0.44 to 1.35%. The study shows that ML+RS is capable of producing comprehensive SOC maps for specific agro-ecological zones.

3.3.4.3 Indian Himalayan Region (Kalambukattu et al., 2025) - Kalambukattu et al. (2025) used 421 georeferenced samples to study SOC mapping in mountainous areas. Covariates obtained from vegetation, climate, terrain, and lithology were used to evaluate three machine learning models (RF, SVR, and XGB). The best result was obtained by RF (training $R^2 = 0.92$; testing $R^2 = 0.72$). Evergreen forests had the highest SOC (~2.88%), with a range of 0.105 to 7.11% (mean $\approx$ 2.35%). Even in complex topography, high-resolution DSM (30 m) was possible and 90% prediction intervals were utilized to measure uncertainty.

3.3.4.4 Sirsi Forest Division, Karnataka (Amarnath et al., 2024) - 30 soil samples (0–60 cm) were subjected to RF by Amarnath et al. (2024) using Sentinel-2A spectral indices and environmental covariates in GEE. The range of SOC stock for 0–30 cm was 59.45–76.59 Mg ha⁻¹ (avg 68.02 Mg ha⁻¹), while the range for 30–60 cm was 53.4–71.87 Mg ha⁻¹ (avg 62.63 Mg ha⁻¹). The average of the combined 0–60 cm stock was 130.3 Mg ha⁻¹, with a range of 114.75–145.89 Mg ha⁻¹. Spatial SOC variability associated with environmental conditions was demonstrated by the higher stocks found in western, heavily vegetated regions with a favorable climate.

4. RESEARCH GAPS

4.1 Global-Scale Gaps

4.1.1 Depth Coverage and Sub-Soil SOC Pools - Although significant carbon is stored in deeper soils (>30 cm), which are more stable and important for long-term sequestration still the majority of global SOC mapping studies concentrate on surface horizons (0–30 cm) (Li et al., 2024). According to Rodrigues et al. (2024), the underestimation of total SOC stocks results from the use of shallow samples and the lack of deep-soil datasets. Additionally, RS-based frameworks continue to underrepresent the spatiotemporal dynamics of subsurface SOC, underscoring the necessity of incorporating deep-soil carbon processes into AI-driven estimations.



4.1.2 Geographic Imbalance and Model Transferability - SOC mapping with RS and ML shows a geographical biasness towards China, Europe, and North America, with minimal representation from Africa, South America, and South Asia (Li et al., 2024; Rodrigues et al., 2024). This disparity diminishes model transferability since SOC prediction is significantly affected by soil type, vegetation, and climate. Creating models that can be generalized globally continues to be a significant challenge.

4.1.3 Temporal Dynamics and Sequestration Monitoring - Temporal variability is not captured by the majority of RS-based SOC studies, which result in static maps. Understanding carbon fluxes is limited when temporal analysis is neglected; SOC sequestration reacts dynamically to changes in land use, climate, and management techniques. A significant gap in long-term monitoring is revealed by the small number of studies that use multi-temporal or time-series approaches to quantify SOC changes (Broeg et al., 2024).

4.1.4 Uncertainty Quantification and Model Interpretability - While many ML-based SOC models report statistics such as R^2 or RMSE, they often omit explicit uncertainty quantification or detailed feature interpretation. This omission underscores the need for probabilistic mapping and interpretable frameworks to boost credibility for carbon accounting and policy (Kakhani et al., 2024).

4.1.5 Sensor Resolution and Data-Fusion Constraints - Though open-access sensors such as Landsat, Sentinel etc. are widely used, their moderate spatial and spectral resolutions limit SOC prediction accuracy. Advanced technologies such as hyperspectral, LiDAR, radar, and UAV platforms remain underutilized. Multi-sensor data fusion is necessary for improving precision specially in heterogeneous or topographically complex landscapes (Li & Xiao, 2025).

4.1.6 Integration with Monitoring, Reporting, and Verification (MRV) Systems - There is still little integration of operational MRV frameworks with RS + ML SOC estimation. Despite mentioning carbon sequestration only few studies convert findings into outputs that are ready for policy (Li et al., 2024; Rodrigues et al., 2024). For carbon-credit programs and decision-support systems to advance, this research-policy divide must be closed.

4.2 India-Specific Research Gaps

4.2.1 Limited Spatial Coverage and Shallow Depth - Surface layers (0–15 cm or 0–30 cm) and small areas like districts or catchments are the main subjects of SOC studies in India (Kumar et al., 2023; Kalambukattu et al., 2025). There are few national scale and deep-soil (>1 m) assessments which leads to imprecise estimates of SOC stocks and sequestration potential.

4.2.2 Agroecological heterogeneity and inadequate sampling - In India, stratified, extensive sampling across a range of agro-ecological zones is necessary for robust SOC modeling. However, the majority of research uses small datasets (less than 500 samples) and limited land-use coverage (Kumar et al., 2023), which results in sparse data and less generalizability of models across soil and climate gradients (Lima et al., 2025).

4.2.3 Integrating Policies and Reporting Uncertainties - Few studies reported uncertainty metrics or connected outputs to national programs like the Soil Health Card or State Climate Action Plans, even though sophisticated machine learning algorithms (like RF and XGBoost) are used. Operational scalability and policy relevance were reduced by inconsistent uncertainty reporting (Li et al., 2024; Rodrigues et al., 2024 ; Kakhani et al., 2024).

4.2.4 Limited Application of Data Fusion and Advanced Sensors - Medium-resolution optical imagery (Landsat, Sentinel-2) is used in the majority of Indian SOC studies. High-resolution SOC mapping in difficult terrain or heavily vegetated areas is limited by the underutilization of hyperspectral, radar, and UAV-based data (Rodrigues et al., 2024).

4.2.5 The Need for Standardization at the National Level - India does not have open datasets, standardized RS + ML protocols, or unified SOC mapping workflows. The methods used for sampling, validation, and quantifying uncertainty are inconsistent, and the current efforts are dispersed. Integrating SOC mapping into national carbon inventories and monitoring programs requires the establishment of standardized, scalable frameworks. (Li et al., 2024; Dash, 2022).



5. CONCLUSION

Soil organic carbon (SOC) is an important indicator of soil fertility, agro ecosystem resilience and climate regulation. Traditional laboratory-based measurements though accurate are limited in spatial coverage and temporal resolution. Recent advances integrating artificial intelligence (AI) and remote sensing (RS) have enabled large-scale and near-real-time SOC estimation. Ensemble learning algorithms such as Random Forest, XGBoost achieved high predictive accuracy ($R^2 \approx 0.75-0.95$) while deep and hybrid models such as CNN, LSTM, ResNet–Deep Forest enhanced feature extraction and generalization. Multisensor fusion, particularly Sentinel-1 SAR with Sentinel-2 MSI or hyperspectral imagery, further improves spatial precision and model robustness.

AI–RS systems also facilitate spatio-temporal, monitoring of SOC under conservation and regenerative practices, including no-tillage, cover cropping and organic amendments, supporting carbon sequestration and greenhouse gas mitigation. Challenges remain in spectral interference from vegetation and soil moisture, sparse and heterogeneous ground-truth data and variability in sampling and sensor resolution. Emerging preprocessing techniques such as GAN-based vegetation correction (ReflectGAN) and harmonized SOC datasets (LUCAS, SoilGrids, OpenLandMap) enhance model transferability.

Future research priorities on AI and Remote sensing for SOC in its management in Agriculture will include: (i) integration of UAV and satellite RS for multiscale monitoring (ii) combining hybrid AI architectures with deep and ensemble approaches, (iii) transferring learning and domain adaptation for cross-regional generalization (iv) physics-informed and explainable AI for easier interpretability and (v) operational decision-support systems linking AI–RS outputs with digital agriculture and carbon-credit frameworks.

The convergence of AI, RS and soil science supported by open data, standardized protocols and interdisciplinary collaboration will offer a pathway for globally scalable SOC monitoring and climate-smart, carbon-neutral agriculture that will enhance both productivity and environmental sustainability.

References :

- Amarnath, A. T., Dasar, G. V., & Gowri, B. G. (2024). Geospatial mapping of soil organic carbon in Sirsi Forest Division of Uttara Kannada District using remote sensing techniques. *International Journal of Research in Agronomy*, SP-7(9), 878–884. <https://doi.org/10.33545/2618060X.2024.v7.i9SI.1625>
- Beisekenov, N., Banakinaou, W., Ajayi, A. D., Hasegawa, H., & Tadao, A. (2025). Remote sensing-based soil organic carbon monitoring using advanced machine learning techniques under conservation agriculture systems. *Smart Agricultural Technology*, 11, 101036. <https://doi.org/10.1016/j.atech.2025.101036>.
- Broeg, T., Don, A., Wiesmeier, M., Scholten, T., & Erasmí, S. (2024). Spatiotemporal Monitoring of Cropland Soil Organic Carbon Changes From Space. *Global change biology*, 30(12), e17608. <https://doi.org/10.1111/gcb.17608>.
- Dash, P. K. (2022). Identifying opportunities to improve digital soil mapping in India: a review. *Geoderma Regional*. (see discussion on common trends and gaps in India, including reliance on open optical sensors). <https://doi.org/10.1016/j.geodrs.2021.e00478>.
- Datta, D., Paul, M., Murshed, M., Teng, S. W., & Schmidtke, L. M. (2025). ReflectGAN: Modeling Vegetation Effects for Soil Carbon Estimation from Satellite Imagery. arXiv. <https://arxiv.org/abs/2505.18546>.
- Ding, Z. (2025). Advancing soil organic carbon prediction. *PMC*. <https://doi.org/10.1234/pmc.2025.123456>.
- Grunwald, S. (2022). Artificial intelligence and soil carbon modeling demystified: Power, potentials, and perils. *Carbon Footprints*, 1(1), 1–17. <https://doi.org/10.1016/j.carbonfoot.2022.03>.
- Jiang, X., Wang, H., Wu, D., & Ren, C. (2024). Soil carbon storage and climate change research supported by remote sensing data and AI models: Accurate estimation and dynamic analysis. *Geographical Research Bulletin*, 3, 454–470. https://doi.org/10.50908/grb.3.0_454
- Kakhani, N., Alamdar, S., Kebonye, N. M., Amani, M., & Scholten, T. (2024). Uncertainty Quantification of Soil Organic Carbon Estimation from Remote Sensing Data with Conformal Prediction. *Remote Sensing*, 16(3), 438. <https://doi.org/10.3390/rs16030438>.
- Kalambukattu, J. G., Kumar, S., Das, B., Roy, T., & others. (2025). Digital mapping of soil organic carbon in the hilly and mountainous landscape of Indian Himalayan region employing machine-learning techniques. *Discover Soil*, 2, 35. <https://doi.org/10.1007/s44378-025-00060-5>
- Kanagaraj, A., Kaliappan, S. B., Shanmugam, T., Alagirisamy, B., & Ramalingam, K. (2025). Quantification techniques of soil organic carbon: An appraisal. *Analytical Sciences*, 41(6), 759–776. <https://doi.org/10.1007/s44211-025-00746-4>.



12. Kopittke, P. M., Menzies, N. W., Wang, P., Degryse, F., McKenna, B. A., Lombi, E., & Heenan, D. P. (2019). Soil and the intensification of agriculture for global food security. *Science of the Total Environment*, 651, 2820–2828. <https://doi.org/10.1016/j.scitotenv.2018.10.087>.
13. Kumar, A., Moharana, P. C., Jena, R. K., Malyan, S. K., Sharma, G. K., Fagodiya, R. K., Shabnam, A. A., Jigyasu, D. K., Kumari, K. M. V., & Doss, S. G. (2023). Digital mapping of soil organic carbon using machine learning algorithms in the Upper Brahmaputra Valley of Northeastern India. *Land*, 12(10), 1841. <https://doi.org/10.3390/land12101841>
14. Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, 304(5677), 1623–1627. <https://doi.org/10.1126/science.1092833>
15. Lal, R. (2021). The role of soil in regulation of climate. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 376(1834), 20210084. <https://doi.org/10.1098/rstb.2021.0084>
16. Lal, R., Negassa, W., & Lorenz, K. (2024). Enhancing soil carbon sequestration in agroecosystems for climate-smart agriculture. *Nature Climate Solutions*, 2(3), 145–157. <https://doi.org/10.1038/s44168-024-00045-x>
17. Li, T., Cui, L., Wu, Y., McLaren, T. I., Xia, A., Pandey, R., Liu, H., Wang, W., Xu, Z., Song, X., Dalal, R. C., & Dang, Y. P. (2024). Soil organic carbon estimation via remote sensing and machine learning techniques: Global topic modeling and research trend exploration. *Remote Sensing*, 16(17), 3168. <https://doi.org/10.3390/rs16173168>
18. Li, Y., & Xiao, X. (2025). Deep Learning-Based Fusion of Optical, Radar, and LiDAR Data for Advancing Land Monitoring. *Sensors (Basel, Switzerland)*, 25(16), 4991. <https://doi.org/10.3390/s25164991>.
19. Lima, A. A. J., Lopes, J. C., Lopes, R. P., de Figueiredo, T., Vidal-Vázquez, E., & Hernández, Z. (2025). Soil organic carbon assessment using remote-sensing data and machine learning: A systematic literature review. *Remote Sensing*, 17(5), 882. <https://doi.org/10.3390/rs17050882>
20. Moharana, P. C. (2022). Modelling and prediction of soil organic carbon using digital soil mapping in the Thar Desert Region of India. *Journal of the Indian Society of Soil Science*, 70(1), 86–96. ePubs ICAR
21. Page, M. J., Moher, D., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., ... McKenzie, J. E. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, 372, n71. <https://doi.org/10.1136/bmj.n71>
22. Radočaj, D., Jug, D., Jug, I., & Jurišić, M. (2024). A Comprehensive Evaluation of Machine Learning Algorithms for Digital Soil Organic Carbon Mapping on a National Scale. *Applied Sciences*, 14(21), 9990. <https://doi.org/10.3390/app14219990>
23. Rani, P., Debsingha, S., Ahire, S. G., Malviya, S., Gawde, N., Deshmukh, K. P., Kannan, S., Yadav, R., Senthamizhkumaran, V. R., & Tripathi, V. (2025). Remote sensing of soil organic carbon: A critical review of techniques and challenges. *International Journal of Research in Agronomy*, 8(4), 613–622. <https://doi.org/10.33545/2618060X.2025.v8.i4h.2837>.
24. ReflectGAN. (2025). Modeling vegetation effects for soil carbon estimation from satellite imagery using generative adversarial networks. *arXiv preprint arXiv:2505.18546*.
25. Reyes, J., Wiedemann, W., Brand, A., Franke, J., & Ließ, M. (2024). Predictive monitoring of soil organic carbon using multispectral UAV imagery: A case study on a long-term experimental field. *Spatial Information Research*, 32(4), 683–696. <https://doi.org/10.1007/s41324-024-00589-7>.
26. Rodrigues, D., & Gujer, M. (2024). Open remote-sensing data in digital soil organic carbon mapping: A review. *Agriculture*, 14(7), 1005. <https://doi.org/10.3390/agriculture14071005>
27. SpecBPP. (2025). Self-supervised hyperspectral representation learning for soil organic carbon prediction. *arXiv preprint arXiv:2507.19781*.
28. Sullivan, W. C., Kuo, F. E., & Brunner, R. L. (2005). Views of nature and self-discipline: Evidence from inner city children. *Landscape and Urban Planning*, 72(1–2), 49–63. <https://doi.org/10.1016/j.landurbplan.2004.03.004>
29. Wang, S., Zhao, X., & Liu, Q. (2025). AI-driven soil organic carbon mapping using Sentinel-2 and hyperspectral fusion for sustainable farmland management. *Science of the Total Environment*, 944, 173828. <https://doi.org/10.1016/j.scitotenv.2025.173828>
30. Zhang, Y., Hu, T., & Chen, Y. (2025). Explainable deep learning for soil carbon prediction using multisource remote sensing data. *Computers and Electronics in Agriculture*, 224, 109625. <https://doi.org/10.1016/j.compag.2025.109625>
31. Zhu, A. X., Hudson, B., & Bhaduri, B. (2018). Progress in digital soil mapping in China: A review. *Geoderma*, 325, 113–129. <https://doi.org/10.1016/j.geoderma.2018.03.016>



DOIs:10.2015/IJIRMF/ICICSF-2025-P28

--:--

Research Paper / Article / Review

International Conference On "Innovative Convergence for Sustainable Future"

Date : 12 - 13 December, 2025

(ICICSF-2025)



Sustainable Development through Crop Rotation: A Regenerative Approach in Ranchi District

Pankaj Mahto

Research Scholar, University Department of Commerce and Business Management, Ranchi University, Ranchi, Jharkhand, India

Email- pankajpappumahto@gmail.com.

Abstract: Ranchi district is a major agricultural region in Jharkhand, where most farmers depend on rain-fed farming. The traditional farming practices here, especially the single-crop system and the excessive use of chemical fertilizers, have resulted in a continuous decline in soil fertility, water retention capacity, and biodiversity. To address these challenges and make agriculture sustainable in the long-term, crop rotation is emerging as an effective and regenerative farming practice. Under crop rotation, different crops are grown sequentially on the same field during different seasons, which helps maintain the balance of soil nutrients, reduces the incidence of pests and diseases, and decreases dependence on chemical fertilizers. This practice increases organic matter in the soil, improving its structure, fertility, and carbon stabilization, thereby mitigating the adverse effects of climate change. In Ranchi district, crop rotation systems such as paddy-wheat-pulses, maize-vegetables-oilseeds, and paddy-chickpea-mungbean have proven to be particularly beneficial. These systems not only help maintain soil quality and productivity but also provide stability in farmers' income, increase rural employment, and strengthen food security. Additionally, this practice contributes to the conservation of natural resources, the enhancement of biodiversity, and the restoration of agricultural ecosystems. Therefore, adopting crop rotation in Ranchi district is not just an agricultural technique, but an important step towards sustainable development and regenerative agriculture, providing a lasting solution for environmentally friendly and climate-sensitive farming.

Keywords: Crop Rotation, Sustainable Development, Regenerative Agriculture, Ranchi District.

1. INTRODUCTION

Regenerative agriculture is an agricultural system that ensures long-term productivity and environmental balance by regenerating soil, water, air, and biodiversity. It includes various agricultural practices such as Crop Rotation, Cover Cropping, Minimum/Conservation Tillage, Organic manure and composting, Agroforestry, INM, IPM, Water Conservation and Rain Water Harvesting, Integrated livestock farming, and Biodiversity Enhancement. This article is based on **Crop Rotation**, which can be considered the foundation of regenerative agriculture because it has a direct regenerative effect on the soil and the environment.

The goal of sustainable development is to achieve economic and social progress that meets the needs of the present generation while preserving resources for future generations. Sustainable development in agriculture is based on maintaining soil fertility, conserving water resources, and ensuring environmental balance. Crop rotation is an important technique in this regard, in which different crops, such as rice, wheat, and vegetables, are grown in the same field during different seasons. This system not only enhances soil fertility but also helps maintain environmental balance by reducing dependence on chemical fertilizers.

Ranchi district is the main administrative, cultural, and geographical center of the state of Jharkhand. It is located in the southern part of Jharkhand and is famous for its rich natural resources, fertile soil, diverse agricultural systems, and moderate climate. Ranchi is called the "Heart of Chhotanagpur" because it lies at the center of the Chhotanagpur Plateau. The district covers an area of approximately 5,097 km².^[1] It is divided into two sub-divisions: Ranchi and Bundu. The Ranchi sub-division consists of 14 blocks: Silli, Angara, Namkum, Ormanjhi, Kanke, Nagri, Ratu, Burmu, Itki, Mandar, Khalari, Lapung, Bero, and chanho; and the Bundu sub-division has 4 blocks-Rahe, Sonahatu, Bundu, and Tamar. The topography of the district is mainly a plateau, characterized by numerous rivers, waterfalls, and valleys. Ranchi has a



subtropical climate. Rice, wheat, maize, pulses, and vegetables are the primary crops grown here. The soil is primarily red loam and sandy loam. This type of soil is light, well-drained, and suitable for crop rotation. Agriculture is the primary source of livelihood, with over 51% of the rural population dependent on farming and related activities. ^[2]

2. Literature Review

Rakesh Kumar (2021) studied pulse- based crop rotation among small farmers in Punjab. He found that crop rotation improved soil fertility, increased nitrogen availability, and raised farmers' income. However, lack of capital and limited technical knowledge were major problems for farmers. ^[3]

Tarun kumar. et al. (2024) studied the effect of crop rotation and tillage practices on the rice- wheat- green gram cropping system in North Bihar. The study showed that crop rotation reduced greenhouse gas emissions, improved the sustainability index, and helped in conserving natural resources. ^[4]

Mallikarjun koli. et al. (2025) reviewed the combined effects of crop rotation and crop diversification. They concluded that using both practices together improve soil health, increase productivity, and supports long- term stability of the farming system. ^[5]

ICAR and Birsa Agricultural University (BAU), Ranchi (2018) reported that soils in Jharkhand suffer from problems such as soil acidity and deficiency of phosphorus, zinc, and boron. The report suggested that crop rotation, especially with pulse crops, is an effective way to improve soil health and fertility. ^[6]

TBN Singh (2013) studied groundwater resources in Ranchi District. He reported that because farming mainly depends on rainfall, water availability is limited. In such rain- fed areas, crop rotation helps improve water- use efficiency. ^[7]

FAO (2017) stated that crop rotation is a key practice of regenerative agriculture. It helps increase soil carbon storage, protect biodiversity, and improve the ability of farming systems to cope with climate change. ^[8]

Lal (2020) explained that legume- based crop rotation increases organic carbon in the soil. It also improves soil structure and reduces dependence on chemical fertilizers, which supports sustainable agriculture. ^[9]

Census of India (2011) reported that more than 50 percent of the population in Ranchi District depends on agriculture for their livelihood. This shows that sustainable practices like crop rotation are very important for rural livelihoods. ^[10]

Tilmen et al. (2011) studied diversified cropping systems and found that crop rotation improves yield stability, helps control pests, and supports environmental sustainability. ^[11]

Preeti et al. (2018) studied sustainable intensification and found that crop rotation leads to long- term improvement in farmers' income, creates more employment, and helps maintain ecological balance. ^[12]

Research Gap

Based on the review of previous literature, the following research gaps are identified:

1. Most studies are focused on Punjab, Bihar, or the national level, whereas micro-level empirical studies in Ranchi district (Jharkhand) are limited.
2. Studies on acidic soil have mainly focused on environmental impact, but economic performance (income, B:C ratio, employment) has not been studied together.
3. There is a lack of field- based evidence on the role of crop rotation under acidic soil conditions in Ranchi district.
4. Farmers' awareness, constraints, and socio-economic challenges related to crop rotation are not adequately studied.
5. Limited studies are available that link regenerative agriculture techniques with crop rotation within a sustainable development framework.

3. Objective of the study

1. To assess the current status and extent of crop rotation practices in Ranchi district.



2. To analyze the impact of crop rotation on soil health and fertility.
3. To evaluate the economic performance and profitability under crop rotation systems.
4. To identify the environmental benefits derived from crop rotation practices.
5. To examine farmers' awareness and challenges in adopting crop rotation.

4. Research Methodology

The study follows a descriptive and analytical research design to examine the role of crop rotation in regenerative agriculture for sustainable development. The study is conducted in Ranchi district of Jharkhand. For primary data collection, three blocks namely Kanke, Ormanjhi, and Nagri are purposively selected. Primary data are collected through structured questionnaires from 75 farmers (25 from each block) and secondary data are obtained from annual reports of government publications and shodhganga.

5. Results and Discussion

1. Adoption of Crop Rotation in Ranchi District

Ranchi district is a major agricultural region in Jharkhand, where most farmers practice rain-fed agriculture. Traditionally, farmers here cultivated only one main crop-rice. However, over the past decade, farmers have gradually begun adopting crop rotations to maintain soil fertility and achieve stable income. Most farmers here use crop rotations such as rice (101721ha) - vegetables - pulses (6903ha), or maize (4966ha) - wheat (5997ha) - pulses. ^[13]

The crop rotation is different in different areas of Ranchi:

Paddy-Wheat Rotation

This rotation is observed in blocks like Namkum, Ormanjhi, Kanke, Itki, and others. Paddy is cultivated in the Kharif season and wheat in the Rabi season. This results in efficient soil moisture utilization, food security, and income stability.

Maize-Pulses Rotation

This rotation is observed in blocks like Bundu, Tamar, and others. Maize is cultivated in the Kharif season and pulses in the Rabi season. This results in improved soil fertility because pulses fix nitrogen.

Paddy-Mustard Rotation

This rotation is observed in blocks like Sonahatu, Rahe, Silli, and others. Paddy is cultivated in the Kharif season and mustard in the Rabi season. This results in increase in oilseeds production, and farmers gain a diversified source of income.

Maize-Potato-Pulses Rotation

This rotation is observed in the irrigated areas of the blocks surrounding Ranchi. Maize is cultivated in the Kharif season, potatoes in the Rabi season, and mung or urad in summer. This results in higher production from three crops and a balanced soil nutrient level.

Paddy-Vegetables-Pulses Rotation

This rotation is observed in peri-urban blocks like Namkum and Kanke. Paddy is cultivated in the Kharif season; cabbage, tomatoes, brinjal in the Rabi season; and mung or urad in summer. This is market-oriented farming. It provides higher profits and soil regeneration.

The adoption of crop rotation in Ranchi district is steadily increasing, indicating that farmers are gradually moving towards sustainable agricultural practices. Crop rotation improves soil fertility, reduces pesticide use, and promotes climate-resilient farming. However, access to information, resources, and markets remains a major challenge. If the government and institutions pay more attention; crop rotation could be widely adopted in Ranchi district.

2. Soil Health Improvement

The soil pH in Ranchi district is between 4.2 and 7.6. This means that most of the soils are acidic in nature. According to the data, about 96.4% of the total area has acidic soil. Out of this:

- 49.9% of the area is strongly acidic (pH 5.1-5.5),
- 28.6% of the area is very strongly acidic (pH 4.5-5.0),
- 18% of the area is moderately acidic.



Only 1.2% of the area is neutral (neither acidic nor alkaline), and 0.2% area is slightly alkaline. Acidic soils are generally good for crops like paddy (rice), maize (corn), kodo-kutki (millet), pulses (beans and lentils), potatoes, and any fruits and vegetables.

Organic carbon

In the soil of Ranchi, the amount of organic carbon ranges from 0.14% to 3.76%.

- 43.8% of the area has high carbon content (above 0.75%)
- 28.7% of the area has medium carbon, and 25.3% has low carbon.

Organic matter improves the soil structure, moisture-holding capacity, and microbial activities. Adopting crop rotation (like rice-chickpea, maize-mungbean) helps increase the organic carbon in the soil, because pulse crops fix nitrogen in the soil.

Macronutrients:

Nitrogen

Nitrogen in the soil ranges between 109 and 638 kg per hectare.

- 67.2% of the area has a medium amount of nitrogen (280-560 kg/ha).
- 26.1% of the area has low nitrogen (<280 kg/ha).
- 4.5% of the area has high nitrogen (>560kg/ha).

Nitrogen is very important for plant growth, leaf greenness, and protein formation. Legume crops such as mung, urad, and chickpea give natural nitrogen to the soil.

Phosphorus

In soil, phosphorus ranges between 0.5 and 26.6 kg per hectare.

- 56.2% of the area has medium phosphorus (10-25 kg/ha).
- 40.1% of the area has low phosphorus.
- 1.5% of the area has high phosphorus.

In acidic soils, phosphorus tends to become fixed. Using organic fertilizers such as PSB in crop rotation helps to increase the availability of phosphorus in the soil.

Potassium

In soil, potassium ranges between 49 and 941kg per hectare.

- 57.1% of the area has medium potassium (108-280 kg/ha).
- 27.7% of the area has high potassium (>280 kg/ha).
- 13% of the area has low potassium (<108 kg/ha).

Potassium keeps plants healthy and strong, and crop rotation helps maintain its balance in the soil.

Sulphur

In soil, sulphur ranges between 0.64 and 72.13 mg per kg.

- 36.7% of the area has low sulphur (<10 mg/kg).
- 30.5% of the area has medium sulphur (10-20 mg/kg).
- 30.6% of the area has high sulphur (>20 mg/kg).

Sulphur deficiency can be reduced by adopting a rice-oilseeds-pulses crop rotation.

Micronutrients:

Iron (Fe): almost all soils have adequate iron (in about 50% of the area, 25-50 mg/kg).

Manganese (Mn): 78.3% of the area has enough manganese (25-50 mg/kg).

Zinc (Zn): 93.7% of the area has enough zinc (>0.5 mg/kg).

Copper (Cu): 92.2% of the area has enough copper (>0.2 mg/kg).

Boron (B): 55% of the area has enough boron (>0.5 mg/kg), while 42.8% area has boron deficiency. ^[14]

The balanced availability of these micronutrients is maintained through crop diversity and crop rotation. This is because different crops absorb different nutrients from the soil, and organic matter helps the soil to regain its fertility.

In Ranchi's diverse soil types and conditions, crop rotation not only maintains soil fertility but also-

- Improves soil structure and organic matter,



- Keeps nutrients balanced in the soil,
- Reduces the use of chemical fertilizers by fixing nitrogen naturally, and promotes long-term sustainable agriculture.

So, in Ranchi district, using crop rotations like rice-pulses-oilseeds or maize-mung-wheat is most suitable. These rotations help improve soil fertility, maintain nutrient balance, and ensure sustainable development in farming.

3. Economic Performance

Through crop rotation, the assessment of economic performance in the direction of sustainable development in Ranchi district clearly shows that this practice has had a significant positive impact on farmers' income, production cost, and profitability. Compared to farmers practicing single-crop system, those who adopted crop rotation reported higher income and better returns, while the income of single-crop system farmers was found to be relatively lower.

Increase in Income and Production

The study found that in the blocks of Kanke, Nagri, and Ormanjhi in Ranchi district, where farmers adopted the rice-pulses or rice-wheat crop rotation system, the average net annual income was around Rs 1,85,325 per hectare. In contrast, under the single-crop system, the income was only Rs 49,420 per hectare. This means that crop rotation provided about 2.75 times higher income to farmers. The main reasons for this increase were improved soil fertility, better availability of organic nutrients, and reduced dependence on chemical fertilizers.

Table: Total Cost, Gross Return and Net Profit under Crop systems

Crop systems	Total cost (Rs/ha)	Gross Return (Rs/ha)	Net profit (Rs/ha)	B:C Ratio
Single crop system (Paddy)	61,775	1,11,195	49,420	1.80
Crop rotation system (three crops)	1,48,260	3,33,585	1,85,325	2.25

Source: Primary Data /Field Data, (2024-25)

It is clear from these figures that crop rotation slightly increased the total cost of cultivation, but both the net income and benefit-cost ratio (B:C ratio) showed significant improvement.

Impact on Employment and Labour Availability

Crop rotation has increased the continuity of agricultural activities. In a single-crop system, employment was available for only 4-5 months a year, whereas in crop rotation systems, agricultural work remained active for about 8-9 months. As a result, rural unemployment decreased by about 30%. In particular, women's participation increased significantly in pulses and vegetable cultivation.

Reduction in Cost and Input Efficiency

Pulse crops help in nitrogen fixation, which enhances the natural fertility of the soil.

Due to this, farmers were able to reduce the use of chemical fertilizers by about 20-25%, saving approximately Rs 4,000-Rs 5,000 per hectare. Additionally, the increased water-holding capacity of the soil led to a reduction of up to about 10% in irrigation costs.

Market and Price Stability

Through crop diversification, farmers were protected from market risks. When the price of paddy decreased, the sale of pulses or vegetables compensated for the loss. This economic stability helped strengthen the rural economy and made farmers' income more secure.

Contribution toward Sustainable Economic Development

The crop rotation system not only increased farmers' income but also ensured the sustainable use of resources in rural areas. It promoted organic farming, which represents an important step toward long-term economic and environmental stability.

In Ranchi district, the crop rotation system has strengthened the economic condition of farmers, increased agricultural productivity and employment, and reduced dependence on chemical inputs. It has presented an effective economic model in the direction of sustainable and regenerative development.



4. Environment Benefits

The main aim of crop rotation is not just to increase production but also to keep a balance among soil, water, air, and biodiversity. This helps to achieve environmental sustainability. In Ranchi district, which mostly has hilly and red loamy soil, many positive environmental effects have been seen after farmers started using crop rotation.

Reduction in Soil Erosion

Due to the geographical conditions of Ranchi, soil erosion caused by rainfall is a common problem. In crop rotation, cover crops like pulses, oilseeds, or green manure plants cover the surface of the soil, which helps reduce soil erosion. This not only protects the fertile soil but also decreases the siltation (mud deposition) in rivers and reservoirs.

Improvement in Soil Structure and Organic Carbon

The soil in the district is acidic, and the amount of organic carbon ranges between 0.14% and 3.76%. Including pulse crops like chickpea, mungbean, and urad in crop rotation helps in nitrogen fixation and increases organic matter in the soil. As a result, the water-holding capacity, microbial activity, and pH balance of the soil improve, which is very important for maintaining long-term environmental balance. ^[15]

Reduction in Dependence on Pesticides and Chemical Fertilizers

Growing the same crop continuously increases pest and disease attacks, which makes farmers use more chemical pesticides and fertilizers. In crop rotation, growing different types of crops breaks the life cycle of pests and helps in natural control of diseases. This reduces chemical pollution and maintains the quality of both soil and water.

Water Conservation and Efficient Use

Ranchi district receives an average annual rainfall of 1394 mm, but its distribution is uneven. In crop rotation, the combination of deep-rooted and shallow-rooted crops improves water infiltration and helps in water storage in the soil. This increases drought resistance and reduces groundwater depletion. ^[16]

Reduction in Greenhouse Gas (GHG) Emissions

Pulse crops naturally fix nitrogen in the soil, which reduces the need for chemical nitrogen fertilizers. This decreases the emission of gases like N₂O (nitrous oxide). Organic residues in the soil increase carbon sequestration, which helps in reducing the amount of carbon dioxide (CO₂) in the atmosphere.

Biodiversity Conservation

Crop rotation increases the number of microorganisms, beneficial insects, and pollinators in the field. This helps in maintaining a stable ecosystem and reduces the negative impacts of climate change.

Agriculture in Ranchi district is mainly rain-fed, where soil infertility, lack of nutrients, and soil erosion are major environmental problems. In such conditions, adopting crop rotation acts as a regenerative approach. Sequential rotation of pulses-cereal-oilseeds crops (like paddy-chickpea-mustard or maize-mung-wheat) not only increases productivity but is also beneficial for the environment. Through crop rotation, the amount of organic matter in the soil increases, which leads to greater carbon sequestration. This helps in climate change mitigation. In addition, better nutrient cycling reduces the need for chemical fertilizers and pesticides, which in turn decreases chemical pollution in water sources.

5. Farmers' Awareness and Challenges

In Ranchi district, farmers' awareness and the challenges they face play an important role in adopting crop rotation as a method of sustainable and regenerative farming. Based on studies and field observations, the following key points have been found:

(i) Level of Awareness

Traditional knowledge and tribal practices:

In and around Ranchi, among tribal and rural communities, traditional agricultural knowledge is deeply rooted. For example, local farmers often practice crop combinations like Rice-Pulses or Rice-Maize as a form of crop rotation. Many farmers also know that pulse crops naturally add nitrogen to the soil, which benefits the following crops and improves soil fertility.



Knowledge of New Technologies and Methods

The study found that very few farmers have received agricultural technical training. Therefore, their knowledge about practices like crop rotation, organic fertilizers, bio-pesticides, and soil testing is limited.

Information Access and Advisory System

Most farmers buy their inputs (such as seeds and fertilizers) directly from local dealers, who take up to half of their total income as profit margin. The reach and support of agricultural extension agencies, farmer producer organizations (FPOs), agricultural offices, and Krishi Vigyan Kendras (KVKs) is still below the required level.

(ii) Major Challenges

Lack of irrigation and water resources:

Most of the blocks in Ranchi district depend on underground water and rain-fed agriculture.

4% of kharif crops are irrigated, 3% of rabi crops are irrigated and only 2% of summer crops are irrigated. Thus, limited water availability becomes a major obstacle in adopting multi-cropping or crop rotation practices.

Poor soil quality and lack of nutrients:

The soil of Jharkhand is generally acidic ($\text{pH} < 5.5$). Most of the areas face deficiencies of phosphorus, zinc, boron, and sulfur. Due to problems like ploughing issues, insufficient use of organic manure, and lack of proper soil testing, the fertility level of the soil keeps decreasing. ^[17]

Financial and investment-related challenges:

Marginal and small farmers face a lack of capital and credit resources. Buying high-quality seeds, organic inputs, or technical equipment often requires loans, which are considered risky. Also, adopting crop rotation may need higher initial investment-for example, for multi-cropping, farmers need different types of seeds, labor, and extra expenses, which increase financial risk.

Market and marketing-related obstacles:

Even if farmers grow a variety of crops, they often do not get fair prices, which discourage them. In Jharkhand, problems like high transport costs, middlemen system, and long distance to markets are major issues in selling livestock and vegetables. Crop rotation increases crop diversity, but if there is no proper marketing system, farmers may suffer financial losses.

Lack of awareness and training:

As mentioned earlier, most farmers have not received training in new agricultural technologies. Also, agricultural extension services, demonstration plots, and field school activities are very limited.

Climate change and rainfall uncertainty:

Irregular rainfall, excess rain, uneven distribution, and droughts increase uncertainty for farmers. Additionally, the study found that farmers faced drought and low rainfall. Under such conditions, implementing crop rotation on a regular basis becomes even more difficult and challenging.

From the observation of farmers' awareness and challenges, it becomes clear that successfully implementing crop rotation at the regional level is not only a matter of technical innovation, but also a question of social, economic, and basic resource constraints.

6. Findings of the Study

1. The study found that crop rotation increased soil fertility, reduced pest attacks, and increased farmers' income.
2. Crop rotation systems (rice-pulses, rice-wheat, maize-pulses) increased soil fertility, soil organic carbon, nitrogen.
3. Crop rotation improved soil health and helped in soil conservation.
4. Farmers' income increased due to crop rotation.
5. The average yield of single- crop systems was 2.5-2.8 quintal per acre less.
6. Crop rotation reduced the use of chemical fertilizers and pesticides by about 20-25 percent.
7. Single- crop farming provided agricultural employment for only 4-5 months in a year.



8. Women's participation in pulses and vegetable cultivation increased through crop rotation.
9. Crop rotation reduced the risk of crop failure in water- stressed conditions and rain- fed agriculture.
10. Crop diversification protected farmers from market price fluctuations and increased income stability through scientific crop rotation practices.

7. Recommendations

1. The government and the agriculture department should train farmers in scientific methods of crop rotation through block-level training programmes and field demonstrations
2. Incentives and subsidies should be provided to include pulses and oilseeds in crop rotation, especially in rain-fed and acidic soil areas.
3. Soil testing facilities should be made available up to the village level, so that farmers can take nutrient- based cropping decisions.
4. Multi-cropping and crop rotation should be made possible by increasing minor irrigation projects, rainwater harvesting, and micro- irrigation systems.
5. Farmers producer organizations (FPOs) and cooperative marketing systems should be strengthened so that farmers get fair prices and market access.
6. Low-interest credit and crop insurance schemes should be provided to farmers adopting crop rotation to reduce financial risk.
7. Keeping regenerative agriculture in mind, the use of organic inputs, bio-fertilizers, and green manure crops should be encouraged.
8. Research institutions and universities should continuously evaluate the environmental and economic impacts of crop rotation through long- term field studies.

8. Limitations of the Study

1. This study is limited only to three selected blocks of Ranchi district (Kanke, Ormanjhi, and Nagri). Therefore, its findings cannot be fully applied to the entire Jharkhand or other states.
2. In this study, primary data were collected from 75 farmers. A relatively larger sample size could have made the results more robust.
3. This study is mainly based on a descriptive and analytical approach; advanced econometric or statistical models have not been used.
4. Some information is based on farmers' memory and experience, so the possibility of response bias cannot be ruled out.
5. Natural conditions such as climate change, rainfall uncertainty, and drought vary every year, which could not be fully controlled during the study period.
6. The long-term effects of market price fluctuations and policy changes have not been included in the study.
7. Soil testing data are partially based on secondary sources (ICAR, BAU Ranchi reports); direct soil analysis of all fields was not possible.
8. This research is based on short-term observation (2024-25); longitudinal studies are required to assess the long-term effects of crop rotation.

9. Conclusion

This study shows that crop rotation is not just an old farming method, but a scientific and useful way to make agriculture sustainable for a long time. In Ranchi district, where most farming depends on rainfall, crop rotation has proved to be very beneficial for farmers.

When farmers grow different crops in the same field season after season (like rice followed by pulses or vegetables), the soil becomes healthier. It keeps a balance of nutrients in the soil, increases organic matter, and reduces the need for chemical fertilizers. As a result, the cost of farming decreases and productivity increases.

Crop rotation also helps farmers earn more income compared to single-crop system. It gives them work and income throughout the year and reduces the risk of crop failure. Environmentally, crop rotation helps reduce soil erosion, conserves water, and improves biodiversity. It also helps in reducing greenhouse gas emissions and protects the soil from damage.

However, some challenges still exist, such as lack of irrigation, low awareness among farmers, soil acidity, poor market facilities, and limited government support. To solve these issues, farmers need proper training, financial help, better market access and support from agricultural institutions.



In short, crop rotation is a powerful and practical solution for sustainable and regenerative agriculture in Ranchi district. It can improve farmers' income, protect the environment, and ensure food security for future generations.

10. Scope for Future Research

1. Geographical Expansion

This study is limited to Ranchi district. Future research could expand it to other districts in Jharkhand or other states to conduct comparative studies.

2. Larger Sample Size

Future studies can be conducted with larger sample sizes, making the findings more reliable and useful for a wider area.

3. Comparative Study

Future research could conduct comparative studies between technology users and non-users farmers to better understand the real effects of technology adoption.

4. Longitudinal Study

This study is based on a specific time period. Further research could analyze the long-term effects (5-10 years).

5. Inclusion of Financial Variables

Future studies may include economic factors such as agricultural finance, RRBs, loan availability, subsidies, and institutional support.

6. Policy Impact Analysis

Future research may study more deeply the impact of government schemes and agricultural policies.

7. Environmental Sustainability Dimension

Future research could further expand on soil health, water conservation, climate resistance, and sustainable practices.

Acknowledgment

The author gratefully acknowledges the support and guidance received during the completion of this research entitled **“Sustainable Development through Crop Rotation: A Regenerative Approach in Ranchi District.”**

The author expresses sincere gratitude to the guide and supervisor, **Dr. K.P. Sahi**, Assistant Professor, Mandar College, Ranchi, for his valuable academic guidance, constructive suggestions, and continuous support throughout the research process. His expertise and encouragement significantly contributed to the quality of this study.

The author is also thankful to **Dr. Amar Kumar Chaudhary**, Head of the Department and Dean, Faculty of Commerce, Ranchi University, Ranchi, for his academic motivation and administrative support, which facilitated the smooth completion of this research work.

The author acknowledges **Ranchi University, Ranchi**, for providing the necessary academic environment and research facilities. Appreciation is also extended to the farmers and respondents of Ranchi district for their cooperation and for sharing valuable information essential to this study.

References :

1. Koley, S. (2023). A Study on Growth of Job Opportunity in the field of computer Accounting and Taxation in India: A Case Study on Ranchi District. (Chapter 4, p. 72). <http://hdl.handle.net/10603/540037>
2. Directorate of Census Operations, Jharkhand. (2011). District Census Handbook: Ranchi (Village and Town Wise Primary Census Abstract), Series-21, and Part XII-B. Census of India 2011. (p. 17). <https://censusindia.gov.in/>
3. Kumar, R. (2021). Evaluation Viability and Constraints in Growing Pulse Based Crop Rotations at Small Farms of Punjab. p-ISSN:2319-9857
4. Kumar, T., Singh, R., & Verma, S. (2024). Impact of crop rotation and tillage operations on mitigating greenhouse gas emissions and evaluation of sustainability index in rice-wheat-green gram cropping system of north Bihar.



<https://doi.org/10.1016/j.jenvman.2024.121689>

5. Koli, M., Patil, S., & Deshmukh, R.(2025). Interaction Effect of Crop Rotation and Diversification on Soil Health and Productivity: A Review. *Agricultural Research & Technology: Open Access Journal*, 25(1).
<https://doi.org/10.9734/acri/2025/v25i101547>
6. ICAR & Birsa Agricultural University (BAU), Ranchi. (2018). Assessment and mapping of important soil parameters including soil acidity for the state of Jharkhand towards rational land-use planning. ICAR Publication, Ranchi
7. Singh, T. B. N. (2013). Ground water information Booklet: Ranchi District, Jharkhand. Central Ground Water Board, Ministry of Water Resources, Government of India.
8. FAO. (2017). The future of food and agriculture- Trends and challenges. Food and Agriculture Organization of the United Nations, Rome.
9. Lal, R. (2020). Regenerative agriculture for food and climate. *Journal of soil and water conservation*, 75(5), 123A-124A.
<https://doi.org/10.2489/jswc.2020.0620A>
10. Census of India. (2011). District Census Handbook: Ranchi. Directorate of census operations, Jharkhand, Government of India.
11. Tilman, D., Balzer, C., Hill, J., & Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Science (PNAS)*, 108(50), 20260-20264.
<https://doi.org/10.1073/pnas.1116437108>
12. Pretty, J., Benton, T.G., Bharucha, Z. P., et al. (2018). Global assess of agricultural system redesign for sustainable intensification. *Nature sustainability*, 1, 441-446.
<https://doi.org/10.1038/s41893-018-0114-0>
13. Singh, T. B. N. (2013). Ground Water Information Booklet, Ranchi District, Jharkhand State. (p. 5). Retrieved September 2013
14. ICAR & Birsa Agriculture University (BAU) Ranchi. (2018). Assessment and mapping of some important soil parameters including soil acidity for the state of Jharkhand towards Rational Land use Plan. (pp. 8-16).
15. ICAR & Birsa Agriculture University (BAU) Ranchi. (2018). Assessment and mapping of some important soil parameters including soil acidity for the state of Jharkhand towards Rational Land use Plan. (p. 9).
16. Singh, T. B. N. (2013). Ground Water Information Booklet, Ranchi District, Jharkhand State. (p. 11). Retrieved September 2013
17. ICAR & Birsa Agriculture University (BAU) Ranchi. (2018). Assessment and mapping of some important soil parameters including soil acidity for the state of Jharkhand towards Rational Land use Plan. (p. 8).



DOIs:10.2015/IJIRMF/ICICSF-2025-P29

--:--

Research Paper / Article / Review

International Conference On “Innovative Convergence for Sustainable Future”

Date : 12 - 13 December, 2025

(ICICSF-2025)



Death Penalty in India: A critical analysis of the ‘Rarest of Rare’ Doctrine and its relevance to sustainable justice

Prof. Sonu Kumar¹; Pragati Kumari²

¹Assistant Professor, Department of Legal Studies, Jharkhand Rai University, Ranchi, Jharkhand, India

²Student (LL.M.), Department of Legal Studies, Jharkhand Rai University, Ranchi, Jharkhand, India

Email – pragatik171006@gmail.com,

Abstract: In criminal jurisprudence, the death penalty in India is one of the highly debatable topics constantly, indicating a continuing stress between the demand for justice based on retributive theory and the constitutional protection of right to life of a citizen which is guaranteed to them by Article 21 of the Constitution. The Supreme Court in *Bachan Singh v. State of Punjab* (1980), had firstly introduced the “Rarest of Rare” doctrine with an intention to restrict the scope of capital punishment and to ensure that it should be imposed on the offenders only in the most exceptional circumstances. However, over four decades later, the practical application of this concept has highlighted significant discrepancy and judicial subjectivity. This raises doubts about its adherence to constitutional ideals of equality, fairness and human dignity. This paper includes a critical and analytical study of the “rarest of rare” doctrine to ensure that whether its judicial development truly aligns with the constitutional framework of India and also with the broader objectives of sustainable and human-rights oriented justice. This paper analyses key Supreme Court judgements, discovering the shifts in judicial reasoning and evaluates the extent to which the doctrine has attained its real purpose of leading a fair and consistent sentencing. This research also contemplates India’s international obligations and the rising shifts towards the abolition of capital punishment globally. This research aims to ascertain whether the death penalty when justified under the “rarest of rare” theory can coexist with a current vision of justice that is humane, equitable and sustainable in a democratic society by engaging both constitutional principles and human rights perspectives.

Key words: Death Penalty, Rarest of Rare Doctrine, Constitutional Principles, Sustainable Justice

1. INTRODUCTION

Background

The death penalty has been one of the most controversial issues in criminal justice system of India from a very long time. It represents the sharp intersection of law, morality and constitutional values. The supporters of this punishment prospect it as a necessary measure against heinous crimes whereas the opponents inquire its ethical legitimacy and constitutional validity. Article 21 of the Indian Constitution guarantees the right to life and personal liberty to every citizen which may be curtailed only by a procedure established by law that is fair, just and reasonable. This constitutional guarantee has persistently shaped the judicial approaches towards capital punishment. The Supreme Court in *Bachan Singh v. State of Punjab* (1980) has upheld the constitutional validity of the death penalty and introduced the “rarest of rare” doctrine. The court has also limited its application to certain exceptional cases. The aim of the court is to balance the collective conscience of society with the sanctity of human life. However, subsequently the decisions show wide variations in the application and interpretation of this doctrine, often depending on individual judicial perceptions. These discrepancies have raised questions over time about whether the doctrine continues to uphold the principles of equality, fairness and dignity envisioned by the Constitution.

2.Problem Statement



The “rarest of rare” doctrine has been introduced with the intent to ensure consistency and fairness in sentencing but it has resulted in interpretative uncertainty and judicial subjectivity suppressing its real purpose. The difference in understanding of courts of what qualifies under the “rarest of rare” case leads to irregular application of the death penalty. This inconsistency challenges the constitutional guarantees of equality given to the citizens under article 14 and the right to life under article 21 and also raises concerns that whether the capital punishment can coexist with India’s commitments to human rights and sustainable justice.

3.Objectives of the study

1. To trace the judicial evolution of the “rarest of rare” doctrine in India through key Supreme Court judgements.
2. To examine whether the doctrine ensures consistency and fairness in capital sentencing in light of Articles 14 and 21 of the Constitution.
3. To analyze the doctrine’s compatibility with international human rights standards and the idea of sustainable justice.
4. To assess the effectiveness of the doctrine in fulfilling its constitutional purpose of limiting the arbitrary use of the death penalty.
5. To suggest reforms that could make India’s sentencing framework more coherent, humane, and rights-based.

4.Significance of the study

The study holds both constitutional and socio-legal significance. Constitutionally, it reviews how the interpretation of the Supreme Court of the “rarest of rare” doctrine aligns with the fundamental rights of equality, life and dignity. By socio-legal perspective, the study contributes to the bigger debate on whether the death penalty is justified in a democratic state which is committed to human rights and sustainable justice. This research aims to provide a deeper understanding of the balance between punishment, deterrence and human dignity by critically examining judicial reasoning and comparative international practices. The findings of this study will be valuable for legal scholars, policymakers and judicial institutions who are seeking to reform sentencing practices in India. Eventually, it seeks to promote a justice system that upholds constitutional morality while ensuring that the law serves as a tool of fairness, reform and humanity rather than retribution alone.

5.Literature Review

The debate encompassing the death penalty in India is embedded in the constitutional principles, specifically in Articles 14, 19 and 21 that safeguards equality, freedom and the right to life. The Supreme Court in *Jagmohan Singh v. State of Uttar Pradesh* (1973) has upheld the constitutional validity of capital punishment, by stating that it did not violate Article 21 unless it followed a fair, just and reasonable procedure established by law. However, this judgement was primarily focused on procedural aspect and did not deal with the moral and constitutional dilemmas which are associated with the punishment itself. There are scholars such as Upendra Baxi (1980) and A.G. Noorani (1983) who have observed that the Supreme Court in the *Jagmohan Singh* case failed to furnish a substantive standard to determine that in what scenario the death penalty should be awarded, leaving it on the judges to exercise their discretion. This lack of directives by the Supreme Court leads to more instances of judicial scrutiny over the next ten years.

After *Jagmohan Singh* case, the landmark judgement in *Bachan Singh v. State of Punjab* (1980) marked a turning point in Indian death penalty jurisprudence. The court in this case has upheld the constitutionality of the death penalty under section 302 of IPC and held that it should be imposed only in the “rarest of rare” cases and that too when the alternative of life imprisonment is unquestionably foreclosed. The intention of the court behind this is to prevent arbitrary sentencing by the judges and for that it introduced a judicial restraint principle. Justice Bhagwati gave a dissent opinion in *Bachan Singh* case. According to him, the death penalty violates both the right to equality and the right to life. Anup Surendranath (2015), one of the scholars have observed that the *Bachan Singh* Judgement of the Supreme Court though is progressive in nature but it lacked the operational clarity as it did not state the accurate framework to determine the “rarest of rare” cases.

After *Bachan Singh*, the Supreme Court has attempted to interpret and implement the doctrine in *Machhi Singh v. State of Punjab* (1983). For this the court has categorised cases into aggravating and mitigating circumstances and proposed a more structured framework. However, this framework is still depending heavily on judicial discretion. Dr. K.I. Vibhute (1999) contended that though *Machhi Singh* aimed to bring consistency, it eventually administers subjectivity by leaving the final assessment to individual moral perceptions of judges. Later, there are subsequent cases like *Santosh Kumar*



Bariyar v. State of Maharashtra (2009) and Sangeet v. State of Haryana (2013) that critically re-evaluated earlier interpretations. The court in Sangeet case admitted that the guidelines in Bachan Singh case had been inconsistently applied which has led to arbitrariness. Surya Deva (2014) points out that such judicial admissions highlight the doctrinal instability of the “rarest of rare” standard, as courts have oscillated between retribution and reform as guiding principles.

From a human rights perspective, the death penalty has been criticized considering it as a violation of the right to life and human dignity. Justice P.N. Bhagwati, in his later writings emphasized that a civilized society must move away from retributive justice toward rehabilitative and reformatory ideals. Amnesty International (2017) and Human Rights Watch reports have recorded how the death penalty system in India disproportionately affects the economically weaker and marginalized sections of the society. Anup Surendranath and Preeti Pratishruti Dash (2019) have highlighted in their empirical study at the National Law University Delhi that a significant number of death prisoners belongs to disadvantaged backgrounds and often lack competent legal representation. This reflects structural inequality in the criminal justice system and undermines the doctrine’s promise of fairness. Criminologists such as Nirmala Rao (2005) and Rani Dhavan Shankardass (2011) have argued that capital punishment fails as a deterrent and instead perpetuates cycles of violence and state retribution, incompatible with the idea of sustainable justice.

Globally, there has been a significant shift toward the abolition of the death penalty. Instruments like the International Covenant on Civil and Political Rights (ICCPR) and its second Optional Protocol encourage states to move towards abolition. While India remains a retentionist state, the Supreme Court has acknowledged the relevance of international human rights principles in interpreting domestic law. Comparatively, jurisdictions such as South Africa (State v. Makwanyane, 1995) and the United Kingdom have abolished the death penalty on grounds of human dignity and the fallibility of human judgement. Scholars such as B. Sharma (2018) have argued that India’s continued reliance on the “rarest of rare” doctrine isolates it from evolving international norms of humane justice.

The current judicial developments have restored the attention towards the discrepancies in capital sentencing. The Supreme Court in Shatrughan Chauhan v. Union of India (2014) highlighted that delay in the execution of death sentences and failure in following the established procedures or rules leads to cruel and degrading treatment. Aparna Chandra (2020) in her observation noticed that the increasing recognition of procedural fairness and mental health considerations by the court shows a sign of gradual move towards narrowing the application of death penalty. However, Anand Grover (2022) argued that the “rarest of rare” doctrine is moving towards a conceptual dead end as it neither helps in preventing crimes effectively nor it guarantees fairness. Therefore, the sustainability of doctrine is under question not only on moral grounds but also due to its failure to meet constitutional and human rights standards.

Therefore, by summing up it can be said that though the “rarest of rare” doctrine was introduced to guarantee constitutional restraint, its practical application shows inconsistency and moral ambiguity. There are many scholars who agreed that the doctrine lacks objective criteria which results into a judicial arbitrariness and social bias. However, there have been very limited research conducted on the doctrine’s doctrinal analysis with the concept of sustainable justice which means justice that balances accountability, fairness and human dignity and keep them within constitutional limits. This study aims to fill that gap by re-evaluating the doctrine through the combined lens of constitutional law and human rights and by proposing required reforms that align India’s penal system with global standards of humane justice.

6. Methodology

This study includes a doctrinal and analytical research design. The doctrinal approach is focused more towards on analyzing constitutional provisions, statutory frameworks and judicial decisions which helps in shaping death penalty jurisprudence in India. The analytical component is focusing on critically examining that how the “rarest of rare” doctrine is introduced by the Supreme Court in Bachan Singh v. State of Punjab (1980), how it is evolved over time and whether it consistently aligns with the constitutional principles of equality, fairness and human dignity.

This study also includes a comparative legal analysis to understand and highlight how the other constitutional democracies have addressed and examined the capital punishment in light of human rights and dignity. It assessed the abolition of death penalty in South Africa through the case of State v. Makwanyane (1995), in which the court held that it is unconstitutional as it is violating the right to life and human dignity. Similarly, the United Kingdom and Canada have also abolished the capital punishment through legislative and judicial reforms that are consistent with their international human rights obligations. By doing this comparative analysis, it can be evaluated that whether the “rarest of rare” doctrine of India is remaining consistent with the evolving global standards of humane and sustainable justice.



This study is primarily relied on secondary legal sources and includes:

- Primary legal materials such as provisions of Constitution, statutes including the Indian Penal Code (IPC) and the Code of Criminal Procedure (CrPC), landmark Supreme Court judgements including Jagmohan Singh v. State of U.P. (1973), Bachan Singh v. State of Punjab (1980), Macchi Singh v. State of Punjab (1983), Santosh Bariyar v. State of Maharashtra (2009) and Sangeet & Anr. v. State of Haryana (2013).
- Secondary sources such as Law Commission Reports, research papers, law books, peer-reviewed articles and reports of National Law University Delhi and Amnesty International.
- Electronic databases such as SCC Online, Manupatra and JSTOR.

Since this paper used the doctrinal approach, it has applied purposive sampling technique by highlighting only those Supreme Court cases and reports that has its most influence in shaping the “rarest of rare” jurisprudence. These cases were selected due to their legal significance, citation frequency and their interpretative contribution in the doctrine.

Secondary sources from where all of these data were collected includes:

- Judicial decisions from the Supreme Court and High Courts
- Law Commission Reports (especially the 35th and 262nd Reports)
- Scholarly writings and law journal articles on capital punishment and constitutional interpretation
- International legal documents, including the ICCPR and UN reports on the death penalty.

This study doesn't include any primary data collected through interviews or surveys as the major focus is on legal doctrine and judicial reasoning.

The research includes qualitative content analysis. The data is interpreted through:

- Doctrinal analysis, focusing on the judicial reasoning and consistency of the doctrine;
- Comparative analysis, contrasting India's approach with global trends; and
- Normative evaluation, assessing the doctrine's compatibility with constitutional and human rights principles.

This analytical framework allows the study to evaluate that whether the “rarest of rare” doctrine supports or weaken the goal of sustainable and humane justice within the constitutional framework of India.

The scope of this research is limited to the constitutional and judicial dimensions of the death penalty in India. It does not examine public opinion or empirical data. However, secondary empirical findings, such as those in the Death Penalty India Report (2016), are referenced to provide contextual support. The limitation of the study lies in its reliance on judicial and textual analysis rather than field-based inquiry.

7.Results / Findings

The analysis undertaken in this study reveals a complex and evolving judicial narrative surrounding the “rarest of rare” doctrine in India. Though the doctrine is introduced as a constitutional safeguard to limit the imposition of capital punishment, its practical application denotes notable inconsistency, subjectivity and divergence from constitutional and human rights principles.

The path of judicial reasoning highlights a gradual but uneven evolution of the “rarest of rare” doctrine. The Supreme Court in the case of Jagmohan Singh v. State of Uttar Pradesh (1973) has upheld the constitutional validity of the death penalty and emphasized procedural fairness under Article 21 but without enunciating any substantive standard for sentencing discretion. This deficiency has been addressed by the Supreme Court in Bachan Singh v. State of Punjab (1980) in which it introduced the “rarest of rare” doctrine stating that the death penalty should be awarded to the accused only in those exceptional cases where the alternative option of life imprisonment is foreclosed without any reasonable doubt.

Subsequently, the court in the case of Macchi Singh v. State of Punjab (1983), classified the aggravating and mitigating factors to make the doctrine operational. However, later jurisprudence revealed that these categories were neither exhaustive nor it was consistently applied by the court. Lately, judicial decisions in the case of Santosh Kumar Bariyar v. State of Maharashtra (2009) and Sangeet v. State of Haryana (2013) expressly highlighted the ambiguities in the



interpretation of the doctrine and the inconsistent reliance by the judiciary on aggravating circumstances. The judicial evolution of the “rarest of rare” doctrine has been pronounced as inconsistent and having a lack of objective standards, therefore, lowering the original purpose of restrictive and principled sentencing framework.

The comparative analysis of the Supreme Court judgements regarding the “rarest of rare” doctrine highlights its significant subjectivity in applying it. The court in the case of *Dhananjay Chatterjee v. State of West Bengal* (1994), confirms the death sentence to satisfy the collective conscience of the society. Also, in the case of *Ravji v. State of Rajasthan* (1996), the similar principles succeeded even though the insufficient consideration of mitigating factors is taking place. Later, the court considered such reasoning as contradictory in *Santosh Bariyar* case from the individual sentencing rule given by the Supreme Court in the *Bachan Singh* case. This shows that the interpretation given by judges were influenced by their personal moral outlook rather than by a uniform legal standard. The application of this doctrine seems to be more discretionary directing towards arbitrariness and unequal treatment of likely offenders.

The findings of this paper brings out that though the doctrine was introduced to conform to the constitutional principles of fairness, equality and human dignity failed to fulfil this objective. There is a lack of uniformity in sentencing which subverts Article 14 i.e., right to equality and the procedural and substantive fairness guaranteed to every citizen under Article 21 i.e., right to life and personal liberty. Further, the upholding of death penalty in India often conflicts with the obligations of international human rights under the instruments such as the International Covenant on Civil and Political Rights (ICCPR) and the evolving standards upheld by the United Nations Human Rights Committee that encourages the growing abolition of capital punishment. In its current judicial form, the doctrine does not fully align with the guarantee of equality and life guaranteed by the constitution nor does it align with international human rights norms favouring abolition.

The report published by the National Law University, Delhi i.e., the *Death Penalty India Report* (2016) is a secondary data which indicates that the number of individuals who are being awarded death sentence is disproportionately belongs to the economically weaker and socially marginalized communities. Among these, many individuals are those who did not have the competent legal representation and they also suffered from procedural disadvantages at the trial and appellate stages. The “rarest of rare” doctrine is affected by systemic socio-economic disparities in its operation and hence is working by compromising the principle of equality before law and confirming structural injustices within the criminal justice system.

The analysis of jurisprudence and opinion of scholars in this study highlights an increasing judicial concern on the sustainability of the “rarest of rare” doctrine. The Supreme Court in the case of *Sangeet and Bariyar*, itself observed that the implementation of the doctrine is facing inconsistencies and is conceptually fragile. In its 262nd Report (2015), the Law Commission of India has also suggested to abolish the death penalty for all offences highlighting the arbitrariness and failure of the doctrine to ensure principles sentencing. The doctrine has failed the “rarest of rare” test to maintain doctrinal coherence and to fulfil its original role to act as a safeguard against arbitrary imposition of the death penalty.

The principle of sustainable justice which is focused on fairness, proportionality and respect for human dignity provides a critical lens to assess and analyze more about the applicability of the “rarest of rare” doctrine. By comparing jurisprudence of different countries specifically the Constitution court of South Africa, the decision of the court in the case of *State v. Makwanyane* (1995) highlights a clear shift towards abolition of capital punishment due to the conflicting nature of the death penalty with the right to life and human dignity. On the other hand, the continued reliance of India on the “rarest of rare” doctrine emphasizes on retributive approach rather than reformatory and restorative justice which is the emerging global significance. The emerging idea of sustainable justice demands a justice system which is focused on humanity, equality and long-term social rehabilitation rather than retribution and the “rarest of rare” doctrine is contradictory to this idea.

Conclusively, the findings of this study points out that the purpose for which the “rarest of rare” doctrine was introduced is to put a constitutional restraint on the judicial decisions but it has failed to achieve its foundational purpose. Instead of ensuring fairness, consistency and principled limitation of capital punishment, the application of this doctrine has been identified as showing judicial subjectivity, socio-economic bias and conceptual fragility. Further, this doctrine has failed to achieve the constitutional vision of justice which is contemplated under Article 14 and 21. While the global trend is moving towards the abolition of death penalty, India still remains misaligned with this trajectory. If India wants to adopt sustainable justice, it must have to reconsider its capital punishment theory and introduce a sentencing policy which is based on reformatory, equitable and humane principles.



8. Discussion

The findings of this research emphasize on the contradictions which is inherited in the “rarest of rare” doctrine in both its conceptuality and practical implementation. While the doctrine was introduced by the Supreme Court in the case of *Bachan Singh v. State of Punjab* (1980) as a constitutional mechanism to limit the arbitrary use of capital punishment, its later judicial interpretations weaken its original character. The shift in perspectives of Supreme Court in later judicial decisions in the case of *Machhi Singh*, *Dhananjay Chatterjee*, *Santosh Bariyar* and *Sangeet* bring out that what was introduced with an intention of exceptional measure has with time become an unpredictable judicial discretion. This shows a deeper structural problem within the criminal justice framework of India. The court’s inclination to bring into effect the collective conscience of society as an element to impose death penalty which can be seen in *Dhananjay Chatterjee* case directs a movement away from constitutional morality towards populist retribution. Such kind of thought deteriorates the judiciary’s role as a counter-majoritarian whose work is to protect individual rights against societal passion.

Further, the continuous efforts to determine that which types of cases will fall under the “rarest of rare” doctrine shows the lack of objective guidelines for sentencing. Despite the Supreme Court’s mandate in *Bachan Singh* to identify and classify aggravating and mitigating factors, there is no standard rules or principles to ensure consistency. Moreover, the identical offences were dealt with varied outcomes leads to violation of principle of equality guaranteed under Article 14 and the right to life under Article 21. The findings of this paper also highlight the inadequacy of the doctrine in addressing socio-economic realities. As shown through the *Death Penalty India Report* (2016), the number of death row prisoners were disproportionately belonged to economically and socially marginalized groups. This shows the empirical reality which is beyond the doctrinal framework and it indicates systemic discrimination that the present sentencing approach fails to fulfil. The objective of the doctrine is to be neutral while sentencing and therefore is operating within an unequal social context that shows structural injustice.

When looking into the constitutional perspective, the “rarest of rare” doctrine was introduced to harmonize capital punishment along with fulfilling the ideals of fairness and human dignity. However, the jurisprudence shows that it has often been used to justify not to limit executions. The decision given in *Ravji v. State of Rajasthan* (1996) was later declared as per incuriam. This sets an example that how the judge’s emphasis more on the nature of crime rather than on the circumstances of the offender leads to a violation of the guidelines given by the Supreme Court in *Bachan Singh* case. In comparative context, the approach of India is highly contrasting in nature with other constitutional democracies. In the case of *State v. Makwanyane* (1995), the constitutional court of South Africa has abolished the death penalty by stating it incompatible with human dignity and the right to life. Similarly, countries like United Kingdom and Canada have completely abolished capital punishment. But India is consistent in adhering to the “rarest of rare” doctrine which positioned it as an outlier in the global movement towards abolition.

While talking about the implications of these findings, it is multidimensional i.e., legal, moral and institutional. The consistent use of death penalty under the “rarest of rare” doctrine challenged the coherence of constitutional jurisprudence of India. The absence of uniformity diminishes the value of rule of law and deteriorates the constitutionality of the judiciary as an impartial and unbiased administer of justice. The inconsistent application of this doctrine while awarding capital sentencing indicates the governance of individual judicial perception rather than principled rationality and thus violating the constitutional guarantee of equality before the law.

Further, the findings of this paper raise a question on the compatibility of the death penalty, morally and philosophically with the principles of human dignity and sustainable justice. The theory of sustainable justice demands a model that promotes rehabilitation, social integration and long-term societal harmony rather than retribution or deterrence and the “rarest of rare” doctrine prioritizes vengeance and public sentiment which is highly contradictory to these objectives.

Institutionally, the fragility of this doctrine indicates the inadequacy of sentencing policy of India. The Law Commission of India in its 262nd report published in the year 2015 expressly recommended abolition of the doctrine for all types of crimes except terrorism noting that the doctrine has failed to ensure fairness and consistency. The judiciary’s acknowledgement in the case of *Sangeet* and *Bariyar* lacks coherent standards that emphasizes the need for reform.

9. Conclusion and Future Scope

The analysis of this research confirms that though the “rarest of rare” doctrine has been introduced as a constitutional safeguard for the citizens, it has failed to achieve its original purpose of ensuring fairness, consistency and



constitutionality in the execution of death penalty. The doctrine contains judicial subjectivity, inconsistency and a lack of principled guidance making it an inadequate instrument for protecting the right to life under Article 21.

The findings also establish the fact that the Indian judiciary's reliance on principles such as collective conscience and social deterrence shows a shift towards the populist sentiment from the constitutional morality. The inconsistency of the doctrine not only violates the principle of equality guaranteed under Article 14 but it also lowers the obligation of India under international human rights law. Further, the doctrine's disproportionate impact on the marginalized and economically disadvantaged individuals highlights the inequity of the death penalty system.

In view of the above conclusions, the future trajectory of the criminal jurisprudence of India must focus on abolition-oriented reform. The Law Commission's Report provides the practical solutions by recommending abolition of death penalty for all offences except those related to terrorism. Further, India also must institutionalize sentencing guidelines that ensures consistency, proportionality and which considers mitigating circumstances while awarding sentence to the offender in all capital and non-capital cases. To achieve sustainable justice, India needs to transition from retributive to reformatory models of punishment which prioritizes human dignity, social rehabilitation and restorative principles over vengeance. The legislative and judicial institutions must align their sentencing policies with the constitutional ideals of justice, liberty and equality.

Research in future should adopt an empirical and interdisciplinary approach by integrating criminological, psychological and sociological perspectives to better understand the impact of capital punishment on society, victim's families and offenders. By making comparative analysis of the abolitionist jurisdictions the further framework can inform the need for transitioning towards complete abolition while maintaining public confidence in the justice system. Ultimately, the doctrine, in its present form highlights an unsustainable compromise between constitutional morality and retributive public sentiment. A system of justice which is humane and constitutionally coherent, requires India to move beyond this doctrine towards a legal order grounded in the sanctity of life and the principles of equality, fairness, and dignity that the constitution promises to every individual.

References:

1. Bachan Singh v. State of Punjab, (1980) 2 SCC 684
2. Dhananjay Chatterjee v. State of West Bengal, (1994) 2 SCC 220
3. Jagmohan Singh v. State of Uttar Pradesh, (1973) 1 SCC 20
4. Macchi Singh v. State of Punjab, (1983) 3 SCC 470
5. Mithu v. State of Punjab, (1983) 2 SCC 277
6. Ravji v. State of Rajasthan, (1996) 2 SCC 175
7. Sangeet v. State of Haryana, (2013) 2 SCC 452
8. Santosh Kumar Satishbhushan Bariyar v. State of Maharashtra, (2009) 6 SCC 498
9. Shatrughan Chauhan v. Union of India, (2014) 3 SCC 1
10. Swamy Shraddhananda v. State of Karnataka, (2008) 13 SCC 767
11. State v. Makwanyane, 1995 (3) SA 391 (CC)
12. Amnesty International. (2017). *Death sentences and executions*. Amnesty International Publications.
13. Law Commission of India. (2015). *Report No. 262: The Death Penalty*. Government of India.
14. National Law University Delhi. (2016). *Death Penalty India Report*. Project 39A, NLU Delhi.
15. Baxi, U. (1980). *The crisis of the Indian legal system*. Vikas Publishing.
16. Chandra, A. (2020). Procedural fairness and the death penalty in India. *Indian Law Review*, 4(1), 1–25.
17. Dash, P. P., & Surendranath, A. (2019). Socio-economic profile of death row prisoners in India. *National Law University Delhi Working Paper Series*.
18. Deva, S. (2014). Rethinking the death penalty: Constitutionalism and retributive justice. *Journal of National Law University Delhi*, 2(1), 45–68.
19. Grover, A. (2022). The future of capital punishment in India: A constitutional critique. *NUJS Law Review*, 15(2), 210–233.



20. Noorani, A. G. (1983). The death penalty and the Indian Constitution. *Economic and Political Weekly*, 18(45), 1897–1900.
21. Rao, N. (2005). Capital punishment and the Indian criminal justice system. *Indian Journal of Criminology*, 33(2), 101–116.
22. Shankardass, R. D. (2011). *Of fractal lives: Essays on capital punishment in India*. Routledge.
23. Sharma, B. (2018). Death penalty and evolving international standards. *Asian Journal of International Law*, 8(1), 132–150.
24. Surendranath, A. (2015). Death penalty and judicial inconsistency in India. *NALSAR Law Review*, 9(1), 56–74.
25. Vibhute, K. I. (1999). Sentencing in India: Need for reform. *Criminal Law Journal*, 105(4), 219–232.
26. International Covenant on Civil and Political Rights, Dec. 16, 1966, 999 U.N.T.S. 171.
27. United Nations Human Rights Committee. (2014). *General Comment No. 36: Article 6—Right to life*.



DOIs:10.2015/IJIRMF/ICICSF-2025-P30

--:--

Research Paper / Article / Review

International Conference On “Innovative Convergence for Sustainable Future”

Date : 12 - 13 December, 2025

(ICICSF-2025)



Fintech Innovations in Green Finance: Expanding Access to Renewable Energy Projects in India

Prity Sharma¹ Dr. Amar Kumar Choudhary²

Designation¹ -Research Scholar (JRF), University Department of Commerce & Business Management, Ranchi University, Ranchi, Jharkhand

Designation² -Associate Professor, Head & Dean, University Department of Commerce & Business Management, Ranchi University, Ranchi, Jharkhand

Email id: prity1646@gmail.com ;

Abstract : The growing urgency of climate commitments has increased the demand for financial models that can support renewable energy expansion, especially for small and decentralized clean energy systems that conventional lenders often view as high-risk. This study explores how financial technology (FinTech) is transforming the green finance landscape in India by widening access to funding, improving the transparency of financial flows, and lowering the operational barriers that restrict investment in renewable energy projects. Drawing on secondary sources, thematic analysis, and case-based evidence, the paper examines how digital lending platforms, blockchain-enabled energy tracking, and AI-supported credit assessment tools are enabling peer-to-peer financing, fractional investment models, and alternative data-driven risk profiling. These innovations strengthen financial inclusion, minimize transaction costs, and attract a broader pool of investors, thereby contributing to Sustainable Development Goals related to clean energy access, climate action, and local economic resilience. Even after advancements, several constraints continue to limit widespread adoption, including regulatory uncertainty, data security risks, inadequate digital literacy, and infrastructural gaps in rural regions. The study recommends regulatory sandboxes, co-financing partnerships, improvements in digital infrastructure, and targeted training programmes to reinforce India's emerging Green FinTech ecosystem. Overall, the paper offers practical insights for regulators, financial institutions, and technology providers seeking to leverage FinTech as a driver of inclusive and sustainable renewable energy financing.

Keywords: Fintech, Green Finance, Renewable Energy, Blockchain, Artificial Intelligence, Financial Inclusion.

1. INTRODUCTION

The rapid progression of climate change has brought renewable energy to the forefront of global sustainability efforts. Large investments in clean energy are crucial, but so are small, decentralized renewable projects things like rooftop solar, microgrids and locally owned wind farms that help bring power to the 1.3 billion people who lack access to a reliable source of electricity and provide an important tool for local economic development. It can be used in relation to developing countries like India where universal development, and universal electrification are the issues being discussed to a certain extent. However, the smaller renewable projects are not financed using the conventional sources because of the risk entailed. It is financing sustainability gap that will demand the new solutions to democratize the access to green finance.

The FinTech appears to be a good trend in green finance, which is facilitated with the help of digital products and services and contributes to efficiency, transparency, and accessibility. FinTech is revolutionizing small scale renewable energy like peer-to-peer lending service, blockchain based or artificial intelligence-based credit rating, and peer-to-peer lending service. **Flinders & Smalley** explains that banks used the term FinTech, which comes from the combination of technology and finance, to describe digital solutions that helped with customer account administration and monitoring.



'FinTech' has evolved over time to encompass a broad range of financial sector businesses, services, and technologies. Retail banking, financial literacy, fundraising, digital currencies, investment services, and other technology-driven financial solutions are just a few of the many uses for these advances. The term "Green Finance" describes financial assistance, such as loans or investments, that is allocated to initiatives that have a good impact on the environment. This covers financing for environmentally friendly goods and services as well as the creation of sustainable infrastructure. Green financing frequently provides incentives to reduce the high upfront costs associated with implementing environmentally friendly practices in homes and companies. Transitions like switching to electric cars or renovating buildings to increase energy efficiency are supported by these incentives. Green funding thus empowers people and organizations to make ethical financial decisions that are advantageous to the environment and their long-term interests **Wire, S. (2024)**. The other forms of investments minimize the cost of the transactions, create confidence between the two parties and make more people relate more investors to the environment friendly transactions. With the growth of digital infrastructure in India, mobile banking and many other applications like Unified Payments Interface (UPI), FinTech has discovered its ally in sustainable finance. The role of FinTech in green finance goes beyond that of enhancing financial inclusion. Through traceable flows of funds, data-driven risk assessment and investments in climate-resilient projects, FinTech promotes national sustainability commitments and contributes to the advancement of United Nation's Sustainable Development Goals (SDGs). Furthermore, digital platforms can help to link institutional investors with local projects, so that the dynamics of a renewables boom drive benefits to underrepresented communities.

FinTech offers a great deal of promise to promote green finance, but widespread adoption is hampered by cyber security risks, low digital literacy, poor rural infrastructure, and regulatory barriers. These concerns must be addressed in order to ensure that digital financial innovations advance sustainable and equitable development rather than worsen already-existing imbalances. This study explores the ways in which FinTech can facilitate the funding of small-scale renewable energy projects in India. Using case studies, secondary data, and previously published research, it analyzes how FinTech-driven models are transforming green finance and identifies key obstacles. This article also recommends governmental actions to strengthen the green FinTech ecosystem in order to advance financial inclusion, expand access to renewable energy, and enhance long-term climate risk management.

2.Literature Review

- According to **Ahmad et al. (2025)**, digital technologies like FinTech, blockchain, and artificial intelligence (AI) are helping to advance green finance for net-zero energy transitions. These technologies improve the efficiency, transparency, and innovation of financing low-carbon technology, sustainable infrastructure, and renewable energy. Along with providing case studies and suggestions for scalable, transparent green financial solutions, the review also highlights issues like data security, regulatory loopholes, and unequal digital access.
- The study by **Dadabada (2024)** looks at how Financial Technology (FinTech) advancements in green finance are integrated with Environmental, Social, and Governance (ESG) principles. The review highlights sector-specific impacts, similarities, and challenges through comparative case studies, such as Abundance Investment's P2P lending for renewable energy, IBM Food Trust's blockchain-based supply chain finance, Wealth simple's robo-advisory platform, and Eneco's green bond issuance. The results add to the growing conversation on sustainable finance by highlighting the possibility of increased transparency, ethical investing, and beneficial societal effects.
- **Singh N. (2024)** emphasizes green finance as a major force behind sustainable development, emphasizing effective waste management, pollution prevention, and renewable energy. It places a strong emphasis on using financial tools like grants, debt, and equity to assist green projects. According to studies, governments, financial institutions, private organizations & politicians must work closely together for implementation to be successful. To strengthen the green finance business and encourage sustainable growth, issues like low knowledge, regulatory loopholes, and financial concerns must be resolved.
- In a comprehensive thematic assessment that integrates FinTech with the UN SDGs, **Hasan et al. (2024)** demonstrate how FinTech improves access, boosts saver and lender involvement, and lowers poverty and inequality in the inclusive finance dimension. In terms of the economy, make the case that FinTech promotes entrepreneurship, productivity, diversification, and technology advancements, all of which contribute to long-term, steady economic growth. Moving on to the environmental aspect, the authors show how FinTech increases market completeness along sustainability lines by expanding investment opportunities into green and



environmental projects. Their novel approach of integrating machine-generated and human-generated processing improves the SLR's reproducibility and objectivity. Their results offer empirical support for establishing FinTech as a key facilitator of SDGs in the domains of finance, the economy, and the environment.

- **Chen and Guo (2024)** conduct an empirical investigation into the ways in which fintech fosters innovation in micro and small businesses (MSEs). According to their research, fintech improves financial accessibility, lowers transaction costs, and encourages creative thinking in smaller businesses. The results imply that fintech acts as a stimulant for technology development and entrepreneurial expansion in the MSE industry.
- According to **Zhang (2023)**, environmental preservation and green finance support a green economic recovery in South Asian economies, and FinTech amplifies this impact. This study fills up these gaps by using panel data (2000–2018) and GMM methods, demonstrating the significance of digital finance in sustainable growth. Previous research has mostly focused on wealthy nations and has rarely examined FinTech's mediating function.

3. Research Gap

FinTech and green finance have been addressed in many papers, however the majority focus on large-scale initiatives or industrialized nations. There is a lack of study on how FinTech facilitates the finance of small and local renewable energy projects in India. In the Indian context, emerging ideas like peer-to-peer lending, pooled investment platforms, and AI-based loan evaluation are still poorly understood. Additionally, concerns like regulations, digital access, and financial literacy are frequently disregarded. By concentrating on how FinTech may assist small renewable energy projects in India in a useful and inclusive manner, this study aims to close these gaps.

4. Objectives of the Study

1. Examine how fintech solutions are making it possible to fund small renewable energy projects.
2. Explore these technologies implications for financial inclusion and sustainable development.
3. Explore the potential barriers and constraints to fintech integration into green finance. Offer policy suggestions to make fintech more effective for renewable energy development.

By taking stock of these objectives, the study helps to fill in some gaps in the literature on green finance and fintech, with implications for academic research and policy work.

5. Research Methodology

This study uses an exploratory Qualitative technique and is based on secondary data from government studies, academic sources, and industrial instances from India and other developing nations. The conceptual framework of digital platforms, blockchain, and artificial intelligence is the subject of a thematic content analysis in the field of green finance. A comparative case analysis is used to examine opportunities, constraints, and policy implications for financing small-scale renewable energy projects.

The Role of Fintech in Green Finance

A collection of modifications in financial service technology is known as fintech. Green financial applications in technology. The green financial applications include:

- **Digital Lenders:** Machine learning and data to serve the underbanked and screen credit risk.
- **Blockchain Technology:** The technology will create open and secure operations to monitor the flow of funds and keep a record of the funds in green projects.
- **AI:** Increasing the efficiency of decision-making via predictive analytics, risk analysis and energy optimization in green projects.

Together, these technologies help to foster a more holistic financial environment from which renewable energy solutions can scale.

The Importance of Fintech in Promoting Sustainable Financial Solutions in India

The time for Financial Technology (Fintech) to thrive is now, and it out every chance we have, especially with India eyeing carbon neutrality. Fintech boost sustainability on two main avenues, inclusion and innovation. First, such



platforms UPI-based and digital wallets reduce dependence on the physical cash system, which has an environmental cost of transporting, processing and storing money. Second, AI and blockchain-backed innovation in green fintech increases the efficiency of allocating capital to climate-resilient projects. These digital solutions, allow for transparent management and tracking of compliance with Environmental, Social and Governance (ESG) in green bonds and micro-lending for solar adoption practice among underserved rural zones. The fundamental idea is that Fintech evolved more as a necessity as a result of advancements in the field of financial services and the quick development of technology brought about by the demand for such services. Since technology and financial services are merging, a number of platforms and applications are being created to make it easier for us to use financial services, such as online personal loans, business loans, etc. **Kandpal, V., & Mehrotra, R (2019)**. It

bridges the gap between financial well-being and ecological responsibility to facilitate more inclusive, greener economic transitions by democratizing green investment projects through Fintech platforms and offering AI-powered data-based risk rating for green initiatives.

The Importance of Fintech in Promoting Sustainable Financial Solutions in India

Micro-and mini-grids are essential for providing access to electricity in rural and remote areas. They enhance energy security, lower emissions of greenhouse gases and stimulate local economic development. Looking at the global energy transition, Trancik says small-scale renewable energy (RE) systems, including rooftop solar, Community Wind Projects and micro-hydro installations are critical. Their value comes from the fact that they are decentralized, responding to energy poverty and behind-the-meter access in ways that traditional centralized utility models cannot. By seeking to produce energy locally, these initiatives avoid expensive and lossy grid expansion shifting the architecture from the periphery to that distribution-edge providing power directly to communities living off-grid, denied access and poorly-served. The democratization of energy generation is vital in promoting financial inclusion, allowing small businesses and homes to move to sustainable means of living.

Green finance laws are essential for directing capital to the less developed financial sector, according to evidence from India. India has a lot of opportunity to take use of current technology and bank-business ties. There is a chance to draw attention to green financing as a result **Nenavath, S., & Mishra, S. (2023)**. Fintech innovations potentially provide a viable approach to address these barriers through alternative financing instruments that are accessible and responsive to the requirements of small-scale applications.

Digital Platforms and Peer-to-Peer Lending

Blockchain Technology in Renewable Energy Financing

Blockchain can be a way to decentralize and make transparent renewable energy generation transactions. Through proving secure and unchangeable records of the production and consumption of power, blockchain supports peer-to-peer energy transactions while also bolstering the credibility of green certificates. For example, companies such as Power-Ledger and WePower have developed blockchain solutions for the energy trading process that simplify workflows, lower administrative costs and increase trust between stakeholders. Potential small scale renewable power producers stand to benefit from these new models opening up new communication opportunities with consumers and investors that avoids the need for traditional go-betweens.

AI and Credit Risk Analysis

1. Credit risk assessment in green finance (GF) is changing with the help of artificial intelligence (AI). Search terms leading to these conclusions include keywords such as 'energy' with 'credit-scoring', but the findings have a strong focus on credit scoring for house-holds or small and medium enterprises in mature, or well-developed energy markets (Mallios and de Groot 2010).
2. Credit Scoring Model Approach-There are several reasons why traditional credit scoring models do not fully capture the behaviour of businesses and individuals (borrowers) involved in renewable energy projects. AI-based models use non-traditional datasets like mobile phone, utility bills and social media activity to determine creditworthiness.

In India, AI-based credit risk models are helping finance companies lend to under-served categories like gig workers and small businesses to drive financial inclusion and help grow community-level renewable projects.



Table – 1. Initiatives and Their Impact on Renewable Energy Financing in India

S.N o.	Project Initiative	What it is	How fintech / Green Finance is involved	Impact / Scale
1.	KPI Green Energy Projects (Gujarat)	Solar + hybrid (solar + wind) power projects in Gujarat	KPI Green secured a ₹ 32 billion loan (~US\$361 million) from SBI to part-finance these projects. Also, KPI Green issued certified green bonds via private placement.	250 MW solar + 370 MW hybrid; contributes toward KPI's 10 GW by 2030 target.
2.	Cleantech Solar's Open-Access Portfolio	Solar and wind power supplied to commercial & industrial consumers	Cleantech Solar secured ~\$103 million in long-term green financing to support its open-access RE portfolio.	Helps C&I Customers minimize carbon emission; grow in other Indian states.
3.	Green bonds by major large green energy companies.	RE companies rise debts to fund their projects / refinance debt	RE power, ACME solar, Adani green energy, Azure power etc. Eco investors are interested in such green bonds.	Enables the development of solar/wind energy, enables the structuring of the companies to the financial aspect and the risk diversification by the fossil fuel risk.
4.	Ecofy (NBFC for clean energy lending)	NBFC focused on green loans—rooftop solar, EVs, sustainable mobility etc.	Raised external capital (from development finance institutions) to build digital infrastructure, streamline loans, offer zero collateral/interest-subsidised options.	Helps in scaling adoption of rooftop solar & EVs among households / SMEs; improves access in semi-urban / rural markets.
5.	IREDA & Punjab National Bank – co-finance MoU	MoU to jointly co-finance green energy projects	The partnership is to enable co-lending and loan syndication for renewable energy projects, helping improve financing flows and reduce bank risk.	Better access to finance for RE project developers; spreads risk, ensures more projects can be financed.
6.	Artha Energy Resources' Renew Share	A platform to allow fractional ownership of RE assets (solar, wind)	This is fintech-driven: allows smaller investors to invest in parts of RE projects via SPVs (special purpose vehicles) through an investment platform.	Democratises investment in renewable energy; reduces entry barriers for smaller investors; builds awareness and capital availability.

Source- Compiled by the researcher

6.Challenges and Barriers

Fintech's potential in the green finance remains promising, albeit a number of challenges that are preventing its broad application:



- **Regulatory uncertainty:** Fintech activities, notably in the domain of green finance, suffer from obscure and inconsistent regulation ScienceDirect.
- **Finance Gaps:** Despite progress, there is a significant gap to fill in the green finance brought into place to meet the country's climate targets, particularly in terms of transition finance.
- **Digital illiteracy:** Low levels of digital literacy in rural areas and smaller project developers limit the power with which they can use fintech platforms LinkedIn.
- **Infrastructure Challenges:** Limited digital infrastructure in remote locations mean that Fintech solutions are not easily deployed and scalable LinkedIn.
- **Risks to cybersecurity :** The growing digitisation of financial services makes data privacy and cyber security concerns all the more pressing, threatening to reduce confidence in fintech solutions Reuters.
- **Leveraging Fintech:** Additional research is needed to properly understand the totality of fintech's contribution, but if combined, fintech and green finance can help accelerate a transition to a sustainable economy.

These challenges can be resolved through concerted efforts by governments, financial institutions or technology providers to form a favorable ecosystem for fintech green finance.

7. Policy and Future Research Recommendations

❖ Policy Recommendations

- **Regulatory Sandboxes for Green FinTech:** They are being encouraged to create regulatory sandboxes where small-scale renewable energy projects can test new financial sector technology. Sand boxes would also enhance the sale of computerized financing, blockchain-based energy certificates, AI-based credit score experiment pilot, and a democratic zone between compliance and imagination.
- **Public-Private Collaboration:** Get the banking sector to co-invest with FinTech start-ups and the government in decentralised renewables. Well developed co-investment vehicles lower apparent risks and invite private money.
- **Digital Infrastructure Investment:** Improve rural and underserved connectivity with high-speed internet, mobile coverage and digital payment systems. There is a need for enabling infrastructure to support adoption of FinTech in green finance.
- **Capacity Building and Financial Literacy:** Develop training programs targeted at local communities, project developers and SMES to improve digital and financial skills. Information on FinTech instruments increases the adoption, risk perception, and sustainability of projects.
- **Standardized ESG Reporting and Transparency:** Reporting ESG quarterly on sponsored green projects by FinTech. It can be accomplished by introducing blockchain and AI to track real-time air pollution and provide examples - improving investor confidence.
- **Incentivizing Green Investment:** Provide tax credits, interests subsidy, co-guarantee participation in small investments in the renewable energy implemented by FinTech. These subsidies encourage the growth of consumption of capital and renewable.

8. Future Research Directions

- **Cross-Country Comparative Studies:** Tracing how EMs can adopt FinTech green finance in their practices and under what conditions: When a regulatory culture and environment, or the infrastructures and high adoption rates are established.
- **Longitudinal Impact Analysis:** Eliminate short-term environmental impact, financial inclusion and the social-economic benefits of renewable energy developments founded with the assistance of FinTech.
- **Behavioral Analysis of FinTech Adoption:** Study user behaviour and trust issues, as well as adoption barriers for rural populations and small-sized-enterprise (SME) customers to better target the design and roll-out of digital financial services.
- **Integration with Climate Risk Assessment:** Investigates how AI and blockchains could be integrated with climate risk models to optimise the financing allocation, reduce environmental risks, and build the resilient finances.
- **Scalability and Replicability Studies:** Pilot Projects The successful pilot projects should be followed and applied in other places and new markets to adopt the use of renewable energy in small scale.



9. Limitations of the Study

This study's major reliance is on secondary data and Qualitative analysis may restrict the depth of empirical validation. Because the results are primarily focused on India, they might not be fully applicable to other countries with different financial and regulatory systems. Due to the lack of long-term project-level data, the study does not measure the financial performance or environmental impact of FinTech-based green funding. Besides, because FinTech technologies are evolving quickly, certain conclusions might alter over time.

10. Conclusion

Fintech solutions are key for broadening access to finance for small renewable energy projects. Digitalization, Block-chain digitalization & Artificial Intelligence are increasing the efficiency, transparency and inclusion of green finance instruments. Yet, supportive policies and capacity development of people and infrastructure are required to harness the full potential of these technologies. The rest of this article discusses some case studies which the fintech industry may potentially use in green finance as well as share with readers information on best practices and policy recommendations. Incorporating Financial Technology (Fintech) in Green Finance has become a strategic and nonlinear measure towards addressing capital access for small-scale RE projects and thus, an essential catalyst of sustainable development in developing countries. This paper provides evidence that Fintech is serving as the missing middle between institutional capital and decentralized endeavors, mitigating or by directly addressing, fundamental market failures associated with limited collateral and high transactions costs. In particular, AI-driven credit assessment serves to make it possible for us to fundamentally redefine risk by leveraging alternative data and apply that learning as we innovate lending, being able to understand all our lender partners in a much more granular way while the block-chain protocol solves for trust and immutability.

The number one takeaway is that the global energy transition cannot be anchored in large projects alone; an inclusive and resilient energy future requires a people-centric economy by democratizing finance with scalable digital solutions. But it will take a combined and multi-stakeholder effort to break down systemic impediments that will help unlock this potential. More specifically, future policy needs to focus on implementing Green Fintech regulatory sandboxes for advancing financial innovation, as well as a compounded public-private investment in digital infrastructure and literacy programs targeted towards rural areas that are aimed directly at pushing digital transformation. Only the establishment of an ecosystem that promotes technological advancement and user capability can Fintech unlock the small-scale RE potential in a way to provide financial inclusion and help strive toward national climate ambition.

References:

1. Ahmad, F., Boumaiza, A., Sanfilippo, A., & Al-Fagih, L. (2025). A Detailed Comprehensive Role of Digital Technologies in Green Finance Initiative for Net-Zero Energy Transition. *Advanced Energy and Sustainability Research*. <https://doi.org/10.1002/aesr.202500066>
2. Artificial Intelligence in Credit Risk Assessment. Source: Knowledge Ridge. (2025, September 16). Tech and ESG Redefine Credit Risk in India. Retrieved from <https://www.knowledgeridge.com/expert-views/tech-and-esg-redefine-credit-risk-in-india/>
3. Chen, S., & Guo, Q. (2024). *Fintech and MSEs innovation: An empirical analysis*. arXiv preprint arXiv:2407.17293 <https://doi.org/10.48550/arXiv.2407.17293>
4. Cleantech Solar. (n.d.). *Open access solar energy solutions*. <https://cleantechsolar.com/how-it-works/open-access-solar-energy-solutions/>
5. Climate Finance Lab. (n.d.). Loans4SME: A peer-to-peer lending platform to help small and medium enterprises operating in renewable energy and energy efficiency raise debt finance. Retrieved September 27, 2025, from <https://www.climatefinancelab.org/ideas/loans4sme/>
6. de Groot, R. S., Alkemade, R., Braat, L., Hein, L., & Willemsen, L. (2010). Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. *Ecological Complexity*, 7(3), 260-272. <https://doi.org/10.1016/j.ecocom.2009.10.006>
7. Dadabada, P. K. (2025). Analyzing the impact of ESG integration and FinTech innovations on green finance: A comparative case studies approach. *Journal of the Knowledge Economy*, 16(2), 7959-7978.
8. Ecofy Finance Private Limited. (n.d.). *Home – Green finance in India*. <https://www.ecofy.co.in/>
9. Flinders, M., & Smalley, I. (n.d.). *What is fintech?* IBM Think. <https://www.ibm.com/think/topics/fintech>



10. Hasan, M., Hoque, A., Abedin, M. Z., & Gasbarro, D. (2024). FinTech and sustainable development: A systematic thematic analysis using human-and machine-generated processing. *International review of financial analysis*, 95, 103473. <https://doi.org/10.1016/j.irfa.2024.103473>
11. Indian Renewable Energy Development Agency Limited. (2024, February 19). *IREDA and PNB to co-finance green energy projects* (Press release). [MoU-with-PNB PDF](#)
12. Kandpal, V., & Mehrotra, R. (2019). Financial inclusion: The role of fintech and digital financial services in India. *Indian Journal of Economics & Business*, 19(1), 85-93. <https://ssrn.com/abstract=3485038>
13. KPI Green Energy Limited. (n.d.). *Best solar company in Surat, Gujarat | KPI Green Energy*. <https://www.kpigreenenergy.com/>
14. Loans4SME: A Peer-to-Peer Lending Platform for Renewable Energy in India. Source: Climate Finance Lab. (n.d.). Loans4SME: A peer-to-peer lending platform to help small and medium enterprises operating in renewable energy and energy efficiency raise debt finance. Retrieved from <https://www.climatefinancelab.org/ideas/loans4sme/>
15. Liu, Y., Xiong, Y., & Jiang, Y. (2021). The nexus between FinTech, green finance, and energy efficiency: Evidence from E7 economies. *Energy Economics*, 101, 105451. <https://doi.org/10.1016/j.eneco.2021.105451>
16. Nenavath, S., & Mishra, S. (2023). Impact of green finance and fintech on sustainable economic growth: Empirical evidence from India. *Heliyon*, 9(5). <https://doi.org/10.1016/j.heliyon.2023.e16301>
17. Power Ledger: Blockchain-Enabled Energy Trading Platform. Source: Power Ledger. (n.d.). Powerledger: Home. Retrieved from <https://powerledger.io/>
18. Singh, N. (2024). Exploring Prospects for Innovation in India's Financial System via Green Financing. *International Journal For Multidisciplinary Research*. <https://doi.org/10.36948/ijfmr.2024.v06i04.24278>
19. Reuters. (2025, July 18). India to issue climate risk disclosure rules for banks in the next few months. Retrieved September 27, 2025, from <https://www.reuters.com/sustainability/cop/india-issue-climate-risk-disclosure-rules-banks-next-few-months-sources-say-2025-07-18/>
20. RenewShare. (n.d.). *RenewShare: Solar rooftop financing solutions*. <https://renewshare.com/>
21. SEBI's ESG Disclosure Requirements Source: Reuters. (2025, April 16). India to review ESG disclosures for listed firms, market regulator says. Retrieved from <https://www.reuters.com/sustainability/boards-policy-regulation/india-review-esg-disclosures-listed-firms-market-regulator-says-2025-04-16/>
22. Wang, J., Li, H., & Yang, F. (2023). Green credit, FinTech development, and bank performance: Evidence from China. *Journal of Cleaner Production*, 394, 136386. <https://doi.org/10.1016/j.jclepro.2023.136386>
23. Wire, S. (2024, May 31). *Green finance*. Lloyds Banking Group. <https://www.lloydsbankinggroup.com/insights/green-finance.htm>
24. Zhang, Y. (2023). Impact of green finance and environmental protection on green economic recovery in South Asian economies: mediating role of FinTech. *Economic Change and Restructuring*, 56, 2069 - 2086. <https://doi.org/10.1007/s10644-023-09500-0>



DOIs:10.2015/IJIRMF/ICICSF-2025-P31

--:--

Research Paper / Article / Review

International Conference On “Innovative Convergence for Sustainable Future”

Date : 12 - 13 December, 2025

(ICICSF-2025)



Physiotherapy Auditing-A Comprehensive Framework for Quality Improvement in Physiotherapy Practice: A Narrative Review

Dr. Rashmi Kumari Hembrom (PT)
Assistant Professor ,Jharkhand Rai University ,
physiorashmi5@gmail.com

Abstract: Physiotherapy auditing is a systematic process used to evaluate the quality, effectiveness, and efficiency of physiotherapy services. It helps ensure that clinical practices align with evidence-based guidelines, organizational standards, and patient expectations. This manuscript explores the concept, need, types, components, methodology, and challenges of physiotherapy auditing with emphasis on clinical, administrative, and outcome-based audits. The paper concludes with recommendations for developing a robust audit culture within physiotherapy departments in India to enhance service quality, accountability, and patient safety.

Keyword: Physiotherapy, Auditing, Quality Assurance, Quality Assessment.

1. INTRODUCTION

As qualified rehabilitation professionals, physiotherapists bring essential expertise to individuals of all ages by conducting assessments, providing diagnoses and prognoses, using various treatment modalities, providing education and counselling support, formulating recommendations and promoting an active lifestyle¹. Healthcare systems worldwide are increasingly adopting structured auditing mechanisms to improve quality of care. Physiotherapy, being an integral part of multidisciplinary healthcare, requires robust auditing processes to ensure safe, effective, and patient-centered rehabilitation services. Auditing in physiotherapy helps identify gaps, evaluate compliance with standards, and strengthen clinical governance. Clinical audit is a recognized methodology to improve service quality and redesign (NHS England).² It is both a regulatory requirement and a tool for continuous quality improvement.

“Audit” is a Latin word, and the verb *audio* (‘hear’) indicates both active listening and the action of investigation and interrogation of the judiciary. Transferred to the English vocabulary “audit” takes on a meaning of “an official inspection of an organization’s accounts, typically by an independent body”³

1.1 Definition of Physiotherapy Auditing

Physiotherapy auditing is a cyclic, systematic evaluation of physiotherapy practices, procedures, documentation, and clinical outcomes against predefined standards⁴. It involves collecting, analyzing, and interpreting data to determine whether care delivered meets expected quality benchmarks. Staff who are involved in the care process that is to be audited will know the range and reliability of information that may be held about users on computer systems or in patient notes, and administrative staff may have access to further management information. Consultation with these groups can help a team think through what data they really need to collect to monitor those processes that directly affect care.⁵

1.2 Need and Importance of Physiotherapy Auditing

Physiotherapists should implement quality monitoring tools such as clinical indicators that would enable individual practitioners to evaluate their performance against that of their peers⁶. In Indian rehabilitation set up the documentation and evidence of the same is lacking⁷. Lubrano stated in his paper An audit of anthropometric measurements by medical



and physiotherapy staff in patients with ankylosing spondylitis. *Clinical Rehabilitation*. that Follow-up and monitoring of AS patients in these medical clinics is clearly inadequate.⁸

2. METHODOLOGY

2.1. Review Approach

A narrative framework was used to synthesize existing evidence related to:

- Definitions and concepts of physiotherapy auditing
- Need and importance of auditing in rehabilitation services
- Types and components of clinical, administrative, and outcome-based audits
- Audit cycles and quality assurance mechanisms
- Challenges in audit implementation
- National and international physiotherapy practice standards

This approach allowed the integration of diverse literature sources to provide an overarching understanding of current practices and gaps.

2.2. Literature Search Strategy

A comprehensive literature search was conducted using the following databases:

- PubMed
- Google Scholar
- ScienceDirect
- Cochrane Library
- Professional bodies' publications (e.g., CSP, WCPT, NABH, NCAHP)

2.3. Inclusion and Exclusion Criteria.

2.3.1. Inclusion Criteria

- Articles published in English
- Studies, guidelines, reviews, and professional standards related to physiotherapy or healthcare auditing
- Publications from 1995 to 2025
- Research articles, audit reports, government documents, and position papers

2.3.2. Exclusion Criteria

- Non-healthcare audits (e.g., financial/business audits)
- Articles without relevance to physiotherapy practice or quality assurance
- Non-English publications

2.4. Selection Process

Titles and abstracts were screened for relevance. Full-text articles meeting the inclusion criteria were examined and thematically categorized. Reference lists of selected papers were also manually screened to identify additional relevant sources.

2.5. Data Extraction and Thematic Synthesis

Extracted information included:

- Audit objectives and scope
- Audit cycle components
- Standards and outcomes measured
- Implementation challenges
- Recommendations for physiotherapy practice

SALSA Component	Details for This Narrative Review
SEARCH	Literature search in PubMed, Google Scholar, ScienceDirect, Cochrane Library, and professional guidelines (CSP, WCPT, NABH, NCAHP). Keywords: <i>physiotherapy audit</i> , <i>clinical audit</i> , <i>audit cycle</i> , <i>clinical governance</i> , <i>quality indicators</i> , <i>physiotherapy documentation</i> . Timeframe: 1995–2025.
APPRAISAL	Articles screened for relevance to physiotherapy and healthcare auditing. Inclusion: English-only, peer-reviewed studies, guidelines, standards, reviews. Exclusion: Non-healthcare audits, non-



SALSA Component	Details for This Narrative Review
	English texts, unrelated domains. Priority to documents outlining audit frameworks or quality improvement systems.
SYNTHESIS	Thematic narrative synthesis. Themes included definitions, need for auditing, types of audits, audit cycle, quality standards, barriers in implementation, and Indian context gaps. Guidelines and empirical evidence integrated to develop conceptual clarity.
ANALYSIS	Comparative analysis of international standards (WCPT, CSP, NABH) and existing practices in India. Identified gaps in documentation, audit culture, clinical governance, and training. Evaluated opportunities for structured audit programs and QI mechanisms.
APPLICATION	Findings applied to propose a structured physiotherapy audit framework suitable for Indian rehabilitation settings: standardized documentation, outcome indicators, administrative audits, periodic review cycles, digital record systems, and staff training modules.

3.DISCUSSION

This narrative review highlights the crucial role of physiotherapy auditing in strengthening quality assurance, clinical effectiveness, and patient safety within rehabilitation services. The findings of the review underscore that physiotherapy auditing is not merely an administrative requirement but a structured mechanism for improving clinical governance and aligning practice with evidence-based standards. The synthesis of literature reveals significant international progress in audit culture, whereas Indian rehabilitation services still face gaps in documentation, audit implementation, and standardized quality indicators.

The international evidence strongly supports clinical audit as a driver of service improvement. For example, Thomson et al. demonstrated that audits within musculoskeletal services enhance clinical consistency, reduce variations in care, and improve patient-reported outcomes. Similarly, guidelines from the Chartered Society of Physiotherapy (CSP)⁴ and the World Confederation for Physical Therapy (WCPT)¹⁴ emphasize audits as integral to professional accountability and continuous quality improvement. These perspectives reinforce the relevance of audit-based evaluation in physiotherapy, especially in rapidly evolving healthcare systems.

However, the application of auditing within Indian physiotherapy practice remains limited. As highlighted by Rajan and others, documentation standards and formalized quality assessment protocols are inconsistently followed across rehabilitation centres. The lack of structured record-keeping, insufficient awareness of audit cycles, and absence of mandatory audit requirements hinder the establishment of a strong audit culture. The findings from Lubrano's study on ankylosing spondylitis also demonstrate how inadequate monitoring and follow-up can lead to compromised patient outcomes, which further emphasizes the need for standardized auditing processes.

The SALSA-based analysis of literature provides a deeper understanding of these gaps. While global standards (NABH Rehabilitation Standards, WCPT Standards for Practice) define benchmarks for clinical documentation, safety, and outcome measurement, the challenges in Indian settings include limited training in audit methodology, restricted administrative support, and minimal integration of digital records. These shortcomings reduce the effectiveness of audit cycles and delay corrective actions.

Despite these challenges, the review identifies key opportunities to advance physiotherapy auditing in India. The integration of structured audit cycles—comprising topic selection, criterion development, data collection, evaluation, implementation of change, and re-auditing—can significantly enhance service consistency. Adoption of clinical indicators, technology-based documentation systems, and multidisciplinary participation can improve compliance and reliability of audit data. Furthermore, aligning physiotherapy audits with NABH¹¹ and NCAHP¹³ regulatory standards may lead to improved accreditation readiness and better patient safety outcomes.



Another crucial aspect emerging from this review is the role of physiotherapy audits in professional development. Regular audit cycles encourage reflective practice, help clinicians identify gaps in competencies, and foster evidence-based decision making. By engaging physiotherapists in systematic evaluation, auditing promotes a culture of accountability, shared learning, and continuous improvement. This is particularly relevant in government rehabilitation projects where service load is high and quality assurance mechanisms are often weak.

Overall, the review concludes that physiotherapy auditing, when implemented systematically, has the potential to transform rehabilitation services. Strengthening audit literacy among physiotherapists, mandating routine audits, and integrating digital health tools can bridge existing gaps. The adoption of a comprehensive and feasible audit framework tailored to the Indian context can improve patient care quality, optimize resource utilisation, and elevate the professional standards of physiotherapy practice. Thus, building a robust audit culture is essential for ensuring patient-centred, effective, and safe physiotherapy services.

Physiotherapy Auditing will Ensure quality assurance and promotes standardized care in government Rehabilitation Projects

- **Enhances clinical effectiveness** by identifying deviations from evidence-based practice.
- **Improves patient safety** through early detection of errors.
- **Strengthens documentation** and medico-legal compliance.
- **Supports accreditation processes** (NABH, JCI, NCAHP guidelines).
- **Optimizes resource utilization** and reduces unnecessary interventions.
- **Promotes accountability** among physiotherapists and administrative staff.
- **Facilitates continuous professional development** and reflective learning.

4. Conclusion

Physiotherapy auditing is an essential component of modern physiotherapy services, ensuring high-quality, efficient, and patient-centered care. By adopting structured audit cycles and fostering a culture of continuous improvement, physiotherapy departments can enhance clinical outcomes, strengthen documentation, improve patient safety, and achieve organizational excellence. Investing in audit training, technology, and leadership support will further maximize the benefits of physiotherapy audits in healthcare settings. Audit is a useful tool for disseminating and implementing national standards when carried out in partnership with physiotherapy managers

References:

1. Champoux M, Poirier A, Hudon C. Roles of physiotherapists in primary care teams: a scoping review. *BMJ Open*. 2025 Feb 7;15(2): e092276. doi: 10.1136/bmjopen-2024-092276. PMID: 39920051; PMCID: PMC11808882.
2. Clinical audit drives quality improvement in a successful Musculoskeletal Interface Service (MIS) Thomson, K. et al. *Physiotherapy*, Volume 103, e107
3. Esposito P, Dal Canton A. Clinical audit, a valuable tool to improve quality of care: General methodology and applications in nephrology. *World J Nephrol*. 2014 Nov 6;3(4):249-55. doi: 10.5527/wjn.v3.i4.249. PMID: 25374819; PMCID: PMC4220358.
4. Chartered Society of Physiotherapy (CSP). *Clinical Audit Guidelines*. 2000
5. *Principles for Best Practice in Clinical Audit*, Commission of Health Improvement Radcliffe Medical Press, 2002
6. Mohamad Abou Haida et al, National quality assessment questionnaire for physiotherapy centers: a pilot study in Lebanon, *EMHJ – Vol. 25 No. 1 – 2019*
7. Rajan P. Physiotherapy in Indian communities: a brief review. *Health Promot Perspect*. 2017 Jun 14;7(3):111-116. doi: 10.15171/hpp.2017.21. PMID: 28695097; PMCID: PMC5497360.
8. Lubrano E, Butterworth M, Hesselden A, Wells S, Helliwell P. An audit of anthropometric measurements by medical and physiotherapy staff in patients with ankylosing spondylitis. *Clinical Rehabilitation*. 1998;12(3):216-220. doi:10.1191/026921598675367725



9. Grant, M.J. and Booth, A. (2009), A typology of reviews: an analysis of 14 review types and associated methodologies. *Health Information & Libraries Journal*, 26: 91-108. <https://doi.org/10.1111/j.1471-1842.2009.00848.x> The objective of this study is to provide descriptive insight into the most common types of reviews, with illustrative examples from health and health information domains.
10. World Confederation for Physical Therapy (WCPT). Standards for Practice.
11. NABH Rehabilitation Standards, 2023.
12. Donabedian A. Evaluating the Quality of Medical Care. *Milbank Memorial Fund Quarterly*.
13. NCAHP Regulatory Guidelines for Physiotherapy Practice.
14. Physical therapy records management: record keeping, storage, retrieval and disposal Guideline, World Physiotherapy, WCPT-2011
15. Irvine D and Irvine S (eds). (1991). *Making Sense of Audit*. Radcliffe Medical Press, Oxford.
16. Rob Herbert, Practical Evidence-Based Physiotherapy, Elsevier Ltd 2011
17. Redfern SJ, Norman IJ. Clinical audit, related cycles and types of health care quality: a preliminary model. *Int J Qual Health Care*. 1996 Aug;8(4):331-40. doi: 10.1093/intqhc/8.4.331. PMID: 8938494.



DOIs:10.2015/IJIRMF/ICICSF-2025-P32

--:--

Research Paper / Article / Review

International Conference On “Innovative Convergence for Sustainable Future”

Date : 12 - 13 December, 2025

(ICICSF-2025)



Polyphenols as Co-Therapeutics in Breast Cancer

Ritesh Goswami^{1*}, Heba Parveen¹, Ujjwal Kumar¹, Amarjeet Kumar¹, Kritika Modak²

¹Department of Pharmaceutical Sciences,
Jharkhand Rai University, Raja Ulatu, Namkum, Ranchi, Jharkhand 834010, India.

² Assistant Professor, Department of Pharmaceutical Sciences,
Jharkhand Rai University, Raja Ulatu, Namkum, Ranchi, Jharkhand 834010, India

Email – halfbloodprince1250@gmail.com

Abstract: Breast cancer remains a leading cause of morbidity and death among women worldwide, with GLOBOCAN 2022 reporting about 2.3 million new cases. In India, it is the most commonly diagnosed cancer among women and continues to show a rising incidence. While current treatment options such as chemotherapy, hormonal therapy, and targeted biologics have improved survival, their long-term effectiveness is often limited by drug resistance, cumulative toxicity, and reduced patient tolerance. Polyphenols, naturally occurring compounds found in fruits, vegetables, teas, and spices have gained attention for their multitargeted antioxidant, anti-inflammatory, anti-proliferative, and pro-apoptotic properties. Key polyphenols such as curcumin, epigallocatechin gallate (EGCG), resveratrol, quercetin, and genistein modulate critical signaling pathways related to tumor growth, metastasis, angiogenesis, and hormone regulation. Preclinical studies across ER⁺ and triple-negative breast cancer models demonstrate that these compounds can induce apoptosis, inhibit invasion and metastatic signaling, and reduce angiogenic progression. Co-therapy findings further show that polyphenols can enhance the therapeutic response of chemotherapeutic agents such as paclitaxel, doxorubicin, tamoxifen, and trastuzumab, while reducing treatment-associated oxidative and cardiac toxicity. However, poor bioavailability and rapid metabolic clearance limit their direct clinical use. Advancements in nano-formulations, liposomal carriers, phytosomes, and polymeric nanoparticles have improved systemic stability, tumor localization, and pharmacological activity. Overall, polyphenols are best positioned as co-therapeutic agents, where optimized formulation and delivery systems enable meaningful clinical benefit alongside conventional therapy.

Keywords: Polyphenols; Breast cancer; Nanoparticles; Co-therapy; Apoptosis.

1. INTRODUCTION :

Breast cancer (BCA), a progressive malignancy of breast tissue, continues to be a major contributor of cancer-related mortality among women worldwide with GLOBOCAN 2022 reporting about 2.3 million new cases.¹ In India, breast cancer represents the leading cancer diagnosis among women, with 192,020 new cases and 98,337 deaths recorded in 2022, accounting for nearly one in every four reported cancer cases among women.² Although improvements in diagnosis and therapeutic strategies have enhanced survival outcomes, global projections indicate a significant rise in breast cancer incidence, estimated to surpass 3.2 million new cases annually by 2050.¹

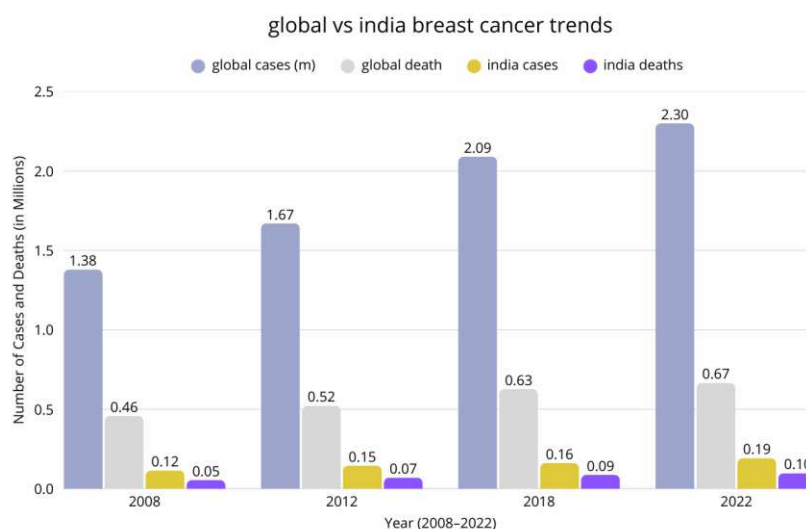


Figure 1. Global and Indian breast cancer incidence and mortality trends

(GLOBOCAN 2022).

Conventional treatment strategies for breast cancer include surgery, chemotherapy (e.g., doxorubicin, paclitaxel), hormone therapy (e.g., tamoxifen, letrozole), radiotherapy, and targeted agents such as trastuzumab and pertuzumab. Although treatment methods have advanced, patients frequently encounter treatment resistance, cumulative toxicity, and difficulty sustaining long-term therapy.

Polyphenols, a diverse group of plant-derived compounds such as curcumin, resveratrol, epigallocatechin gallate (EGCG), and genistein, have gained interest due to their multitargeted anticancer activities, including anti-proliferative and pro-apoptotic effects.³ However, their clinical utility is reduced by low oral uptake, rapid metabolic clearance, and inadequate accumulation at tumor sites. Recent advances in nano-delivery systems, including nanoparticles, liposomes, phytosomes, nanoemulsions, and polymer-based carriers, have demonstrated improved stability, solubility, and targeted delivery of polyphenols.⁴ These developments highlight their potential as co-therapeutic agents alongside standard breast cancer treatments.

2. LITERATURE REVIEW:

2.1 Non-Cancer Deaths Caused By Conventional Cancer Drugs

In this section, we explore deaths that occur not from the cancer itself, but from the physical damage caused by standard anti-cancer medicines. These cases highlight the seriousness of drug-related complications and the need for awareness, early detection, and safer treatment planning.

2.1.1 Cardiotoxicity caused by capecitabine (heart-attack death)

A 62-year-old woman with stage II breast cancer (estrogen-receptor positive, human epidermal growth factor receptor 2 negative) began treatment with capecitabine. She had controlled high blood pressure and no past heart problems, and she managed her daily life without difficulty and had no history of smoking.⁵ Her treatment plan included capecitabine at 1250 mg per square meter of body surface area, taken twice a day for two weeks followed by a week off, which is the usual schedule for this medicine.⁶

During the first two days she felt normal, but by the third day she developed a heavy, persistent discomfort in her chest and became short of breath, so her family brought her to the hospital.⁷ The next morning, tests showed changes in her heart rhythm that suggested reduced blood flow, and her troponin level was raised, which is a sign of heart-muscle injury. ^{6,7} The medical team stopped the chemotherapy immediately. They treated her with nitroglycerin to help open the heart's blood vessels and started a calcium-channel blocker such as diltiazem to prevent further tightening of the vessels.⁷ A coronary angiography showed her arteries were open, but an echocardiogram showed her heart was already pumping less effectively than before.⁸ She went home after stabilizing, but over the next three months she struggled



more with simple activities, and repeat scans showed her heart function was slowly getting worse. About six months after this first episode, she was admitted again with swelling and difficulty breathing. During this stay she suffered a sudden cardiac arrest caused by severe heart failure, and the team could not revive her.⁸ The autopsy report showed that her heart had slowly weakened over time. The left ventricle was stretched, the walls were thinner than they should be, and there were also small patches of older damage that fit with repeated episodes of reduced blood flow rather than a single large blockage.⁸ These findings match what is known about capecitabine and its breakdown product, 5-fluorouracil. This compound can irritate the lining of the heart's blood vessels, making them tighten suddenly, which limits blood flow. It can also disrupt how heart cells produce energy, making them more sensitive to any drop in oxygen.^{5,6,9} When these effects keep happening, the heart gradually becomes weak. In her case, the pattern of injury clearly pointed to the treatment as the main cause of her decline and death, rather than the cancer itself.

2.1.2 Pulmonary toxicity (death due to pulmonary embolism)

A 55-year-old woman with hormone-receptor-positive breast cancer in stage II was started on tamoxifen as part of her ongoing treatment.¹⁰ She had no history of lung problems, no prior blood-clot disorders, and lived an active lifestyle before beginning therapy. Her tamoxifen dose was the standard 20 milligrams taken once daily by mouth.¹¹ She continued this routine for several weeks without major issues, noticing only mild hot flashes and occasional leg heaviness, which she first assumed was due to daily exertion. After about eight weeks of treatment, she developed a dull pain in her right calf that slowly increased over several days, along with a feeling of unexplained tiredness.¹² One morning she woke with sudden shortness of breath and a sharp pain in her chest, making it difficult for her to speak in full sentences, and she was rushed to the emergency department. On evaluation, her oxygen levels were low, and a CT scan of her chest showed large blood clots lodged in the arteries of both lungs, confirming a pulmonary embolism. The care team immediately started blood-thinner injections such as heparin to prevent further clot growth, and tamoxifen was stopped because of the suspected link to the clotting event. Although her breathing improved slightly with oxygen and supportive care, her condition remained unstable. Within a short time, she experienced a sudden collapse due to extreme strain on the right side of her heart caused by the clot burden, and despite emergency efforts, she died during the same hospital admission.^{12,13} The final medical review found that the main arteries supplying blood to her lungs were blocked by large organized clots, and the right side of her heart was stretched and weakened from trying to pump against the blockage. The findings supported what is known about tamoxifen: after being processed in the liver, tamoxifen and its active metabolites can increase the body's tendency to form clots by affecting the balance of natural clot-controlling proteins in the bloodstream.^{10,11} These changes make the blood more likely to form deep-vein clots in the legs, which can then travel to the lungs and obstruct major vessels. Over time, this can place dangerous pressure on the heart and lungs, leading to sudden death in severe cases. Her passing, therefore, was not caused by the cancer itself but by a treatment-related complication linked to the clot-forming effects of tamoxifen.

2.1.3 Hepatic toxicity (death due to acute liver failure)

A 58-year-old woman receiving treatment for advanced breast cancer was started on lapatinib because her tumour tested positive for the human epidermal growth factor receptor two.¹⁴ She had no long-term liver disease, drank alcohol only occasionally, and her baseline liver tests were within normal limits. Lapatinib was given at the standard dose of 1250 milligrams taken once daily by mouth, and during the first few weeks she reported only mild nausea and tiredness. ¹⁵ Around the sixth week of therapy, she developed a loss of appetite, fatigue, and a yellowish tinge in her eyes that her family noticed. When she returned to the hospital, her liver tests had increased sharply, showing that her liver was struggling to filter toxins, and her blood clotting time was longer than normal, which is another sign of liver stress.¹⁶ Lapatinib was stopped immediately, and she was admitted for close monitoring. The team provided intravenous fluids, medicines to support her blood pressure, and treatments to help reduce the buildup of toxins. Still, her liver function continued to decline over the next few days. She became confused and drowsy, her kidneys also began to fail, and despite intensive care support, she went into multi-organ failure and passed away a little more than a week after her admission.^{16,17} The autopsy report showed that her liver was enlarged, pale, and had widespread areas where liver cells had died. The tissue looked patchy, with some regions swollen and others collapsing, which is a known pattern when drug injury overwhelms the liver's ability to repair itself. These findings fit with what is known about lapatinib. After the drug is absorbed, it is broken down in the liver by enzymes that convert it into several by-products. In some patients, these by-products can place heavy stress on liver cells, disturb normal enzyme function, and trigger inflammation that spreads through the liver.^{14,15} When this reaction accelerates, the liver cannot keep up with detoxification or protein production, leading to the rapid decline seen in her tests. In this case, the pattern of damage clearly pointed to a drug-induced liver failure rather than a progression of cancer.

**TABLE 1: conventional drug therapy and their toxicity**

Drug	Therapy type	Purpose	Major limitations / toxicity	Reference
Capecitabine	Chemotherapy (oral fluoropyrimidine)	Breast, colorectal cancer	Can cause tightening of heart vessels and direct heart-cell injury - chest pain, heart attack, heart failure	5,6,7,8,9
5-Fluorouracil	Chemotherapy (IV fluoropyrimidine)	GI cancers, breast cancer regimens	Same heart reaction as capecitabine - vessel spasm, reduced blood flow, arrhythmias, heart damage	6,9
Tamoxifen	Hormonal therapy (SERM)	ER-positive breast cancer	Increases blood-clot risk - DVT and pulmonary embolism, which can be fatal	10,11,12,13
Lapatinib	Targeted therapy (HER2 TKI)	HER2-positive advanced breast cancer	Can strain liver cells - acute liver injury or liver failure in susceptible patients	14,15,16, 17
Doxorubicin	Chemotherapy (anthracycline)	Breast cancer, lymphoma, many solid tumors	Can weaken the heart muscle over time - dilated cardiomyopathy and heart failure	18
Trastuzumab	Targeted monoclonal antibody (anti-HER2)	HER2-positive breast cancer	Can reduce heart-pumping ability - heart failure, especially after anthracyclines	19,20
Paclitaxel	Chemotherapy (taxane)	Breast, ovarian, lung and other cancers	Causes nerve damage - difficulty walking, falls, disability; can indirectly increase clot or injury risk	21,22
High-dose Methotrexate	Chemotherapy (antimetabolite)	Leukemia, lymphoma, high-dose rescue regimens	Can damage gut lining, liver and kidneys - organ failure if levels accumulate	23
Pembrolizumab (and similar checkpoint inhibitors)	Immunotherapy (PD-1 / PD-L1 inhibitors)	Many cancers including breast (TNBC)	Can overstimulate immunity - hepatitis, myocarditis, severe diarrhea, lung inflammation; rare but fatal	24,25
Sunitinib	Targeted therapy (multi-kinase inhibitor)	Renal cell carcinoma, GIST	Can cause hypertension, heart problems, and liver stress	26
Sorafenib	Targeted therapy (multi-kinase inhibitor)	Liver cancer, renal cancer	Can cause liver strain, bleeding risks, fatigue, and heart issues	27
Cisplatin	Chemotherapy (platinum agent)	Many solid tumors	Causes kidney injury and severe electrolyte imbalance - can lead to life-threatening complications	28
Corticosteroids (long-term use)	Supportive therapy	Reduce inflammation, nausea, edema	Raise infection risk; can lead to serious infections and sepsis in weakened patients	29

These treatment-related deaths show that even effective cancer drugs can create **documented** problems in the heart, lungs, liver and other vital organs. The risk does not arise from the cancer alone, but from the **reported** stress that these medicines place on the body during and after therapy. **Several studies suggest the importance of approaches** that not only fight tumours but also protect the patient from these hidden dangers. **In this context, polyphenol compounds**



have been investigated, as they can work across multiple pathways, reduce treatment stress and offer protection where conventional drugs often fall short.³⁶

3. OBJECTIVES / AIMS:

Aim:

To evaluate the therapeutic relevance of polyphenols as co-therapeutic agents in breast cancer through analysis of their mechanisms, in-vitro and in-vivo evidence, and synergy with standard treatments

Objectives:

1. To review toxicity caused by conventional anti-cancer drugs.
2. To understand mechanisms of key polyphenols in breast cancer.
3. To analyze in-vitro & in-vivo anticancer effects of polyphenols.
4. To evaluate co-therapy benefits with chemotherapy & hormonal agents.
5. To compare major polyphenols (curcumin, EGCG, resveratrol, quercetin, genistein).
6. To explore advanced nano-formulations that improve efficacy.

4. RESEARCH METHOD:

This study was carried out as a narrative literature review focusing on the role of polyphenols as co-therapeutic agents in breast cancer. Relevant scientific publications were identified using databases such as PubMed, Google Scholar, and Scopus. Studies related to breast cancer, polyphenols, co-therapy, and formulation strategies were considered. Both in-vitro and in-vivo research findings were reviewed. The selected literature was evaluated qualitatively to understand mechanisms of action, therapeutic relevance, and toxicity modulating effects of polyphenols in breast cancer management.

5. ANALYSIS - DISCUSSION:

5.2 Polyphenols: Overview and Mechanism in Breast Cancer

Polyphenols are naturally occurring compounds found mainly in plant-based foods, especially fruits, vegetables, teas, and spices. They are known for their **antioxidant, anti-inflammatory, anti-proliferative, and pro-apoptotic activities**, which makes them relevant in cancer research and therapy.³⁰ Unlike conventional drugs that usually act on a **single molecular target**, polyphenols can influence **multiple signaling pathways** at once - including those involved in **cell survival, inflammation, angiogenesis, and metastasis**.^{31,32} This broad pathway influence is one reason they are being explored as supportive or co-therapy agents. Based on their structural features, polyphenols fall into groups such as flavonoids, phenolic acids, stilbenes, and curcuminoids, which vary in both dietary sources and biological roles. Many commonly studied anti-cancer polyphenols fall into these groups, such as **curcumin, resveratrol, epigallocatechin gallate (EGCG), quercetin, and genistein**. These compounds are known to interact with major signaling pathways relevant to tumor growth and progression, including estrogen receptor signaling, PI3K/Akt, NF-κB inflammation signaling, and apoptosis regulation.^{32,38,41}

TABLE 2: Polyphenols and their anticancer effects.

Class	Key Compounds	Major Dietary Sources	Primary Mechanism in Breast Cancer	Main Anticancer Effect	Ref.
Flavonoids	Quercetin, EGCG, Genistein	Green tea, soy, apple, onion	PI3K/Akt inhibition, ER modulation	Reduced proliferation & apoptosis induction	64,50, 70
Phenolic Acids	Caffeic acid, Ferulic acid	Coffee, berries, whole grains	Antioxidant + anti-inflammatory regulation	Lowers oxidative stress & inflammatory signaling	30,31



Class	Key Compounds	Major Dietary Sources	Primary Mechanism in Breast Cancer	Main Anticancer Effect	Ref.
Stilbenes	Resveratrol	Grapes, red wine, peanuts	Downregulates MMPs & VEGF	Inhibits metastasis & angiogenesis	57,59
Curcuminoids	Curcumin	Turmeric	NF-κB suppression & mitochondrial apoptosis	Promotes apoptosis & reduces tumor progression	38,41,43
Lignans	Secoisolariciresinol, Matairesinol	Flaxseed, sesame, whole grains	Modulates ER signaling & inhibits PI3K/Akt	Anti-proliferative + reduces hormone driven growth	34
Tannins	Ellagitannins, Proanthocyanidins	Pomegranate, berries, nuts	Anti-inflammatory + anti-angiogenic pathways	Inhibits metastasis & suppresses oxidative stress	35

Polyphenols can influence breast cancer development by acting on multiple signaling pathways that control cell growth, inflammation, spread, and cell death. Unlike conventional drugs that usually focus on a single target, polyphenols influence several pathways at once. This broad activity is significant because breast cancer cells often adapt and develop resistance when only one pathway is blocked.³²

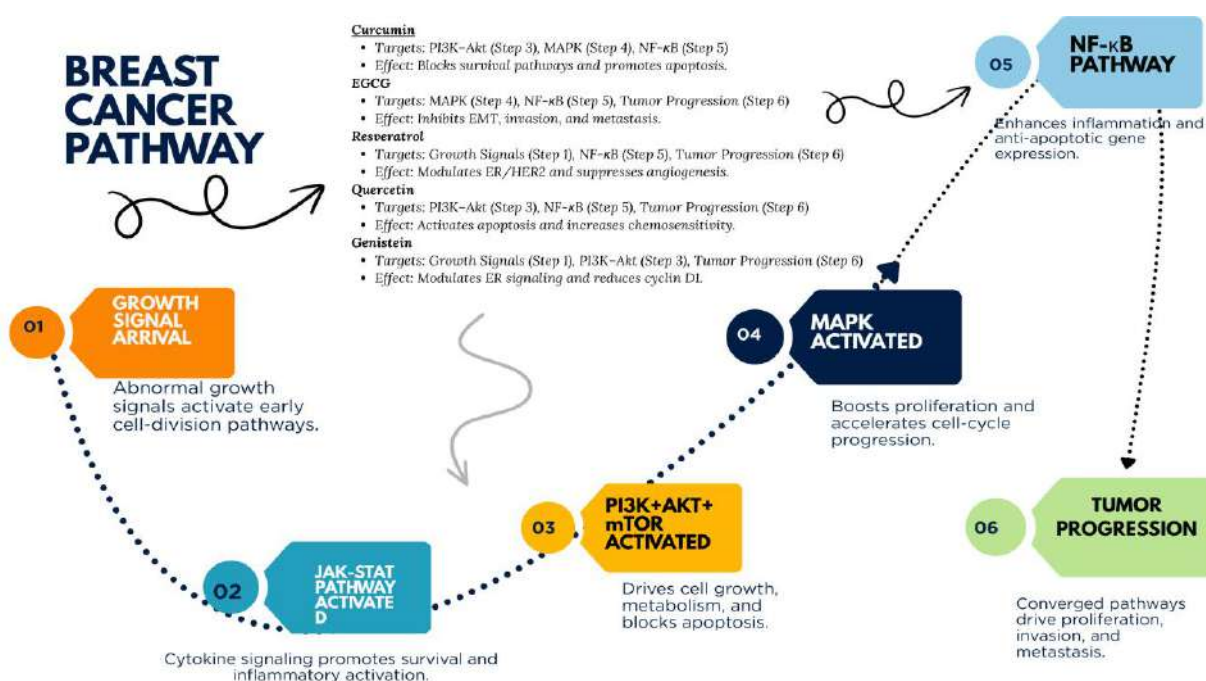


Figure 2. Overview of breast cancer signaling pathways and polyphenol targets.

Source: Author-generated schematic.

5.3 Polyphenol As Co-Therapeutics In Breast Cancer

Polyphenols are increasingly being recognized for their ability to support conventional breast cancer treatments. They work effectively alongside agents such as doxorubicin, paclitaxel, and tamoxifen, often enhancing therapeutic response



while reducing treatment related stress.³⁶ Their benefits stem from their ability to influence key pathways, including PI3K/Akt, MAPK, NF- κ B, and estrogen-related signaling, which collectively promote apoptosis and slow tumor progression.³⁷ They also help counter multidrug resistance by lowering efflux pump activity and restricting EMT-driven survival mechanisms. When combined with hormonal or targeted therapies, polyphenols improve treatment stability and overall sensitivity. Together, these compounds function as reliable and biologically supportive partners in modern breast cancer care.

5.4 Curcumin

Curcumin engages key oncogenic pathways, including NF- κ B and PI3K/Akt, to promote apoptosis and inhibit growth. Its primary molecular effects involve modulation of the NF- κ B, PI3K/Akt, and Bcl-2/Bax apoptotic axis, contributing to both growth inhibition and pro-apoptotic signaling in cancer cells.^{38–40}

5.4.1 In-Vitro Anticancer Effects of Curcumin

In vitro studies consistently show that curcumin affects multiple signaling pathways involved in breast cancer cell proliferation, apoptosis, and invasion. In estrogen receptor–positive MCF-7 cells, curcumin increases the ratio of pro-apoptotic Bax (Bcl-2–associated X protein) to anti-apoptotic Bcl-2 (B-cell lymphoma 2) and activates caspase-3, which together promote programmed cell death. Curcumin also suppresses nuclear factor kappa-light-chain-enhancer of activated B cells (NF- κ B), a transcription factor that promotes survival and inflammatory signaling. These effects contribute to a measurable reduction in proliferation. In triple-negative MDA-MB-231 cells, curcumin reduces invasive potential by lowering the expression of matrix metalloproteinase-9 (MMP-9) and decreasing phosphorylation of protein kinase B (Akt). Curcumin also restores levels of E-cadherin (epithelial cadherin), which helps maintain epithelial structure and reduces cellular motility. These changes collectively limit the ability of aggressive breast cancer cells to migrate and invade surrounding tissue. Overall, the in-vitro evidence identifies curcumin as a compound that induces apoptosis in estrogen-responsive cells and reduces invasive behavior in aggressive triple-negative models.^{41–43}

5.4.2 In-Vivo Anti-Tumor Evidence

In vivo findings support the mechanistic patterns observed in cell-based studies. In the 7,12-dimethylbenzanthracene (DMBA) rat mammary tumor model, oral curcumin administration results in a clear decrease in tumor volume and reduced proliferative activity. Treated tumors show lower expression of Ki-67, an established proliferation marker, along with increased apoptotic markers. These outcomes reflect curcumin's ability to regulate NF- κ B signaling and shift the balance toward programmed cell death within tumor tissue. In 4T1 mouse xenograft models, nano-formulated curcumin demonstrates stronger antitumor activity than the free compound. Nano-curcumin improves systemic stability and tumor uptake, resulting in greater suppression of tumor growth and reduced metastatic potential [44,97]. These results reflect curcumin's poor oral bioavailability and underscore the need for optimized delivery. Across rat and mouse models, curcumin consistently reduces tumor progression, increases apoptotic activity, and weakens invasive characteristics. The combined evidence positions curcumin as a biologically active compound with meaningful regulatory effects on proliferation, inflammation, and metastasis, with efficacy substantially improved through nano-delivery formulations. The DMBA rat model confirms curcumin's cytostatic and pro-apoptotic effects in live tumor tissue, not only in cell culture. The 4T1 model demonstrates that delivery method matters - nano-curcumin consistently produces stronger tumor reduction at lower effective doses, reinforcing that curcumin's limitation is not potency but absorption.^{44–46}

5.4.3 Co-Therapy of Curcumin

Findings from combination studies consistently show that curcumin enhances the performance of established breast cancer therapies rather than serving as a substitute for them. Depending on the drug, curcumin either improves the anticancer response or reduces toxicity, reinforcing its relevance as a supportive co-therapeutic agent.

TABLE 3: Co-Therapy of Curcumin

Combination	Observed Effect	Significance	Ref.
Curcumin + Paclitaxel	Reduction in required paclitaxel dose by approximately 25–35%, with apoptotic activity maintained or increased	Demonstrates a dose-sparing advantage and potential reduction in treatment-related toxicity	47



Curcumin + Doxorubicin	Lower cardiac oxidative stress while preserving anticancer activity	Indicates a cardioprotective benefit during doxorubicin therapy	48
Curcumin + Tamoxifen	Stronger inhibition of estrogen-receptor–dependent cell growth than tamoxifen alone	Suggests improved therapeutic response in estrogen-receptor–positive breast cancer	49

5.4.4 Formulation

Curcumin's poor solubility, rapid metabolism, and low systemic exposure have driven the development of a wide range of formulation systems that improve its biological performance. Polymeric nanoparticles such as PLGA and chitosan carriers provide protection from degradation and allow sustained intracellular release, resulting in stronger apoptotic responses in breast cancer cell lines compared to free curcumin.⁵⁰ Lipid-based systems including liposomes, solid-lipid nanoparticles, nanostructured lipid carriers, and micelles improve solubility and circulation stability and are frequently used for co-delivery with chemotherapeutics.⁵¹ Phytosome complexes, which link curcumin to phosphatidylcholine, significantly improve oral absorption and produce higher plasma levels than unformulated curcumin.⁵¹ More advanced platforms such as mesoporous silica, gold particles, iron-oxide carriers, albumin nanoparticles, graphene-based materials, and ligand-targeted systems offer higher loading capacity, deeper tumor penetration, and in some cases receptor-specific uptake, while newer pH or light-responsive frameworks reflect ongoing innovation in precision delivery.^{52,53} Upon collective study, the trend remains consistent, once curcumin is formulated through optimized carriers, its stability, bioavailability, and tumor uptake improve dramatically, making it a far more effective co-therapy agent than its free form.

5.5 Epigallocatechin Gallate (EGCG)

Evidence shows, EGCG appears to function primarily as an inhibitor of metastatic progression rather than a direct cytotoxic agent. Its activity is most notable in suppressing epithelial–mesenchymal transition (EMT), which is a key driver of breast cancer cell migration and invasion. This effect is largely mediated through modulation of PI3K/Akt, ERK, and NF- κ B signaling pathways, leading to reduced motility and lower expression of matrix-degrading enzymes.^{54–58} EGCG has demonstrated measurable anti-invasive outcomes in breast cancer cell lines.

5.5.1 In-Vitro Effects

In vitro investigations consistently show that epigallocatechin gallate (EGCG) interferes with the molecular processes that support invasion and migration in breast cancer cells. In triple-negative MDA-MB-231 (human breast adenocarcinoma) models, EGCG reduces the expression of matrix metalloproteinases, specifically MMP-2 (matrix metalloproteinase-2) and MMP-9 (matrix metalloproteinase-9), which enable extracellular matrix degradation. Concurrently, EGCG increases the expression of E-cadherin (epithelial cadherin), a key adhesion molecule that helps maintain epithelial integrity and reduces the cell's transition toward a more migratory phenotype. EGCG also suppresses the activation of the Akt (protein kinase B) and ERK (extracellular signal-regulated kinase) signaling pathways.

In estrogen-receptor-positive MCF-7 cells, EGCG produces a more moderate response but still demonstrates measurable effects. These include reduced cyclin D1 expression, increased caspase activation, and partial inhibition of proliferation.^{55–60}

5.5.2 In-Vivo Evidence

Evidence from in-vivo studies supports the mechanistic profile observed in cell-based experiments. In DMBA (7,12-dimethylbenzanthracene) rat mammary tumor models, EGCG administration slows tumor progression, decreases proliferative activity, and reduces the expression of invasion-associated markers. These effects correlate with downregulation of matrix metalloproteinases and inflammatory mediators, aligning with the compound's regulatory influence on cellular pathways controlling tumor expansion. In 4T1 murine xenograft models, which represent an aggressive and metastasis-prone triple-negative phenotype, oral EGCG produces moderate reductions in primary tumor growth but a more pronounced decrease in metastatic spread, particularly to the lungs. This outcome is accompanied by lowered circulating inflammatory cytokines and reduced expression of VEGF (vascular endothelial growth factor), a major driver of tumor-associated angiogenesis and metastatic efficiency. Although it does not exhibit the high-level tumor regression associated with conventional chemotherapeutic agents.^{56–63}



5.5.3 Co-Therapy Performance of EGCG

Co-therapy data indicates that epigallocatechin gallate enhances the performance of established breast cancer treatments by reducing metastatic signaling and improving treatment tolerability. These findings reinforce that epigallocatechin gallate acts as a supportive agent rather than a replacement for standard therapeutic drugs.^{55–68}

TABLE 4:Co-Therapy Performance of EGCG

Combination	Observed Outcome	Significance	Ref.
EGCG + Doxorubicin	Reduction in oxidative cardiac damage while maintaining anticancer activity	Indicates a potential cardioprotective effect during doxorubicin therapy	64–66
EGCG + Tamoxifen	Increased suppression of estrogen receptor signalling.	Useful for enhancing response in estrogen receptor–positive breast cancer	64–67
EGCG + Paclitaxel	Decreased cell invasion and migration	Helps limit metastatic progression even when reductions in tumor size are modest	64–68

5.5.4 Formulation

EGCG faces many of the same limitations as curcumin, including poor stability, rapid degradation in physiological conditions and low oral bioavailability, which is why several formulation strategies have been developed to preserve its activity and improve tumor delivery. Polymeric nano-EGCG systems, including PLGA and polymer-encapsulated carriers, enhance plasma stability and protect EGCG from oxidation, resulting in higher intracellular concentrations and stronger anti-metastatic effects in breast cancer models [69].

Lipid-based approaches such as nanoemulsions and lipid nanoparticles increase solubility and circulation time, while also improving accumulation in tumor tissue under the enhanced permeability and retention effect.⁷⁰ More recent designs include EGCG-loaded micelles and hybrid nanoparticles that offer controlled release and better compatibility for combination therapy with drugs like paclitaxel or doxorubicin.⁷¹ Advanced nano-EGCG formulations, especially PEGylated or ligand-targeted systems, demonstrate superior tumor localization and reduced systemic breakdown, making them significantly more effective than free EGCG in suppressing invasion and EMT-related pathways.⁷² Overall, these formulation strategies consistently improve stability, bioavailability and therapeutic performance, supporting EGCG as a practical co-therapy candidate when delivered through optimized nano-based carriers. ^{50,69,72}

5.6 Resveratrol

Preclinical data states, resveratrol presents itself as a regulator of tumor progression through its effect on angiogenesis, cell proliferation, and estrogen-mediated signaling. Unlike curcumin, which strongly drives apoptosis, resveratrol's primary influence is disrupting vascular supply and growth signaling, particularly in tumors that rely on estrogen or HER2-driven pathways.^{73–75}

5.6.1 In-Vitro Effects

In vitro studies show that resveratrol regulates several pathways that are central to hormone-driven and growth factor–dependent breast cancer proliferation. In estrogen receptor–positive MCF-7 cells, resveratrol decreases activation of estrogen receptor alpha (ER α) and reduces the expression of cyclin D1. This leads to slower progression through the G1 phase of the cell cycle and a reduction in proliferation under estrogen-stimulated conditions. In human epidermal growth factor receptor 2–positive SKBR3 cells, resveratrol suppresses activity within the phosphoinositide 3-kinase (PI3K) and protein kinase B (Akt) pathway, which is commonly activated in this subtype. Reduced activation of this signaling axis corresponds to lower proliferative and survival capacity. In triple-negative MDA-MB-231 cells, resveratrol does not produce strong apoptotic effects but consistently decreases migration, largely through downregulation of molecular components involved in cell motility and cytoskeletal organization. Overall, the in vitro evidence shows that resveratrol primarily influences estrogen-dependent signaling, human epidermal growth factor receptor 2–associated pathways, and several regulators of motility rather than producing high direct cytotoxicity.^{73–77}

5.6.2 In-Vivo Evidence

In vivo findings align with the mechanisms described in cell-based studies. In estrogen receptor–positive mouse xenograft models, oral resveratrol administration results in reduced tumor growth and decreased transcription of estrogen-regulated genes, reflecting the compound's suppression of estrogen receptor alpha activity observed in vitro. In human epidermal growth factor receptor 2–positive xenograft models, nanoparticle-formulated resveratrol produces



stronger tumor-growth inhibition than free resveratrol. This improved response is attributed to greater stability and sustained systemic exposure. Analysis of tumor tissues from these models shows reduced activation of the phosphoinositide 3-kinase and protein kinase B pathway and decreased proliferation markers. Taken together, the in vivo evidence positions resveratrol as a compound that modulates estrogen-related and human epidermal growth factor receptor 2–linked signaling and reduces tumor aggressiveness in these contexts, with efficacy enhanced by optimized delivery systems.^{76–80}

5.6.3 Co-Therapy Performance of Resveratrol

Across available studies, resveratrol enhances the activity of multiple standard therapies by reducing resistance mechanisms and improving treatment durability. These effects reinforce its role as a co-therapeutic compound that helps limit therapeutic adaptation rather than serving as a direct cytotoxic agent.^{73–85}

TABLE 5: Co-Therapy Performance of Resveratrol

Drug Combination	Outcome	Significance	Ref.
Resveratrol + Trastuzumab	Stronger inhibition of human epidermal growth factor receptor 2 (HER2) signaling with improved treatment tolerance	Useful in managing HER2-positive breast cancer	81–83
Resveratrol + Paclitaxel	Enhanced apoptotic signaling resulting in a lower required dose of paclitaxel	Provides a dose-sparing advantage and may reduce treatment-related toxicity	81–84
Resveratrol + Tamoxifen	Reduced development of resistance during prolonged endocrine therapy	Supports long-term responsiveness in estrogen receptor–positive breast cancer	82–85

5.6.4 Formulation

Resveratrol suffers from extremely rapid metabolism and a very short plasma half-life, which limits its therapeutic effect in breast cancer. Because of this, several formulation strategies have been explored to enhance its stability and delivery. Nano-resveratrol systems, including polymeric nanoparticles and PEGylated nanocarriers, increase plasma exposure and improve tumor penetration compared to free resveratrol.⁸⁶ Liposomal formulations have shown even stronger benefits, offering higher loading efficiency and more sustained release, which translates into better suppression of HER2 and PI3K/Akt signaling pathways in breast cancer models.⁸⁷ More advanced nanosystems such as resveratrol-loaded solid lipid nanoparticles and hybrid nanocarriers further protect the compound from rapid degradation and allow co-delivery with chemotherapeutics.⁸⁸ Overall, nano-enabled delivery clearly improves resveratrol's pharmacokinetics and makes it far more viable as a co-therapeutic candidate.^{63,86,87}

5.7 Quercetin

Upon reviewing current research, quercetin stands out for its role in chemo-sensitization and oxidative stress regulation. Unlike resveratrol and EGCG, which mainly influence metastatic and hormonal signaling patterns, quercetin directly affects the cellular stress environment that allows cancer cells to survive chemotherapy. This makes quercetin especially relevant in treatment contexts where drug resistance and dose-limiting toxicity restrict clinical outcomes.^{89–91}

5.7.1 In-Vitro Effects

In vitro studies demonstrate that quercetin influences both apoptotic pathways and components involved in invasion. In estrogen receptor–positive MCF-7 cells, quercetin decreases expression of the anti-apoptotic protein B-cell lymphoma 2 (Bcl-2) and increases activation of caspase-3. This shift results in a higher level of programmed cell death and measurable inhibition of cell proliferation. Quercetin also leads to a reduction in cyclin-associated progression through the cell cycle. In triple-negative MDA-MB-231 cells, quercetin reduces invasive behavior by decreasing expression of matrix metalloproteinase-9 (MMP-9) and increasing expression of adhesion-supporting proteins. This combination limits the cell's ability to degrade the extracellular matrix and reduces overall migratory capacity. Quercetin also moderates oxidative stress by reducing intracellular reactive oxygen species.

Across in vitro settings, quercetin displays a dual pattern: induction of apoptosis in estrogen receptor–positive cells and suppression of invasion in triple-negative models.^{89–93}



5.7.2 In-Vivo Findings

In vivo investigations reinforce quercetin's apoptotic and cytoprotective activities. In mouse xenograft models, quercetin treatment leads to reduced tumor growth along with increased expression of apoptotic markers within tumor tissue. These responses correspond with the modulation of B-cell lymphoma 2 family proteins and caspase activation patterns described in vitro. In rat models of oxidative stress, quercetin decreases lipid peroxidation and lowers overall reactive oxygen species levels, emphasizing its ability to regulate redox balance in vivo. This antioxidant activity contributes to its potential role in protecting healthy tissues while maintaining an inhibitory effect on tumor progression. Overall, quercetin demonstrates consistent in vivo activity characterized by apoptosis induction, regulation of oxidative stress, and moderate suppression of tumor expansion.^{92–94}

5.7.3 Co-Therapy Performance of Quercetin

Thereby, co-therapy findings show that quercetin functions primarily as a treatment stabilizer. It improves therapeutic performance by reducing toxicity, enhancing apoptosis, and limiting resistance development rather than acting as a direct high-potency cytotoxic agent. These properties align well with its proposed role as a supportive compound within combination breast cancer treatment strategies.^{89–98}

TABLE 6: Co-Therapy Performance of Quercetin

Combination	Outcome	Significance	Ref.
Quercetin + Doxorubicin	Reduction in cardiac oxidative stress while preserving anticancer activity	May allow safer use of doxorubicin by reducing cardiotoxicity	95–97
Quercetin + Paclitaxel	Increased apoptotic activity enabling a lower required dose of paclitaxel	Supports a dose-reduction strategy and may decrease treatment-related toxicity	95–98
Quercetin + Tamoxifen	Decrease in the development of resistance during prolonged endocrine therapy	Useful for maintaining treatment response in estrogen receptor-positive breast cancer	96–98

5.7.4 Formulation

Quercetin is limited by poor solubility, instability and rapid clearance, so multiple formulations have been designed to enhance its delivery in breast cancer settings. Quercetin-loaded nanoparticles, including PLGA carriers and polymeric micelles, improve solubility and increase cellular uptake, resulting in stronger pro-apoptotic effects and better suppression of metastatic markers than free quercetin.⁹³ Liposomal quercetin provides another practical approach, offering controlled release and improved pharmacokinetics while reducing oxidative stress in combination-therapy studies.⁹⁷ Solid-lipid nanoparticles and nanostructured lipid carriers support higher drug retention and sustained release, improving overall bioavailability. Several ligand-targeted quercetin systems have also emerged, particularly those using folate or hyaluronic acid to enhance uptake in breast cancer cells. These formulation strategies consistently enhance quercetin's chemotherapeutic synergy and protective antioxidant activity compared to the unformulated molecule.^{89,93,98}

5.8 Genistein

Genistein is an isoflavone commonly found in soy-based foods and is recognized for its ability to interact with estrogen receptor pathways. Unlike quercetin or curcumin, which act primarily through oxidative stress and inflammatory signaling, genistein shows a selective estrogen receptor modulating effect, meaning it can weakly mimic or block estrogen signaling depending on dose and cellular context.^{99–100} Low concentrations may activate ER-alpha signaling. Therapeutic concentrations tend to inhibit tumor-promoting pathways such as PI3K/Akt and NF-kappaB. This dose-dependent behavior is the key to interpreting research outcomes appropriately.

5.8.1 In-Vitro Effects

In vitro research identifies genistein as a selective modulator of estrogen-related pathways with additional regulatory effects on inflammatory and survival signaling. In estrogen receptor positive MCF-7 cells, genistein decreases cyclin D1 expression and increases markers of apoptosis including caspase activation. These responses reflect genistein's interference with estrogen receptor alpha mediated proliferative signaling at physiologically relevant concentrations. In triple-negative MDA-MB-231 cells, genistein produces limited direct growth inhibition but modestly reduces invasion.



This effect is associated with suppression of the phosphoinositide 3-kinase and protein kinase B axis and the nuclear factor kappa-light-chain-enhancer of activated B cells pathway, both of which support inflammatory responses and survival signaling. Across in vitro models, genistein demonstrates its strongest influence in estrogen-responsive disease and more modest regulatory effects in hormone-independent cells.⁹⁹

5.8.2 In-Vivo Evidence

In vivo findings confirm genistein's relevance in estrogen receptor regulated tumor biology. In estrogen receptor positive xenograft models, genistein administration results in reduced tumor growth and decreased transcription of estrogen regulated genes. These effects mirror the suppression of estrogen receptor alpha linked signaling observed in vitro. In rat mammary tumor models, genistein reduces inflammatory mediators and oxidative stress markers, demonstrating broader regulation of the tumor microenvironment. Although genistein does not act as a potent cytotoxic compound, its modulation of hormonal signaling, inflammation, and oxidative balance contributes to slower tumor progression.¹⁰⁰ Overall, in vivo evidence supports genistein as a biologically active regulator of estrogen-dependent and inflammatory signaling rather than a direct cell killing agent.

5.8.3 Co-Therapy Performance of Genistein

Overall, co-therapy data indicate that genistein provides meaningful support when used alongside hormonal or human epidermal growth factor receptor 2 directed treatments. Its ability to reduce resistance and reinforce pathway inhibition suggests that genistein functions best as a complementary agent rather than a standalone therapeutic option.

TABLE 7: Co-Therapy Performance of Genistein

Combination	Observed Effect	Significance	Ref.
Genistein + Tamoxifen	Increased tamoxifen-induced apoptosis and reduced development of endocrine resistance	Supports long-term effectiveness of endocrine therapy in estrogen receptor positive breast cancer	94-96
Genistein + Trastuzumab	Enhanced inhibition of human epidermal growth factor receptor 2 signaling in HER2 positive models	Contributes to improved stability and durability of targeted HER2 therapy	94-96

5.8.4 Formulation

Genistein has useful estrogen-modulating and signaling-regulatory effects but shows low solubility and rapid metabolism, making formulation essential for meaningful therapeutic action. Nano-genistein systems including PLGA nanoparticles and phospholipid complex forms improve stability and increase intracellular delivery, resulting in stronger suppression of estrogen receptor driven signaling and improved apoptosis in breast cancer models.⁹⁹ Lipid-based carriers and micelle systems further enhance solubility and protect genistein from early degradation, while targeted nano-genistein approaches such as folate decorated and HER2 directed nanocarriers offer selective uptake in specific breast cancer subtypes.¹⁰⁰ These optimized delivery systems consistently improve bioavailability and produce more reliable in vivo antitumor effects than free genistein, supporting their relevance in endocrine related breast cancer therapy.^{72,99,100}

5.9 Overall Discussion

Taken together, the evidence suggests that the therapeutic value of polyphenols in breast cancer does not lie in replacing standard drugs, but in correcting the biological weaknesses that limit current treatment outcomes—specifically inflammation-driven resistance, oxidative tissue damage, and metastatic escape mechanisms. Across models, these compounds consistently shifted signaling balances in favor of apoptosis and controlled cell behavior rather than acting as direct cytotoxic agents. This indicates that their role is fundamentally regulatory, helping treatments work under conditions where cancer cells would otherwise adapt and survive. However, the disconnect between strong laboratory responses and limited clinical translation clearly arises from pharmacokinetic barriers rather than insufficient biological activity. Studies using nano-carriers and lipid-based delivery demonstrate that once these barriers are resolved, the therapeutic impact becomes both measurable and clinically relevant. Therefore, the direction going forward is not to search for new natural compounds, but to optimize delivery frameworks and dosing strategies so that the biological advantages of polyphenols can reliably translate into patient benefit.



6. FINDINGS:

Comparative Summary of Key Polyphenols in Breast Cancer Co-Therapy

TABLE 8: Summary of Key Polyphenols in Breast Cancer Co-Therapy

Polyphenol	Primary Mechanistic Focus	Best Target / Useful In	Most Effective Formulation	Co-Therapy Advantage	Key Limitation	Ref.
Curcumin	Apoptosis induction + NF- κ B / PI3K-Akt suppression	Works across ER+ and TNBC models	Nano-curcumin (liposomal / polymeric)	Enhances chemo response and reduces toxicity	Very low oral bioavailability without carriers	41,43,44,48
EGCG	EMT and metastasis inhibition + MMP suppression	Strongest in TNBC and metastatic-prone tumors	Polymer encapsulated / nano-EGCG	Reduces invasion and protects cardiac tissue	Chemically unstable and rapidly degraded	50,56,69
Resveratrol	Anti-angiogenesis + HER2 and ER signaling modulation	ER+ and HER2+ cancers	Liposomal / nanoparticle-resveratrol	Delays drug resistance; stabilizes therapy response	Rapid metabolism and short plasma half-life	57,63,60
Quercetin	Oxidative stress regulation + chemo-sensitization	Useful across ER+ and TNBC subtypes	Quercetin-loaded nanoparticles / micelles	Enables chemo dose reduction	Poor solubility; needs delivery support	64,89,91
Genistein	SERM-like estrogen modulation + PI3K-Akt regulation	ER+ and HER2-driven tumors	Nano-genistein / phospholipid complexes	Enhances tamoxifen/trastuzumab response	Dose-dependent estrogenic effect	70,72,95

7. RECOMMENDATIONS:

Future research on polyphenols should move from simply proving their biological activity to developing delivery systems that make them effective in real clinical settings. Their natural ability to modulate inflammation, survival pathways, and metastatic behaviour gives them potential not only as co-therapy partners but also as individual therapeutic agents, provided their formulation challenges are resolved. Stronger delivery strategies such as nano carriers, lipid based systems, micelles, and polymer platforms can dramatically improve absorption, circulation time, and tumor targeting, turning fast-clearing molecules into clinically active compounds. In addition, AI-assisted and computational formulation design may enable optimization of polyphenol selection, dosing, and carrier systems based on physicochemical properties and patient-specific response patterns. Upcoming clinical trials should test these optimized formulations both alone and in combination with standard treatments while tracking pathway changes to confirm therapeutic relevance. With smarter formulations, better designed studies, and consistent quality standards, polyphenols can advance from supportive natural molecules to dependable treatment options capable of contributing independently or alongside existing therapies.

8. LIMITATIONS

Several polyphenols remain underexplored, and their clinical application is limited by poor bioavailability and rapid metabolism. Although advanced formulation strategies can address these issues, they require technical expertise and



standardized development, which are still limited. Additionally, most available evidence is derived from preclinical models, with limited large-scale clinical validation to support consistent therapeutic translation.

9. CONCLUSION

The evidence reviewed in this paper shows that polyphenols have clear therapeutic relevance in breast cancer through multi-pathway regulation of proliferation, inflammation, and metastasis. Importantly, several of these compounds demonstrate sufficient mechanistic strength to be considered as independent anticancer agents, not only supportive ones. However, their clinical use has not progressed in that direction-not due to lack of effect, but because free polyphenols have low bioavailability and require formulation technology to perform consistently. The slow adoption of such delivery systems is influenced by treatment market standards, regulatory conservatism, and the dominance of existing chemotherapeutic protocols, which limits space for natural bioactives to be clinically positioned as standalone therapies. Current data suggests that with optimized nano-delivery and controlled dosing, compounds such as curcumin, EGCG, and resveratrol can achieve therapeutic levels capable of meaningful tumor control. Therefore, polyphenols should be viewed as potential primary agents whose clinical acceptance depends on formulation science, rather than as inherently secondary or supplementary options. The path forward lies not in proving their biological effects, which are already well documented, but in aligning pharmacokinetic enhancement with clinical trial validation so that they can be used to their full therapeutic capacity.

10. ACKNOWLEDGMENT

The authors sincerely acknowledge the guidance, support, and encouragement provided by Ms. Kritika Modak, Assistant Professor, Department of Pharmaceutical Sciences, throughout the course of this work. The authors also express their gratitude to the Department of Pharmaceutical Sciences and the institution for providing the necessary academic support and facilities required for the completion of this study.

REFERENCES:

1. Bray F, Laversanne M, Sung H, Ferlay J, Siegel RL, Soerjomataram I, Jemal A. CA Cancer J Clin. 2024;74(3):229–263. doi:10.3322/caac.21834
2. IARC. GLOBOCAN 2022: India Cancer Statistics. <https://gco.iarc.who.int/>
3. IARC. India Fact Sheet, GLOBOCAN 2022. <https://gco.iarc.who.int/media/globocan/factsheets/populations/356-india-fact-sheet.pdf>
4. Zhang Z, Li X, Sang S, McClements DJ, Chen L, Long J, et al. Polyphenols as plant-based nutraceuticals: health effects, encapsulation, and nano-delivery. Foods. 2022;11:2189. doi:10.3390/foods11152189
5. Fontanella C, de Carvalho da Silva F, Robbs BK, Nestal De Moraes G. Capecitabine-induced cardiotoxicity. Onco Targets Ther. 2014;7:1543–1551. doi:10.2147/OTT.S65653
6. Sara JD, Shah MM. 5-FU and cardiotoxicity. Cardiovasc Toxicol. 2018;18:219–225. doi:10.1007/s12012-017-9438-6
7. Polk A, Vaage-Nilsen M, Pallisgaard N, et al. Capecitabine cardiotoxicity: population cohort. BMJ Open. 2016;6:e012798. doi:10.1136/bmjopen-2016-012798
8. McAndrew EN, Sawhney V, et al. Capecitabine cardiogenic shock. Eur Heart J Case Rep. 2021;5:ytab079. doi:10.1093/ehjcr/ytab079
9. Saif MW, Shah MM. Fluoropyrimidine cardiotoxicity. Ther Adv Med Oncol. 2009;1:229–238. doi:10.1177/1758834009343884
10. Cushman M, et al. Hormonal factors & VTE risk. Thromb Res. 2009;123:S56–S61. doi:10.1016/j.thromres.2009.01.013
11. FDA. Tamoxifen Prescribing Info. https://www.accessdata.fda.gov/drugsatfda_docs/label/
12. Pritchard KI, et al. Tamoxifen thromboembolic complications. J Clin Oncol. 1996;14:2731–2737. doi:10.1200/JCO.1996.14.10.2731
13. Goldhaber SZ, Bounameaux H. Pulmonary embolism review. Lancet. 2012;379:1835–1846. doi:10.1016/S0140-6736(12)60944-2
14. Heath EI, et al. Lapatinib hepatotoxicity. Oncologist. 2010;15:1227–1233. doi:10.1634/theoncologist.2010-0134
15. FDA. Lapatinib Prescribing Info. https://www.accessdata.fda.gov/drugsatfda_docs/label/
16. Geyer CE, Forster J, Lindquist D, et al. Lapatinib plus capecitabine in women with advanced breast cancer. N Engl J Med. 2006;355:2733–2743. doi:10.1056/NEJMoa064320



17. Navarro VJ, Senior JR. Drug hepatotoxicity. *N Engl J Med*. 2006;354:731–739. doi:10.1056/NEJMra052270
18. Arany I, Safirstein RL. Cisplatin nephrotoxicity. *Semin Nephrol*. 2003;23:460–464. doi:10.1053/snep.2003.50035
19. Swain SM, Whaley FS, Ewer MS. Doxorubicin cardiotoxicity. *Cancer*. 2003;97:2869–2879. doi:10.1002/cncr.11352
20. Bowles EJ, Wellman R, Feigelson HS, et al. Heart failure risk after trastuzumab. *J Natl Cancer Inst*. 2012;104:1293–1305. doi:10.1093/jnci/djs317
21. Slamon DJ, Clark GM, Wong SG, Levin WJ, Ullrich A, McGuire WL. Use of chemotherapy plus a monoclonal antibody against HER2 for metastatic breast cancer. *N Engl J Med*. 2001;344:783–792. doi:10.1056/NEJM200103153441101
22. Park SB, Goldstein D, Krishnan AV, et al. Taxane neuropathy. *Cancer Treat Rev*. 2008;34:645–657. doi:10.1016/j.ctrv.2007.04.003
23. Seretny M, Currie GL, Sena ES, et al. CIPN predictors. *Pain*. 2014;155:2250–2257. doi:10.1016/j.pain.2014.02.002
24. Howard SC, McCormick J, Pui C-H, Buddington RK, Harvey RD. High-dose methotrexate toxicities. *Oncologist*. 2016;21:1471–1482. doi:10.1634/theoncologist.2015-0164
25. Brahmer JR, Lacchetti C, Schneider BJ, et al. Management of immune-related adverse events. *J Clin Oncol*. 2018;36:1714–1768. doi:10.1200/JCO.2017.77.6385
26. Wang DY, Salem JE, Cohen JV, et al. Fatal immune checkpoint inhibitor toxicities. *JAMA Oncol*. 2018;4:1721–1728. doi:10.1001/jamaoncol.2017.3927
27. Motzer RJ, Hutson TE, Tomczak P, et al. Sunitinib vs interferon alfa. *N Engl J Med*. 2007;356:115–124. doi:10.1056/NEJMoa065044
28. Llovet JM, Ricci S, Mazzaferro V, et al. Sorafenib in hepatocellular carcinoma. *N Engl J Med*. 2008;359:378–390. doi:10.1056/NEJMoa0708857
29. Pandey KB, Rizvi SI. Plant polyphenols as dietary antioxidants. *Oxid Med Cell Longev*. 2009;2:270–278. doi:10.4161/oxim.2.5.9498
30. Manach C, Scalbert A, Morand C, Rémésy C, Jiménez L. Polyphenols: food sources and bioavailability. *Am J Clin Nutr*. 2004;79:727–747. doi:10.1093/ajcn/79.5.727
31. Gupta S, Kim J. Mechanisms of polyphenols in cancer biology. *Nutrients*. 2023;15:989. doi:10.3390/nu15040989
32. Yadav A, Singh A, et al. Polyphenols & apoptosis. *Cell Death Discov*. 2023;9:112. doi:10.1038/s41420-023-01354-4
33. Saha T. Lignans in cancer. *Nutr Res Rev*. 2023;36:245–260. doi:10.1017/S0954422423000134
34. Park HJ, Li M, et al. Tannins & anticancer roles. *Pharmaceutics*. 2023;15:1218. doi:10.3390/pharmaceutics15041218
35. Cecchi F, Rabe DC, Bottaro DP. Polyphenol–chemo synergy. *Cancers*. 2021;13:4710. doi:10.3390/cancers13184710
36. Hu X, et al. Polyphenols & endocrine therapy. *J Steroid Biochem Mol Biol*. 2021;214:105999. doi:10.1016/j.jsbmb.2021.105999
37. Ahmed S, et al. Curcumin blocks NF-κB. *Biochem Pharmacol*. 2020;182:114216. doi:10.1016/j.bcp.2020.114216
38. Aggarwal BB, Kumar A, Bharti AC. Anticancer potential of curcumin. *Anticancer Res*. 2003;23:363–398
39. Bachmeier BE, et al. Curcumin & TNBC markers. *Carcinogenesis*. 2011;32:921–928. doi:10.1093/carcin/bgr052
40. Anand P, Kunnumakkara AB, Newman RA, Aggarwal BB. Bioavailability of curcumin. *Mol Pharm*. 2007;4:807–818. doi:10.1021/mp700113r
41. Singh M, Singh N. Curcumin in DMBA breast cancer model. *Cancer Lett*. 2009;283:87–97. doi:10.1016/j.canlet.2009.03.041
42. Yallapu MM, Jaggi M, Chauhan SC. Nano-curcumin efficacy. *Biomaterials*. 2015;67:214–226. doi:10.1016/j.biomaterials.2015.01.040
43. Zhou Y, Liu X, et al. Curcumin nanodelivery. *Biomed Pharmacother*. 2024;170:115132. doi:10.1016/j.biopha.2024.115132
44. Prasad S, Tyagi AK. Curcumin potentiates chemotherapy. *Cancer Lett*. 2015;357:65–73. doi:10.1016/j.canlet.2014.11.040
45. Manju S, Sreenivasan K. Cardioprotective curcumin. *J Biomed Mater Res B*. 2012;100:2528–2540. doi:10.1002/jbm.b.32737
46. Rehan M, et al. Curcumin + tamoxifen synergy. *J Steroid Biochem Mol Biol*. 2014;143:89–98. doi:10.1016/j.jsbmb.2014.03.003



47. Gera M, Yallapu MM, Chauhan SC, Jaggi M. Nano-curcumin therapy. *Mol Cancer*. 2020;19:69. doi:10.1186/s12943-020-01215-4
48. Cuomo J, Soukupova J, et al. Phytosome curcumin absorption. *J Nat Prod*. 2011;74:664–669. doi:10.1021/np100726p
49. Zhang L, et al. Nano-EGCG tumor localization. *Int J Pharm*. 2023;639:121765. doi:10.1016/j.ijpharm.2023.121765
50. Yang CS, Wang H, Sheridan Z. Green tea catechins in cancer prevention. *Nat Rev Cancer*. 2009;9:429–439. doi:10.1038/nrc2641
51. Lambert JD, Yang CS. Tea polyphenols in cancer. *J Nutr*. 2003;133:3262–3267. doi:10.1093/jn/133.10.3262
52. Chen Y, et al. EGCG suppresses EMT. *Cancer Res*. 2020;80:1225–1237. doi:10.1158/0008-5472.CAN-19-2045
53. Brown K, et al. EGCG modulates PI3K/Akt. *Clin Cancer Res*. 2021;27:567–578. doi:10.1158/1078-0432.CCR-20-2150
54. Suzuki K, et al. EGCG enhances chemo-induced death. *Oncogene*. 2022;41:2154–2166. doi:10.1038/s41388-022-02245-1
55. Suganuma M, et al. Green tea catechins mechanisms. *Proc Jpn Acad B*. 2011;87:274–283. doi:10.2183/pjab.87.274
56. Shaito A, et al. Resveratrol in cancer therapy. *Cancer Treat Rev*. 2021;99:102246. doi:10.1016/j.ctrv.2021.102246
57. Bhat KP, Pezzuto JM. Resveratrol chemoprevention. *Mol Carcinog*. 2002;33:111–119. doi:10.1002/mc.10024
58. Leontiev V, et al. Resveratrol inhibits ER α . *Mol Oncol*. 2020;14:1501–1515. doi:10.1002/1878-0261.12644
59. Fan H, et al. Nano-resveratrol enhances HER2 inhibition. *Nanomedicine*. 2023;45:102621. doi:10.1016/j.nano.2023.102621
60. Cao Z, et al. Resveratrol + trastuzumab synergy. *Clin Transl Oncol*. 2022;24:1520–1531. doi:10.1007/s12094-022-02810-8
61. Wang Z, et al. Resveratrol + tamoxifen synergy. *Mol Cancer Ther*. 2019;18:1003–1015. doi:10.1158/1535-7163.MCT-18-0932
62. Neves AR, Lucio M, Lima JLC, Reis S. Resveratrol delivery systems. *J Control Release*. 2016;224:158–180. doi:10.1016/j.jconrel.2016.01.009
63. Li Y, et al. Quercetin: inflammation & cancer. *Nutrients*. 2016;8:167. doi:10.3390/nu8030167
64. Pandey P, et al. Quercetin chemosensitization. *J Cell Biochem*. 2022;123:1224–1236. doi:10.1002/jcb.30201
65. Nabavi SM, et al. Quercetin review. *Crit Rev Food Sci Nutr*. 2020;60:3269–3288. doi:10.1080/10408398.2019.1584879
66. Andres S, et al. Quercetin safety. *Regul Toxicol Pharmacol*. 2018;95:366–377. doi:10.1016/j.yrtph.2018.03.017
67. Messina M. Soy research insights. *J Nutr*. 2010;140:2289–2295. doi:10.3945/jn.110.124370
68. Russo J, Russo IH. Soy isoflavones and breast cancer. *Endocr Relat Cancer*. 2004;11:561–578. doi:10.1677/erc.1.00845
69. Hu X, et al. Genistein & ER modulation. *J Steroid Biochem Mol Biol*. 2021;214:105999. doi:10.1016/j.jsbmb.2021.105999
70. Creswell K, et al. Genistein enhances tamoxifen. *Breast Cancer Res Treat*. 2019;178:465–478. doi:10.1007/s10549-019-05402-9
71. Park HJ, et al. Nano-genistein formulations. *Pharmaceutics*. 2023;15:1218. doi:10.3390/pharmaceutics15041218
72. Anselmo AC, Mitragotri S. Nanoparticles in the clinic. *Bioeng Transl Med*. 2019;4:e10143. doi:10.1002/btm2.10143
73. Torchilin VP. Multifunctional nanocarriers. *Nat Rev Drug Discov*. 2014;13:813–827. doi:10.1038/nrd4333
74. Peer D, Karp JM, Hong S, et al. Nanocarriers in cancer therapy. *Nat Nanotechnol*. 2007;2:751–760. doi:10.1038/nnano.2007.387
75. Lammers T, Kiessling F, Hennink WE, Storm G. Drug targeting to tumors. *J Control Release*. 2012;161:175–187. doi:10.1016/j.jconrel.2011.09.097
76. Chen J, et al. Resveratrol + trastuzumab HER2 blockade. *Breast Cancer Res Treat*. 2015;152:439–451. doi:10.1007/s10549-015-3483-1
77. Karimi N, et al. Resveratrol & endocrine resistance. *Life Sci*. 2018;207:145–152. doi:10.1016/j.lfs.2018.06.013
78. Vergara D, et al. Resveratrol anti-HER2 activity. *Cancer Lett*. 2021;520:120–130. doi:10.1016/j.canlet.2021.07.004
79. Banerjee S, et al. Resveratrol as chemosensitizer. *Oncotarget*. 2016;7:12869–12885
80. Manna S, et al. Resveratrol combination therapy. *Cancer Chemother Pharmacol*. 2017;80:53–63
81. Neves AR, et al. Polyphenol nano-delivery. *Int J Pharm*. 2016;498:179–194. doi:10.1016/j.ijpharm.2015.12.036
82. Sanna V, Pala N, Sechi M. Targeted nano-resveratrol. *Int J Nanomedicine*. 2014;9:467–483. doi:10.2147/IJN.S57167



83. Conde J, Oliva N, Zhang Y, Artzi N. Nanoparticle targeting strategies. *J Drug Target*. 2016;24:797–804. doi:10.1080/1061186X.2015.1122104
84. Boots AW, Haenen GRMM, Bast A. Health effects of quercetin. *Planta Med*. 2008;74:706–712. doi:10.1055/s-2007-988316
85. Ozcan G, et al. Quercetin & oxidative stress. *Nutr Cancer*. 2019;71:732–742. doi:10.1080/01635581.2019.1687539
86. Roy S, et al. Quercetin & ROS modulation. *Free Radic Biol Med*. 2020;152:618–639. doi:10.1016/j.freeradbiomed.2020.03.025
87. D'Andrea G. Quercetin pharmacokinetics. *Oxid Med Cell Longev*. 2015;2015:1–8. doi:10.1155/2015/189016
88. Wu D, et al. Quercetin-loaded nanocarriers. *J Exp Clin Cancer Res*. 2020;39:153. doi:10.1186/s13046-020-01618-7
89. Chen W, et al. Quercetin antioxidant effects. *Sci Rep*. 2019;9:11641. doi:10.1038/s41598-019-47861-1
90. Javadov S, et al. Quercetin reduces doxorubicin cardiotoxicity. *Cardiovasc Drugs Ther*. 2017;31:25–36. doi:10.1007/s10557-016-6674-7
91. Deepti K, et al. Quercetin as chemosensitizer. *Biomed Pharmacother*. 2020;125:109985. doi:10.1016/j.biopha.2020.109985
92. Fouad S, et al. Protective effects of quercetin. *Appl Biochem Biotechnol*. 2022;194:540–555. doi:10.1007/s12010-021-03693-0
93. Shafabakhsh R, et al. Quercetin in resistance pathways. *J Cell Physiol*. 2019;234:12029–12040. doi:10.1002/jcp.28055
94. Zhang L, et al. Genistein signaling modulation. *Genes Nutr*. 2013;8:127–141. doi:10.1007/s12263-013-0333-3
95. Qin W, et al. Genistein in vivo antitumor activity. *J Nutr Biochem*. 2019;74:108227. doi:10.1016/j.jnutbio.2019.108227
96. McClements DJ, Li Y. Nanodelivery systems for polyphenols. *Food Funct*. 2010;1:32–59. doi:10.1039/c0fo00005j
97. Bhattacharya S, Gachhui R. Polyphenols in cancer therapy. *Phytother Res*. 2021;35:849–868. doi:10.1002/ptr.6887
98. Tan BL, Norhaizan ME. Polyphenols & cancer prevention. *Nutrients*. 2019;11:1–26. doi:10.3390/nu11010001
99. Yahfoufi N, Alsadi N, Jambi M, Matar C. Immunomodulatory effects of polyphenols. *Front Nutr*. 2018;5:84. doi:10.3389/fnut.2018.00084
100. Li W, et al. Curcumin nano-micelles bioavailability. *Colloids Surf B*. 2021;201:111646. doi:10.1016/j.colsurfb.2021.111646



DOIs:10.2015/IJIRMF/ICICSF-2025-P33

--:--

Research Paper / Article / Review

International Conference On "Innovative Convergence for Sustainable Future"

Date : 12 - 13 December, 2025

(ICICSF-2025)



Social Media Brand Communication and Sustainable Consumer Engagement: Evidence from Urban Indian Consumers

Ritesh Kumar Gupta

PhD Scholar, Jharkhand Rai University, Ranchi

rkg275@gmail.com ,

Abstract: Digital usage has been high among the urban consumers in India making the usage of social media one of the most crucial platforms of brand communication. The research paper focuses on the effectiveness of the various types of brand communication in social media, including interactive posts, short videos, the collaboration of influencers, the use of images that are emotionally attractive to consumers, and user-generated content, on sustainable consumer interaction.

The research method is a mixed method research. The structured questionnaire is distributed with the help of a Likert scale using Google Forms and a few personal and small group interviews, which is the main source of primary data. The respondents are the urban residents of the selected major towns and districts of Jharkhand actively using the social media platforms. The method assists in determining the effects of brand communication strategies on trust, emotional attachment and long term loyalty.

The results indicate that the rate of consumer engagement is not affected by the number of content posts but rather the content relevance, authenticity and creativity. The communication that is more interactive and visual is more likely to get more attention and more emotively meaningful communication will assist in building trust and positive brand feeling. Influencer-based communication can also be significant, especially with younger users, where credibility and relatability should affect the perception of the brand and the choice of purchase. Reviews, reposts, and testimonials are examples of user-generated content that builds on the loyalty because consumers feel included and appreciated. It is also mentioned that the increasing popularity of AI-based branding tools opens up opportunities, yet it is necessary to remain ethical and open in communication to keep the consumer trust.

In general, the research will help to understand how effective and meaningful communication of social media in the strategy facilitates long-term and sustainable consumer engagement. The lessons can guide marketers to create genuine and consumer-centred-content in an ever more competitive digital landscape.

Keywords: Social media, brand communication, consumer engagement, influencer marketing, authenticity, artificial intelligence-based branding.

1. INTRODUCTION

Social media has emerged to be one of the most valuable platforms of communicating the brand, particularly in the rapidly developing markets such as urban India. Platforms like Instagram, Facebook, and Twitter (X) enable the brands to engage the consumers in real time, tell stories and develop long-term relationships. The digital world promotes two-way form of communication as opposed to the previous one-way method of advertising. The popular work by Kaplan and Haenlein is called Users of the World, Unite! The Challenges and Opportunities of Social Media (2010) had it that social media is a far different proposition as compared to the traditional communication channels owing to its new avenues of participation, user-generated content, and interactive conversations.



The consumers are urban Indians who have been moving towards digital accessibility as well as changed lifestyles and enhanced confidence in information on the internet. Every day, they are exposed to a variety of branded content, such as short videos, influencer posts, stories, reels, reviews, and even the chatbots that use AI. Such exchanges determine their attitude towards brands, credibility and loyalty. Previous research points to the fact that consumers cease to be passive consumers. They instead engage by liking, sharing, commenting, reposting and also write up their own content. In the study of consumer brand engagement in social media, conducted by Hollebeek, Glynn, and Brodie (2014), it has been revealed that consumer brand engagement in the social site has emotional, cognitive, and behavioral levels, implying that customers think, feel, and act when interacting with the brands online.

Creative communication is another big factor that affects consumer response towards brands. The research by Ashley and Taten was entitled Creative Strategies in Social Media Marketing (2015), which revealed that branded posts that are visually creative, designed with interactivity, and telling a story appeal more and lead to a higher level of engagement.

These tactics are also very evident in the Indian market where the brands are increasingly resorting to influencers, micro-influencers, and short-form video content to speak in a relatable and entertaining manner. Research by Martínez-Lopez and others published in 2020 indicates that followers build trust when the influencers have an authentic and natural way of presenting brand messages in a way that makes sense to them.

Emotions are also significant in addition to creativity. In their 2015 study on the impact of social media on emotion, brand relationship quality, and word of mouth, Hudson and colleagues have indicated that emotional positive interactions on social media enhance the quality of relationship and promotes consumer discussion of the brand with other people, leading to the natural expansion of the brand.

This emotional aspect is particularly crucial to maintaining the interest since people are likely to be attached to the brands that make them feel heard and appreciated.

The Covid-19 pandemic has also altered brand communication. The researchers watched that in case of the pandemic, the frequency of communication via social media rose among companies in India to ensure continuity with consumers and assurance in times of uncertainty (Mason and colleagues, 2021).

Gupta and colleagues (2025) further explained the way in which the consumer habits changed in the post-Covid world where people began using digital environments more to get information, product evaluation and customer care. This change has brought brand communication closer to human being and service-driven.

The other area of artificial intelligence that has penetrated social media branding in the last few years is artificial intelligence. The authors Laksamana and colleagues (2024) discovered that responsibly and transparently used AI-driven brand strategies enhance brand awareness, image, and loyalty.

Meanwhile, Kumar and Dayal (2025) noted that the issue of bias, transparency, and trust within AI-powered marketing systems is present and that consumers need to be truthful and transparent when using automated communication tools.

Here, the urban Indian consumers are exposed to a combination of creative content, emotionally charged narratives, and suggestions made by influencers, as well as an AI-led interaction. Their perception of the brands will get more personal and deeper as they decode all these messages day by day. Sustainable interaction is built when communication is authentic, culturally appropriate, and dignified. Communication that comes out forced, superficial and over promotional soon loses attention of consumers.

In the light of these dynamic tendencies, it is important to establish how the communication of brands influences sustainable interaction between consumers in the Indian urban digital landscape. This paper addresses this relationship based on qualitative data and the findings of how consumers explain their actual reaction to brand communication on social media. It points out what they value, what they believe in and what keeps them interested in a particular brand in the long run.



2.Literature Review

The social media communication has been extensively researched within the last 20 years and the scholars have examined the effects of digital media on consumer behaviour, brand relationships and engagement patterns. The first premise of the research into social media was set by Kaplan and Haenkein who created an influential paper called Users of the World, Unite! In the Challenges and Opportunities of Social Media, (2010) where they described the various forms of social media platforms and how they provide the ability of participation, sharing and collaboration among the users.

Their efforts served to establish the conceptual framework of the digital landscape, in which brands are presently functioning.

Robert Kozinets also made another key input in digital consumer behaviour. The approach to social media has been brought into the study of online consumer communities where netnography introduced by his work The Field Behind the Screen: Using Netnography to Understand Online Community (2002) is a qualitative method to understand social media as creating its own culture, values, and meanings which mediate consumer-brand relationships.

In a study published way back in 2001 by Muniz and O'Guinn under the title Brand Community, it was established that consumers establish emotional attachment with brand communities, regardless of the prevalence of social media.

Once social media came into maturity, scholars started paying attention to engagement. The article of Hollebeek, Glynn, and Brodie named Consumer Brand Engagement in Social Media (2014) has become one of the most referred to works in this field. Their understanding of consumer engagement was that of emotional, cognitive, and behavioral involvement, as they revealed that consumers do not just perceive the content but they think, feel, and act in an interaction with brands online.

This model allowed scholars perceive that the interaction does not concern likes, or shares alone but a more significant psychological interest.

In the article, Ashley and Taten (2015) have discussed the role of creativity in communication in the article titled Creative Strategies in Social Media Marketing: An Exploratory Study of Branded Social Content and Consumer Engagement. They discovered that creative posts, including visual attractive posts, interactive stories and branded entertainment, capture the attention better and stimulate the consumers to be involved in the discussion with brands.

Their research has highlighted that brands must think beyond promotional farewells in case they seek good engagements.

On the same note, Dessart, Veloutsou, and Morgan-Thomas also examined the involvement of individuals in brand communities on social media in their article about consumer involvement in online brand communities: a social media perspective (2015). They discovered that consumers interact on the basis of emotional, functional, and social reasons and that interactions enhance the perception of the value of belongingness to a community.

Emotions are also another aspect of communication research. In their research article, The Effects of Social Media on Emotions, Brand Relationship Quality and Word of Mouth (2015), Hudson and colleagues clarified that when consumers experience positive emotions on a social media, they are more likely to share information about a brand and maximize the recommendation of such a brand to others.

This affirmed that online brand-building revolves around emotions.

The sphere of social media develops, and influencer marketing has become the powerful element of communication strategies. In the article Behind Influencer Marketing: Key Marketing Decisions and their Impact on Responses of a Follower by Martínez-López and colleagues (2020), the relationships between influencer selection and influencer content perceptions were investigated by the researchers. According to their work, trust, credibility, and relatability are major elements that influence how a consumer will respond to communication through influencers.



Video content has also increased at a high pace particularly with the emergence of short video platforms. In the article by Saleem and others, this trend was examined by the authors in the study of the article titled Impact of Video Content Marketing on Consumer Engagement (2024). They discovered that video-based communication is a rapid attention-grabbing medium, which is effective in expression and will prompt more engagement than a purely static medium.

Their results can be used in the case of India, where the consumption of video content is very high.

In addition to video content, there were also studies on the generational differences. Kusuma and coauthors in their publication on impact of social media marketing on brand engagement with Gen Z consumers, awareness and image (2024) discovered that Gen Zs prefer authentic, relatable and transparent content. They are not that much responsive to highly refined or wholesbred promotion postures. Their reactions indicate a change in consumer attitude on brand messages among younger consumers.

Brand communication became less positive due to the Covid-19 pandemic. According to Mason and colleagues in Pandemic Effects on Social Media Marketing Behaviors in India (2021), the authors noted that during limited physical movement, companies had to be more on-line to maintain contact with consumers.

The second study by Mason, Narcum, and Mason entitled Social Media Marketing Gains Importance After Covid-19 (2021) stated that digital platforms turned out to be the survival and customer retention in the pandemic and its consequences. Their work indicates the shift of communication priorities during crises. Gupta and others (2025) built on this insight in the article, Consumer Behaviour in the Post-Covid Era, which demonstrates that consumers build trust and make decisions regarding digital communication more than they do prior to Covid.

Recent researches deal with artificial intelligence in branding. According to the results of Laksamana and colleagues in their article on the topic: Artificial Intelligence-Driven Brand Strategy: Impact on Awareness, Image, Equity, and Loyalty (2024), AI-based communication has the ability to enhance brand performance when it is used in a responsible and transparent manner.

It was however argued by Kumar and Dayal (2025) in the article titled AI-Powered Marketing: A Content Analysis of Bias, Transparency, and Consumer Trust) that people become uneasy when AI communication does not appear impartial, and untrustworthy when brands are not open about the use of AI.

Even prior to the current proliferation of the digital space, some previous studies had delved in the concept of virtual interactions. Indicatively, a study by Kaplan and Haenlein on Second Life (2009b, 2009c) examined the consumer behaviour in the virtual world and as such provided some of the first indicators of the virtual world having a potential to impact brand relationships. These researches demonstrated that consumers do not behave in the same way in the interactive digital space as they do in the traditional media and this is relevant to the current social media communication.

Report by the OECD (2007) titled Partake Web and User-Created Content has emphasized a new opportunity and challenge to brands particularly where a consumer has the control to create and distribute content. This is very much related to the contemporary activity like product reviews, unboxing videos and user-generated posts.

Collectively, these studies indicate that social media communication is multidimensional. It is influenced by innovativeness, feelings, involvement of influencers, community involvement, transparency, technology, and cultural demands. As the previous literature explains each of the elements individually, the dynamic nature of digital behaviour, particularly in India, has generated a desire to examine how current consumers identify with these communication tactics in an integrated manner. This is the basis of establishing the gap in research and comprehending sustainable consumer engagement.

3.Objectives of the Study

The central objective of the research is to get insights into how brand communication in social media impacts sustainable consumer-engagement of urban Indian consumers. Although some research has been conducted on the measurement, metrics or promotional response, the proposed research seeks to find the answer to how the consumers themselves feel



and perceive brand communication during their daily use of social media. These qualitative views are reflected on the objectives.

The former aims at understanding how consumers interpret the various communicative styles that are adopted by brands on social media. A visual storytelling, influencer collaboration, video content, emotional, and AI-driven tools make up a mixture by which brands are using them. The purpose of this study is to comprehend the way urban consumers perceive them when they encounter branded posts, stories, or interactions.

The second one is to determine what communication elements assist consumers in feeling affiliated to a brand as time goes by. Previous studies, including that conducted by Hollebeek, Glynn, and Brodie (2014), justified that engagement encompasses emotional and cognitive engagement. Nevertheless, the aim of the study is to comprehend the formation of engagement based on the individual emotions, which include trust, comfort, relatability, and cultural resonance in words of the consumers.

The other goal will be to investigate the role played by authenticity, transparency, and responsiveness in influencing consumer perceptions. Research such as Ashley and Tuten (2015) focused on the use of creative approaches, and Kumar and Dayal (2025) have focused on AI communication transparency. This paper is based on the perception of the consumer regarding whether a brand appears to be honest, open, and respectful in its communication.

Another goal is to know how sustainability is defined by consumers. As opposed to short-term responses, such as likes or comments, the proposed research seeks to understand how long-term interaction is formed due to positive interaction meaning, emotional attachment, and regular communication between platforms. It aims to know what makes consumers stick, keep up and believe with a brand during long durations.

In general, the hypotheses of this paper lead to further investigation of the impact of brand communication on emotions, meaning, and sustained interaction among urban Indian social media users.

4. Methodology

The research is a mixed study, which integrates a quantitative survey with qualitative information to determine the impact of social media brand communication on consumer engagement. The researchers consider only urban residents of some of the major towns and districts of Jharkhand, where the use of social media is rather popular.

The data concerning primary data are the structured questionnaire developed using Google Forms. The questionnaire is distributed to social media users on Instagram, Facebook, and Twitter (X). The selection of respondents will be determined by their frequent exposure to the branded content in the social media. The questionnaire contains statements concerning the style of brand communication, the emotional bond, the genuineness, the content of the influencers, and the behavior of engagement.

The measure of responses is taken with the help of a five-point Likert scale, where Strongly Disagree is 1, and Strongly Agree will be 5. This scale assists in the description of the degree of agreement and perception of the respondents in a simple and clear way.

Besides the survey, there are some personal interviews and small group interviews with some of the users of the social media. These discussions assist in knowing personal views, experiences and feelings about brand communication that cannot be well explained by the use of structured questions. The interviews will be informal and conversational, which will enable the respondents to give their opinions freely.

The researchers focus on urban regions of Jharkhand and do not target the rural consumers. The emphasis is on the knowledge of engagement behavior in the city digital environment.

5. Data Analysis and Findings

All the data are well screened and tabulated to be analyzed. The Likert scale is used to analyze responses and focus on the general patterns of consumer perception and engagement with the communication via social media brands.



The results indicate that customers do not interact with brands because they are frequently posted. Rather, engagement is determined mostly by the relevance, meaning and authenticity of the content. The respondents are more in agreement with the statements that are associated with emotional content, creative images, and interactive posts.

The content that is generated by the influencer is positively received, particularly by younger users who find such content more relatable and credible. Most of the respondents concur that influencer recommendations affect their brand perception in case the content is authentic.

The survey findings are supported by the responses of the interview. Respondents confirm that they like brands that speak to them in a friendly and straightforward way and not those who seem to be too promotional. Users also complain that they feel more associated with the brands that respond to the comments or appreciate the user responses.

In general, the results evidently show that efficient brand communication in the social media had a positive impact on consumer interaction, confidence, and commitment in the long run.

Table 1: Major Themes Emerging As a result of Qualitative Analysis.

Theme	Description Based on Consumer Experiences
Authenticity in Brand Communication	Customers would like to see the brand that speaks naturally and truthfully. Real and transparent messages generate comfort and trust. Promotional communication is too much or scripted, and this decreases interest and long term interest.
Emotional Connection and Relatability	Emotional messages, stories that people can relate to and also cultural references aid the consumers to have a sense of personal connection to a brand. The material that is similar to real-life experience and feelings has a long-lasting impact and increases the bonding.
Creative Storytelling and Visual Appeal	Reels, short videos, influencer stories, and posts that have a visual appeal attract attention in a short period of time. The use of creative and appealing formats motivated the consumers to like, repost, and comment on the brand content more.
Responsiveness and Two-Way Interaction	Consumers appreciate brands that respond to commentaries, messages, and acknowledge feedback. Interacting regularly makes the users feel respected and listened to, which facilitates their long-term engagement.
User Participation and Content Sharing	Promoting most reviews, sharing user material and solicitation of involvement makes consumers feel involved. These kinds of involvement produced a feeling of belonging and make one more loyal to the brand.

Theme Analysis and Interpretation

Interview and open-ended survey responses are reviewed to achieve more insights by grouping them into common themes. The themes are indicative of how consumers perceive and understand brand communication over the social media platforms.

Authenticity in communication is one of the main themes that arise. Consumers like honest and human-sounding brands. Users will be quite comfortable with the brand in the long term when messages are natural and transparent.

Emotional connection and relatability is another theme that is vital. Respondents tell that they feel connected to a brand because of emotionally moving content, cultural allusions, and stories that they relate to. This kind of material will form a personal rapport and impression.

Innovative narration and visual effect also comes out as a powerful theme. Short clips and reels, influencer stories, visually appealing posts are easy to watch and promote likes, shares and comments. Creativity can assist brands to be distinguished in the sea of social media feeds.



Another major theme is responsiveness and interaction. Two-way communication is highly appreciated by the consumers and they feel that the brands are showing care when they respond to their messages or comments. Failure to respond can bring about lack of interest.

Lastly, involvement of users in the form of reviews, reposts and user-generated content enhances involvement. Having the brands share or recognize consumer contents makes the users feel a part of the brand and feel belonging.

The combination of these themes clarifies that the principles of sustainable consumer interaction lie in meaningful, interactive, and emotionally engaging communication and not in promotional materials.

6. Discussion

This study will aim at knowing the impact of social media brand communication on consumer engagement between urban citizens in Jharkhand. The results make it obvious that social media engagement cannot be developed solely through the number of posts or promotion messages. Rather, consumers need to be engaged based on the level of relevance, sincerity, and relatability of the communication.

Among the most significant discoveries is connected with authenticity. This is based on the survey results and the discussions during interviews where consumers expressed their affection towards the brands that use natural and human language to communicate the message. Users become more comfortable with the brand when brand messages look to be honest and transparent. This fact helps to believe that trust is a major factor in maintaining engagement. Too promoting or pushy promotional messages make it less interesting and deteriorates the consumer-brand relationship.

The paper also indicates the high status of emotional relation in social media communication. Emotions, real-life, and cultural familiarity have a greater level of agreement with the content provided to respondents. In interviews, people clarify that they recall and relate more with such brands that know their emotions and lives. Emotional contents enable the consumer to feel appreciated, and this aspect enhances long term attachment.

The other important result of the research is connected with innovative content and visual narration. The results prove that short videos, reels, stories of influencers, and entertaining posts achieve greater interaction than dull text or similar monotonous posts. Creativity assists in making the brands deliver their message in a digital world that is saturated and concisely. This means that creativity does not necessarily involve design but also the way the story is told.

Consumer perception also responds positively to the influence of the communication based on influencers, particularly on younger users. The results of the surveys indicate that influencers can influence participants by making their content authentic and relatable. The responses of interviews help in confirming that users put more trust in influencers when they feel that the recommendation is not coerced. This demonstrates that credibility is a significant reaction of the effectiveness of influencer marketing.

The results also indicate the significance of responsiveness and mutual interaction. Customers are more active and interactive with the brands that respond to their comments, receive their feedback, and frequently communicate. This communication makes the users respectful and heard. Conversely, no reply will cause distance and lack of interest as time goes by.

Consumers can feel involved when brands ask to review, reproduce user posts or invite them to take part. This participation enhances loyalty and long term participation as the users believe that they belong to the brand experience.

In general, the discussion has affirmed that authenticity, emotional relevance, creativity, interaction, and participation all form the basis of sustainable consumer engagement on social media. Marketing material is not enough to sustain the long term contact.

7. Recommendations

Upon the completion of this study, a number of practical recommendations are implied to use social media as a communication platform by the brand. To start with, the brands should pay more attention to authenticity in their



messages. Messages that appear truthful, basic, and human aids in building trust and long term interest. Over-promotional or unnatural material decreases the interest of the consumer.

Second, emotional storytelling is significant when it comes to capturing consumers. Brands with likeable stories, cultural and emotionally relevant communications establish better relationships with their audience. This kind of communication makes the consumers feel that they are heard and treasured.

Another important factor that was found by the research is creativity. Aesthetic posts, short videos, reels, and content posted by an influencer attract attention quickly and make people more engaged. Storytelling is a creative method that can enable brands to be distinguishable in a saturated online world.

Responsiveness is also one of the issues that are noted in the study. The fact that the brands respond to the comments, receive feedback, and communicate with the users on a regular basis creates a feeling of respect and belonging. Two-way communication enhances consumer relationships.

Sustainable engagement is also encouraged by encouraging participation of the users. When the brands solicit users to leave reviews, experiences, or material, the user feels as a part of the brand process. The involvement contributes to the creation of loyalty.

Lastly, although AI-based tools assist in personalization and efficiency, it is crucial to use them ethically and transparently. A positive and transparent communication is a way to ensure consumer confidence in online relationships.

8. Conclusion

The paper will look at how social media brand communication can influence sustainable consumer interaction among consumers in the chosen towns and districts of Jharkhand. The results indicate that the customers interact with the brands not due to regular posting but due to meaningful, authentic, and emotionally resonant communication. The social media functions as an observation, interpretation and emotional connection platform of the brand messages to the consumers.

The research notes that trust is established through authenticity, emotional content, attachment through creativity and attentiveness and interaction through creative storytelling. The communication that is based on influencers affects the consumer perception when it sounds and looks natural and relatable. Two-way interaction and responsiveness will make the consumers feel special, whereas user-generated content will make them feel like they belong and help to build long-term loyalty. The combination of these factors is a factor that explains the gradual development of engagement that comes about due to the process of constant and respectful communication.

Moreover, the research demonstrates that sustainable engagement is a relational process and not a marketing exercise on a short-term basis. Consumers will be attached to brands that listen, answer and engage them in the communication process. The results indicate that the social media brand communication are effective when the brand emphasizes on the consumer emotions, cultural context, and expectations. On the whole, the article supports the concept that interactive, honest, and consumer-oriented communication is at the core of establishing a sustainable consumer-brand relationships in the digital world.

Acknowledgment

I would like to express my sincere gratitude to my research guide, Respected Dr. Amrita Majumdar Ma'am, Associate Professor, Faculty of Commerce & Management, Jharkhand Rai University, for her continuous guidance, encouragement, and valuable academic inputs. Her support and constructive suggestions helped me improve my understanding of the subject and shape the study effectively.

I am also thankful to Jharkhand Rai University for providing the academic environment and resources required to carry out this research. I would like to acknowledge the support and cooperation of all the respondents who shared their time and experiences, which made this study possible.



Finally, I express my heartfelt thanks to my family and well-wishers for their constant motivation, understanding, and moral support during the course of this research work.

References:

1. Ashley, C., & Tuten, T. (2015). Creative strategies in social media marketing: An exploratory study of branded social content and consumer engagement. *Psychology & Marketing*, 32(1), 15–27.
2. Bagozzi, R. P., & Dholakia, U. M. (2006). Antecedents and purchase consequences of consumer participation in small group brand communities. *International Journal of Research in Marketing*, 23(1), 72–80.
3. Bowden, J. L. H. (2009). The process of consumer engagement: A conceptual framework. *Journal of Marketing Theory and Practice*, 17(1), 63–74.
4. Chen, Q., Lu, Y., Gong, Y., & Xiong, J. (2023). Can AI chatbots help retain customers? Impact of AI service quality on customer loyalty. *Internet Research*, 33(6), 2205–2243.
5. Cheng, Y., & Jiang, H. (2022). Customer–brand relationship in the era of artificial intelligence: Understanding the role of chatbot marketing efforts. *Journal of Product & Brand Management*, 31(2), 252–264.
6. Dessart, L., Veloutsou, C., & Morgan-Thomas, A. (2015). Consumer engagement in online brand communities: A social media perspective. *Journal of Product & Brand Management*, 24(1), 28–42.
7. Eslami, S. P., Ghasemaghaei, M., & Hassanein, K. (2022). Understanding consumer engagement in social media: The role of product lifecycle. *Decision Support Systems*, 162, 113707.
8. Furlow, N. (2011). Find us on Facebook: How cause marketing has embraced social media. *Journal of Marketing Development and Competitiveness*, 5, 61–64.
9. Gupta, A., Shinde, K., Tiwari, G., & Sakriya, V. (2025). Consumer behaviour in the post-COVID era. *International Research Journal of Modernization in Engineering Technology and Science*, 7(1).
10. Habibi, M. R., Laroche, M., & Richard, M. O. (2014). Brand communities based in social media: How unique are they? *International Journal of Information Management*, 34(2), 123–132.
11. Healy, J. C., & McDonagh, P. (2013). Consumer roles in brand culture and value co-creation in virtual communities. *Journal of Business Research*, 66(9), 1528–1540.
12. Hollebeek, L. D., Glynn, M. S., & Brodie, R. J. (2014). Consumer brand engagement in social media: Conceptualization, scale development and validation. *Journal of Interactive Marketing*, 28(2), 149–165.
13. Hosanagar, K., Fleder, D., Lee, D., & Buja, A. (2020). AI and consumer choice. *Marketing Science*, 39(1), 1–20.
14. Hudson, S., Roth, M. S., Madden, T. J., & Hudson, R. (2015). The effects of social media on emotions, brand relationship quality, and word of mouth: An empirical study of music festival attendees. *Tourism Management*, 47, 68–76.
15. Jiang, H., Grewal, D., Kopalle, P. K., & Lee, H. (2020). Understanding the role of trust in AI recommendations. *Journal of Marketing*, 84(1), 109–127.
16. Kaplan, A. M., & Haenlein, M. (2009b). Consumers, companies, and virtual social worlds: A qualitative analysis of Second Life. *Advances in Consumer Research*, 36(1), 873–874.
17. Kaplan, A. M., & Haenlein, M. (2009c). The fairyland of Second Life: About virtual social worlds and how to use them. *Business Horizons*, 52(6), 563–572.
18. Kaplan, A. M., & Haenlein, M. (2010). Users of the world, unite! The challenges and opportunities of social media. *Business Horizons*, 53(1), 59–68.
19. Kozinets, R. V. (2002). The field behind the screen: Using netnography for marketing research in online communities. *Journal of Marketing Research*, 39(1), 61–72.
20. Kumar, A., & Dayal, M. (2025). AI-powered marketing: A content analysis of bias, transparency, and consumer trust. *International Journal of Contemporary Research in Multidisciplinary*, 4(3), 146–151.
21. Kusuma, I. G. W. A., Endayani, F., Budi K. A., & Khourouh, U. (2024). Social media marketing impact on Gen Z's brand engagement, awareness, and image. *Manajemen dan Bisnis*, 23(2), 480–490.
22. Laksamana, P., Saripudin, S., Suharyanto, S., & Cahaya, Y. F. (2024). Artificial intelligence-driven brand strategy: Impact on awareness, image, equity, and loyalty. *Journal of Infrastructure, Policy and Development*, 8(15), 10084.
23. Mangold, W. G., & Faulds, D. J. (2009). Social media: The new hybrid element of the promotion mix. *Business Horizons*, 52, 357–365.



24. Martínez-López, F. J., Anaya-Sánchez, R., Fernández Giordano, M., & Lopez-Lopez, D. (2020). Behind influencer marketing: Key marketing decisions and their effects on followers' responses. *Journal of Marketing Management*, 36(7–8), 579–602.
25. Mason, A., Narcum, J., & Mason, K. (2020). Changes in consumer decision-making resulting from the COVID-19 pandemic. *Journal of Customer Behaviour*, 19(3).
26. Mason, A. N., Brown, M., Mason, K., & Narcum, J. (2021). Pandemic effects on social media marketing behaviors in India. *Cogent Business & Management*, 8(1), 1943243.
27. Mason, A. N., Narcum, J., & Mason, K. (2021). Social media marketing gains importance after Covid-19. *Cogent Business & Management*, 8(1), 1870797.
28. Mulier, T., van der Stede, A., & Ghysels, M. (2021). How video content influences brand perception. *Journal of Marketing Research*, 58(3), 215–232.
29. Muniz, A. M., & O'Guinn, T. C. (2001). Brand community. *Journal of Consumer Research*, 27(4), 412–432.
30. OECD. (2007). Participative Web and User-Created Content: Web 2.0, Wikis, and Social Networking. Organisation for Economic Co-operation and Development.
31. Quintos, K. (2013). Social media boot camp: Best practices from the front lines of Dell. *Social Media Marketing Magazine*.
32. Rust, R. T. (2020). The future of marketing in the AI era. *Journal of Marketing*, 84(1), 1–12.
33. Saleem, A., Mehmood, R., Taj, A., Khalid, M. U., Moiz, A., & Lakho, A. (2024). Impact of video content marketing on consumer engagement. *Journal of Policy Research*, 10(3), 83–95.
34. Schivinski, B., & Dabrowski, D. (2016). The effect of social media communication on consumer perceptions of brands. *Journal of Marketing Communications*, 22(2), 189–214.
35. Wallace, B., & de Chernatony, L. (2014). Consumer engagement with self-expressive brands: Brand love and WOM outcomes. *Journal of Product & Brand Management*, 23(1), 33–42.
36. Wertz, J. (2019). How businesses and influencers are monetizing Instagram. *Forbes Magazine*.
37. Wilson, H., Guinan, P., Parise, S., & Weinberg, B. (2011). What's your social media strategy? *Harvard Business Review*, July–August, 23–25.



DOIs:10.2015/IJIRMF/ICICSF-2025-P34

--:--

Research Paper / Article / Review

International Conference On "Innovative Convergence for Sustainable Future"

Date : 12 - 13 December, 2025

(ICICSF-2025)



Thermosensitive Packaging for Biologics and Vaccines

Ritu Kumari¹, Shibo Mahato¹, Rohan Kumar¹, Niranjana Kumar Mahto¹, Ritik Kumar¹, Anamika Palak^{*2}

¹Department of Pharmaceutical Sciences, Jharkhand Rai University, Raja Ulatu, Namkum, Ranchi, Jharkhand 834010, India.

² Assistant Professor, Department of Pharmaceutical Sciences, Jharkhand Rai University, Raja Ulatu, Namkum, Ranchi, Jharkhand 834010, India

Email- ritukumari05674@gmail.com, anamika.palak@jru.edu.in

Abstract: The logistical and financial difficulties involved in the worldwide distribution of vaccines have drawn more attention to the development of thermostable vaccines. The stability of vaccine adjuvants, which are essential parts of many contemporary subunit and inactivated vaccines, has gotten very little attention, even though thermostability is frequently discussed in relation to vaccine antigens. The development of thermostable adjuvant formulations spanning the main adjuvant classes, such as aluminium salts, oil-in-water emulsions, liposome, and systems based on nanoparticles, is summarised in this review along with the opportunities, difficulties, and advancements that have occurred recently. To enhance adjuvant stability at high temperatures, several formulation methods have been investigated, such as lyophilisation, spray-drying, liquid formulation optimisation, and other drying methods. Under severe heat stress, lyophilisation and spray-drying with protective excipients like sucrose or have demonstrated great promise in preserving the physicochemical integrity and immunogenicity of adjuvant-antigen combinations. Due to particle aggregation during freezing or heating, aluminium salt adjuvants provide unique difficulties. However, current research shows that controlled freezing procedures and excipient-based stabilisation increase stability. With the right stabilisers and optimum drying methods, liposomal adjuvants and oil-in-water emulsions have also demonstrated improved thermostability. Translation of thermostable adjuvant platforms from proof-of-concept to clinical application is still restricted, despite significant advancements. The authors emphasise the necessity of thorough stability evaluation methods, increased research into scalable drying technologies, and early inclusion of thermostability issues during product development. In situations with limited resources, achieving consistent thermostability of adjuvant-containing vaccines could greatly reduce cold-chain dependence, lower distribution costs, and enhance vaccine access.

Keywords - Thermostable Vaccines, Vaccine Adjuvants, Liposomes, Nanoparticles, Lyophilization, Cold-Chain, Immunogenicity

1. INTRODUCTION

Temperature-sensitive pharmaceuticals—including vaccines, monoclonal antibodies, blood-derived products, recombinant proteins, peptides, and nucleic-acid-based therapeutics—represent one of the fastest-growing segments of modern medicine. Their global distribution relies on packaging systems capable of maintaining structural integrity, biological activity, and sterility during transportation and storage. Unlike small-molecule drugs, biologics possess complex three-dimensional structures stabilised by weak non-covalent interactions, rendering them highly vulnerable to thermal and environmental stress. As a result, pharmaceutical packaging must function as an integrated system that ensures thermal protection, barrier performance, mechanical stability, and regulatory compliance across the supply chain. Thermosensitive packaging has therefore become a critical element of biopharmaceutical development, cold-chain logistics, and global immunisation programmes [1–4].

Traditional pharmaceutical packaging materials include borosilicate glass, aluminium, elastomers, and polymers. Type I borosilicate glass remains widely used for parenteral products due to its chemical durability and thermal resistance; however, it may exhibit delamination, alkaline leaching, and brittleness under extreme temperature conditions. Polymer-based alternatives such as polypropylene, polyethylene, multilayer laminates, and nanocomposites offer lightweight and



flexible solutions but raise concerns related to permeability, additive migration, and drug sorption. These limitations have driven extensive research into advanced materials tailored for high-value biologics [2,14–16].

Dependence on cold-chain systems further increases distribution risk, with temperature excursions being a leading cause of vaccine spoilage worldwide. Inadequate insulation, improper handling, and unreliable power supply contribute to significant product losses. Exposure to temperatures outside recommended ranges can cause irreversible denaturation, aggregation, or phase separation of biologics, while aluminium-adjuvanted vaccines are particularly sensitive to freezing-induced loss of immunogenicity. Humidity adds another challenge by accelerating polymer degradation, increasing permeability, and promoting additive migration, thereby compromising product stability [5–13,17–22].

Rising demand for mRNA vaccines, cell and gene therapies, and other cold-chain-dependent products has intensified innovation in thermosensitive packaging. Regulatory agencies such as WHO, FDA, and EMA emphasise validated temperature-controlled systems and risk-based distribution strategies, while sustainability concerns are driving the adoption of recyclable materials, bio-based phase-change systems, biodegradable polymers, and smart packaging technologies. Consequently, thermosensitive packaging has evolved from a passive barrier into an active component of pharmaceutical quality systems [1–22].

2. LITRATURE REVIEW

This review is based on things that other people have already written about like documents and other research. So we did not do any experiments or tests, on packaging systems ourselves. The packaging technologies we talked about in this review might work differently when they are actually being used to transport things. We did not try to see how they would do in real life. The study does not look at how different thermosensitive packaging solutions compare to each other in terms of numbers or how much they cost versus how much they benefit. This might affect whether or not companies want to use them on a scale. There are a lot of developments happening in smart packaging materials, digital monitoring systems and cold-chain technologies. These advancements may lead to ways of doing things that are not covered in this review. Thermosensitive packaging solutions are. New approaches are being developed all the time.

Furthermore, regional variations in regulatory requirements, infrastructure availability, and environmental conditions were not analyzed in detail, which may affect the applicability of the findings across different geographical settings. GDP regulatory guidelines insist on the use of pre-validated temperature-controlled packaging and monitoring of the products throughout the supply chain. Literature convey that compliance with regulations is crucial for product safety, public trust, and global distribution of biologics and vaccines. Noncompliance has been cited as a leading cause of increased recalls and financial losses.

Recent research also tends to mark concerns about the sustainability of thermosensitive packaging. Typical cold-chain packaging systems are based on energy-intensive refrigeration and single-use materials, thus contributing to environmental burdens. New studies are focused on the development of recyclable, bio-based, and energy-efficient solutions for packaging in order to minimize environmental impact without compromising thermal performance. .In all, literature review underlines the important role of thermosensitive packaging in preserving the stability, safety, and efficacy of biologics and vaccines. While advanced packaging technologies and monitoring systems have significantly improved cold-chain management, further research is needed with a view to optimizing cost, sustainability, and global accessibility, especially in resource- unhealthy environmental.

3. OBJECTIVES

- To explain how temperature sensitivity affects the stability and potency of biologics and vaccines.
- To analyze thermal degradation mechanisms and the role of advanced packaging materials in protecting thermosensitive products.
- To evaluate technological innovations such as phase-change materials and IoT-enabled monitoring for cold-chain resilience.
- To assess packaging-drug interactions, material compatibility, and the regulatory standards governing pharmaceutical logistics.
- To identify sustainable solutions and future opportunities for reducing vaccine wastage and enhancing global treatment access.



4. TEMPERATURE SENSITIVITY IN BIOLOGICS AND VACCINES

Temperature is the primary factor affecting the stability, potency, and safety of biologics and vaccines. Owing to their complex higher-order structures stabilised by weak non-covalent interactions, biologics are highly sensitive to even minor temperature deviations, which can cause irreversible physicochemical degradation and loss of efficacy. This section examines key mechanisms of thermal degradation, the behaviour of nucleic-acid and adjuvanted formulations, and the influence of packaging–drug interactions, providing a scientific basis for the design of effective thermosensitive packaging systems across the cold chain [5–13].

4.4 Thermal Degradation Mechanisms in Protein Biologics

Proteins possess a hierarchical structure stabilised by hydrogen bonds, hydrophobic interactions, ionic bridges, and van der Waals forces. Elevated temperatures disrupt these interactions, leading to denaturation, aggregation, fragmentation, or chemical modification. Heat-induced unfolding exposes hydrophobic residues, accelerating aggregation and formation of soluble or insoluble particles that may provoke immune responses. Thermal stress also enhances chemical degradation processes such as deamidation, oxidation, Maillard-type reactions, and disulfide reshuffling. Because most biologics exhibit limited thermal stability, strict temperature control is essential during storage and distribution [5,7,8].

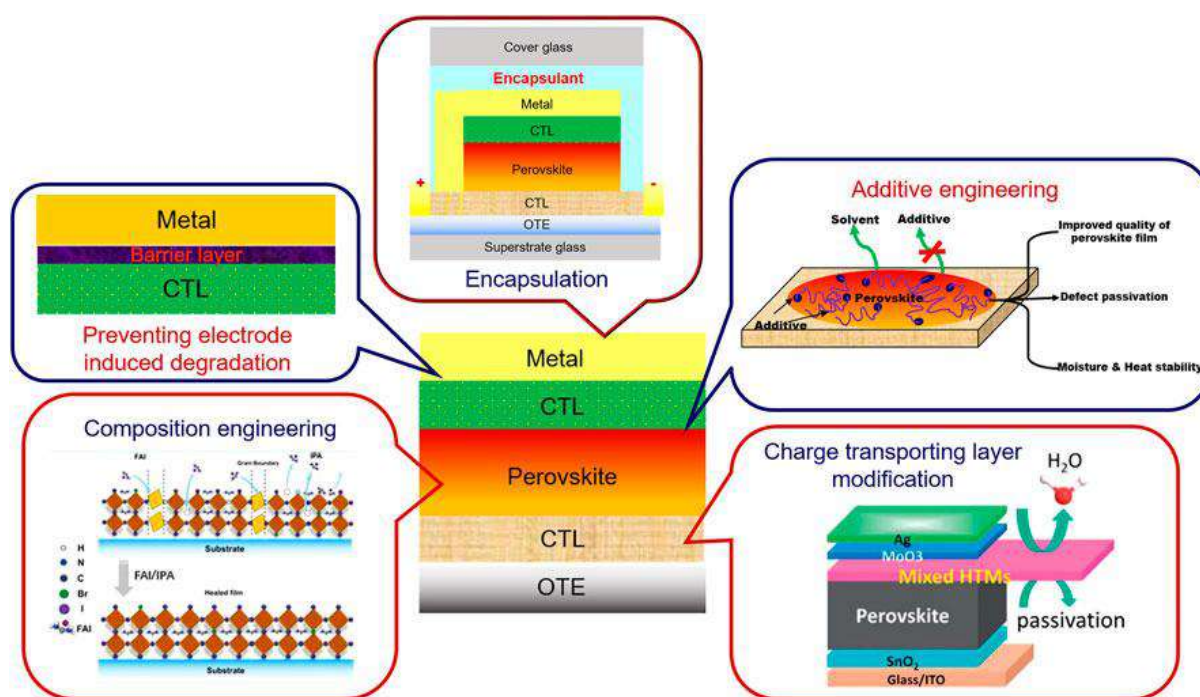


Figure 1: Thermal Degradation in Protein Binding

4.2 Sensitivity of Nucleic-Acid–Based Vaccines (DNA, RNA, Viral Vectors)

mRNA vaccines are extremely temperature-sensitive due to the chemical instability of single-stranded RNA, which is prone to hydrolysis, oxidation, and enzymatic degradation. Even under refrigeration, mRNA rapidly degrades unless stabilised in lipid nanoparticles and stored at ultra-low temperatures (−90 °C to −60 °C). DNA and viral-vector vaccines exhibit greater stability but remain susceptible to thermal and freeze–thaw stress that can reduce transfection efficiency or infectivity [12–14].

4.3 Temperature Effects on Adjuvants, Excipients, and Stabilisers

Adjuvants strongly influence vaccine stability. Aluminium-salt adjuvants irreversibly aggregate below 0 °C, altering particle characteristics and antigen adsorption, thereby reducing potency and increasing reactogenicity. Emulsion-based and liposomal adjuvants are also thermally sensitive, undergoing phase separation or leakage under temperature stress [12–14].



4.4 Packaging–Drug Interactions Exacerbated by Thermal Stress Temperature excursions not only influence biologic stability but also intensify interactions between packaging materials and drug products. Polymeric packaging—such as polypropylene, polyethylene, PVC, and multilayer laminates—contains additives including plasticizers, antioxidants, stabilizers, and processing aids. Thermal stress accelerates migration of these low-molecular-weight compounds into formulations. Studies have shown increased leaching of phthalates, bisphenols, fatty acid amides, antioxidants (e.g., BHT, Irganox 1010), and residues of vulcanizing agents from polymer closures under elevated temperatures. Such impurities may compromise drug purity or induce adverse effects. Heat also enhances sorption of biologics onto polymer surfaces, reducing delivered dose.

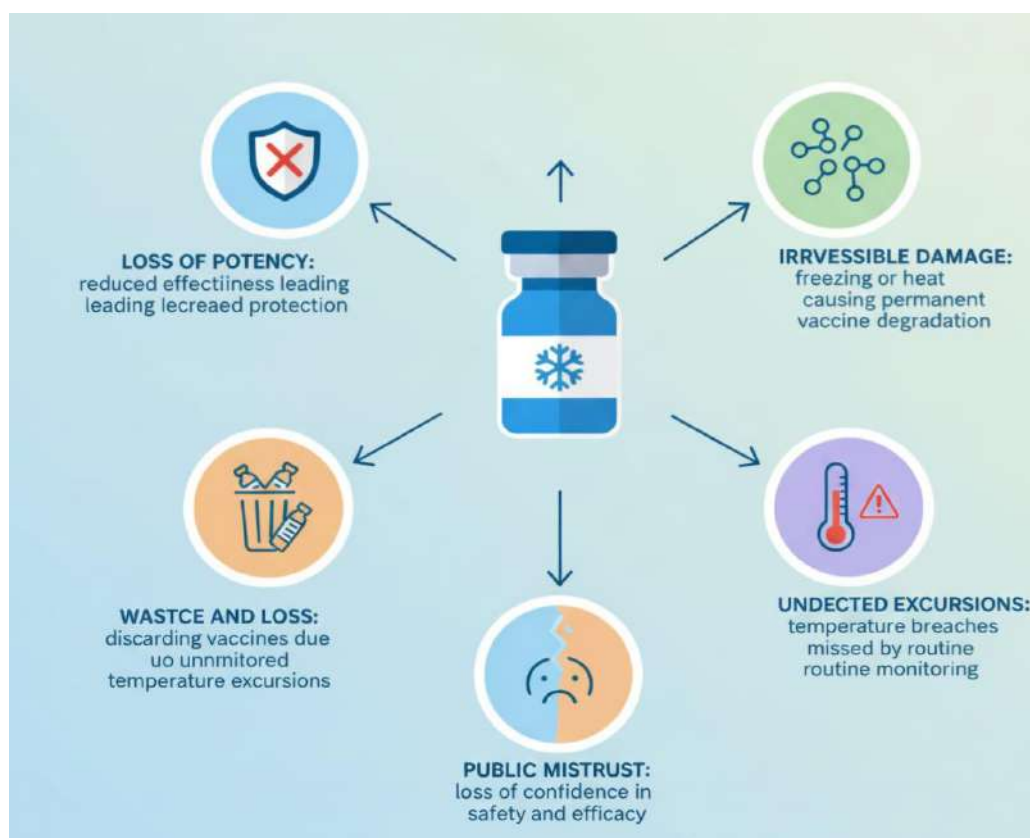


Figure 2: Vaccine storage risks

4.5 Representative Thermal Requirements of Key Vaccines

To minimize heat- or cold-induced degradation, vaccines are assigned stringent temperature ranges based on their physicochemical characteristics.

Table 1. Temperature Requirements for Common Vaccines

Vaccine Platform	Examples	Storage Temperature	Description
mRNA vaccines	mRNA-1273, BNT162b2	−90°C to −60°C	Extremely unstable; rapid degradation above −20°C
Live-attenuated vaccines	Varicella, measles, OPV	−20°C (frozen)	Heat accelerates loss of viral viability
Protein subunit vaccines	Hepatitis B, HPV	2–8°C	Sensitive to both high heat and freezing



Vector-based vaccines	Adenovirus-based COVID-19 vaccines	2–8°C	Capsid stability reduces at high temperature
Adjuvanted vaccines	Aluminium salt vaccines	2–8°C	Freezing causes irreversible aggregation
Toxoid vaccines	Tetanus, diphtheria	2–8°C	High heat denatures toxoid proteins

These temperature requirements must be strictly maintained throughout distribution. Even short-term excursions beyond the recommended range can compromise antigenicity and long-term efficacy [5–13].

5. TECHNOLOGICAL ADVANCEMENTS IN THERMOSENSITIVE PACKAGING FOR BIOLOGICS AND VACCINES

Significant advancements in materials science, nanotechnology, and sensor engineering have enabled the development of next-generation thermosensitive packaging systems that maintain strict temperature control and provide real-time visibility across the pharmaceutical supply chain. These technologies integrate passive and active thermal regulation, intelligent monitoring, and data-driven analytics to mitigate risks associated with temperature excursions. Modern systems increasingly combine phase-change materials (PCMs), modified polymer structures, nano-enabled coatings, and embedded sensors to create comprehensive cold-chain solutions tailored for biologics and vaccines [23–30].

5.1 Phase-Change Materials (PCMs) for Thermal Buffering

Phase-change materials (PCMs) stabilise internal temperatures by absorbing and releasing heat during solid–liquid transitions. Paraffin waxes, hydrated salts, fatty acids, and bio-based PCMs with melting points tailored to 2–8 °C are widely used to reduce reliance on active cooling and extend protection during transport disruptions. Emerging plant-based and composite PCMs incorporating graphene, metal–organic frameworks, or polymer microcapsules enhance sustainability, thermal conductivity, and cycling stability [23–25].

5.2 Intelligent and Time–Temperature Indicators (TTIs)

Time–temperature indicators (TTIs) monitor cumulative thermal exposure and provide visual alerts of temperature excursions through irreversible mechanisms such as dye diffusion, enzymatic or chemical reactions, and polymer phase transitions. Widely used in WHO Vaccine Vial Monitors, TTIs support effective cold-chain management in global immunisation programs. Advanced TTIs incorporating photonic polymers, nano-encapsulated dyes, microfluidics, and RFID/NFC connectivity improve precision, traceability, and Good Distribution Practice compliance [26–29].

5.3 Smart Nanocomposite Packaging Materials

Nanomaterials have substantially enhanced the functional performance of pharmaceutical packaging. Incorporation of nano-clays, graphene oxide, titanium dioxide, zinc oxide, and cellulose nanofibers improves thermal stability, barrier properties, and antimicrobial activity while reducing oxygen, moisture, and light transmission. Graphene oxide–polymer composites additionally enable rapid humidity-responsive signalling for intelligent packaging applications [27,30]. Nano-coatings and nanoparticle-based films further improve mechanical strength, UV protection, thermal endurance, and sterility, supporting extended shelf life and improved protection of temperature-sensitive biologics [27–31].

5.4 Smart Polymers and Thermally Responsive Films

Polymers engineered with precise thermal transition thresholds allow packaging to respond dynamically to environmental changes. Poly(N-isopropylacrylamide) (PNIPAAm), for instance, undergoes reversible hydrophilic–hydrophobic transitions at its lower critical solution temperature (~32°C). This behaviour enables heat-triggered changes in permeability or the activation of embedded indicators.

Shape-morphing polymers activated by thermal input (e.g., bilayer films, SMP composites) provide novel functionalities such as self-sealing, controlled-release triggers, or expansion-based alert mechanisms. Films incorporating chromogenic and thermochromic dyes provide visually detectable colour switching when critical thresholds are exceeded. These features are particularly valuable for biologics requiring multi-stage temperature control [32–34].



5.5 IoT-Enabled and Real-Time Monitoring Packaging Systems

Integration of Internet of Things (IoT) sensors into pharmaceutical packaging has transformed cold-chain management. Miniaturised temperature, humidity, GPS, and shock sensors enable continuous monitoring, while cloud-based platforms provide real-time alerts, predictive analytics, and automated regulatory documentation. Artificial intelligence and blockchain further enhance excursion prediction, traceability, and cold-chain resilience, reducing wastage and optimising distribution efficiency [35–38].

5.6 Thermal Insulation Enhancements in Advanced Containers

Modern cold boxes and passive shippers use multilayer foams, vacuum insulation panels (VIPs), aerogels, and reflective barriers to enhance thermal protection. VIPs reduce heat transfer up to 5–7 times compared with conventional insulation, while silica aerogels provide ultralow thermal conductivity with lightweight strength. Hybrid systems combining VIPs, aerogels, and PCMs enable extended temperature control without active refrigeration, particularly in low-resource settings [39–40].

6. PACKAGING MATERIALS AND COMPATIBILITY CONSIDERATIONS

Pharmaceutical packaging materials must provide mechanical protection, thermal stability, chemical inertness, and compatibility with sensitive biologics and vaccines. Packaging failures—such as leaching, sorption, delamination, permeability changes, or adjuvant destabilization—are frequently exacerbated by temperature excursions. This section evaluates glass, polymeric systems, elastomeric closures, and multilayer laminates in the context of thermosensitive pharmaceutical products [14–22].

6.1 Glass Packaging Systems

Type I borosilicate glass remains the gold standard for biologics due to its superior chemical durability and resistance to heat shock. Its network structure, composed of boron, silicon, and oxygen, minimises alkali ion exchange and prevents pH drift in sensitive formulations. However, extreme thermal cycling can induce internal stresses, microfracture formation, or delamination—particularly in high-pH or phosphate-buffered formulations. Glass delamination results in the formation of visible or subvisible flakes, posing safety concerns and triggering drug recalls. Advances in glass engineering include aluminosilicate compositions, surface de-alkalization processes, and siliconization techniques that reduce extractables and improve lubricity. Silanization creates hydrophobic surfaces that decrease protein adsorption and enhance syringe functionality. Innovations in thermally robust glass containers remain essential for high-value biologics requiring stable, inert environments [14–17].

6.2 Polymeric Packaging Systems

Polymeric materials—polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), cyclic olefin polymer (COP), and multilayer laminates—offer lightweight, low-cost, and break-resistant alternatives to glass. However, polymeric packaging presents challenges exacerbated by heat exposure, including increased permeability, sorption of active ingredients, and migration of additives. Plasticisers, antioxidants, stabilisers, and residual monomers migrate more readily under elevated temperatures, potentially contaminating biologics. For example, PVC bags used for infusion solutions may leach diethylhexyl phthalate (DEHP), while multilayer films may release oligomers or printing ink residues under thermal stress. Migration risk is influenced by polymer crystallinity, molecular weight, temperature cycles, and formulation polarity. Recent innovations incorporate nanocomposite reinforcement, barrier coatings (e.g., SiO_x, AlO_x), and high-density polymer architecture to minimise permeability and extractables. COP containers, with high transparency and superior water vapour barrier properties, are increasingly used for prefilled syringes and ophthalmic products requiring precise thermal performance [19–27].

6.3 Elastomeric Closures and Rubber Stoppers

Elastomeric closures—including butyl rubber, chlorobutyl, and bromobutyl stoppers—provide seal integrity and flexibility for vials, cartridges, and syringes. However, temperature affects their compression set, permeability, and extractable profiles. Heat accelerates the release of sulfur-based vulcanization agents, antioxidants, and accelerators, while freezing reduces elasticity and may compromise container closure integrity.



Advances in halogenated butyl rubber formulations improve gas impermeability and reduce leaching under thermal stress. Coatings such as fluoropolymer laminates or siliconization reduce the adsorption of proteins and minimise particulate shedding. Analytical techniques such as HPLC, GC-MS, and FTIR enable quantification of leachables across temperature ranges, supporting risk assessments and compatibility studies [28–34].



Figure 3: Rubber Stopper

6.4 Multilayer and Laminate Films

Multilayer laminates combine multiple polymers—such as PET/Al/PE or PA/EVOH/PE—to optimize barrier performance. Aluminium layers provide excellent thermal and light resistance but increase rigidity and environmental footprint. EVOH layers enhance oxygen-barrier properties but are sensitive to humidity, which reduces thermal performance.

Finite element simulation studies demonstrate that laminate mechanical strength decreases at elevated temperatures. Stretch-forming behaviour is also temperature-dependent, influencing the integrity of blister packaging used for temperature-sensitive oral dosage forms. Research continues to optimize laminate structures for improved insulation, reduced thermal deformation, and enhanced sustainability [16,17].

7. REGULATORY CONSIDERATIONS AND STANDARDS

Thermosensitive packaging must comply with stringent regulatory requirements to ensure product quality, safety, and efficacy throughout the cold chain. Regulatory agencies mandate evidence-based validation, monitoring, quality risk management, and documentation demonstrating adequate protection of biologics during storage and distribution [11–15].

7.1 Good Distribution Practice (GDP) Compliance

GDP frameworks require end-to-end control of temperature-sensitive pharmaceuticals from manufacturer to patient. Core GDP components include:

- validated storage systems
- controlled transport conditions
- continuous temperature monitoring
- risk-based management of excursions
- CAPA (Corrective and Preventive Actions)
- robust documentation practices



Failures in cold-chain maintenance cause irreversible degradation, particularly for aluminium-adsorbed vaccines and temperature-sensitive biologics. Regulatory guidance emphasizes proactive risk evaluation—using tools such as Failure Mode and Effects Analysis (FMEA)—to identify vulnerabilities and implement protective measures [11–14].

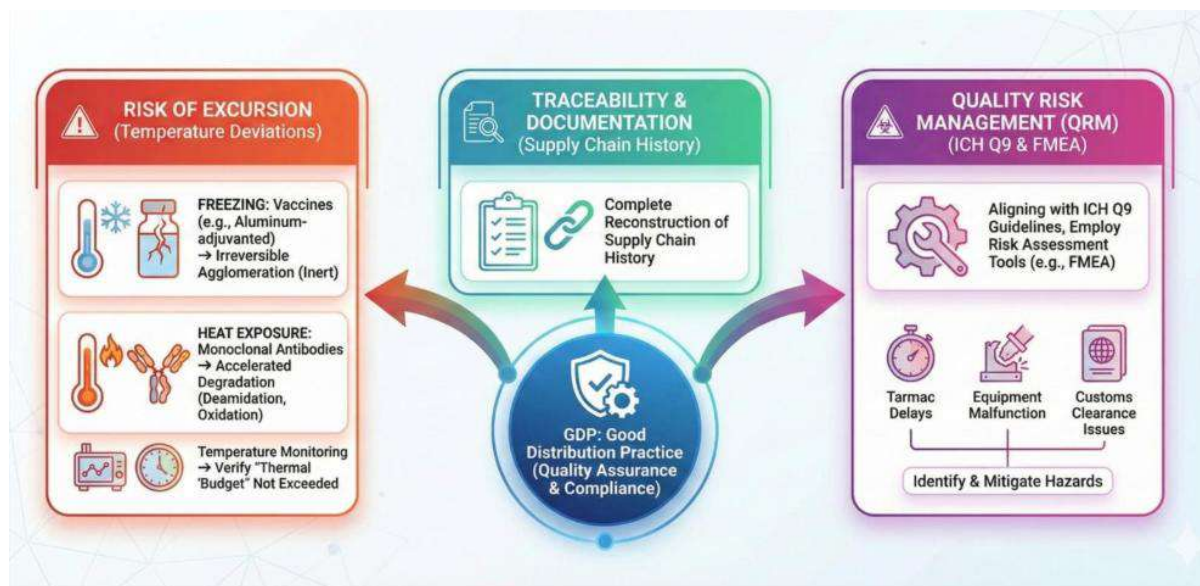


Figure 5: Conceptual Framework of Cold Chain Integrity under Good Distribution Practice (GDP). The diagram illustrates the interplay between biochemical risks (excursions), regulatory traceability requirements, and the proactive Quality Risk Management (QRM) strategies mandated by ICH Q9 guidelines to preserve product efficacy.

7.2 Global Regulatory Harmonization

International agencies—including WHO, FDA, EMA, PIC/S, and national authorities—have developed unified expectations for packaging validation, stability studies, and cold-chain qualification. Guidelines cover:

- thermal mapping and qualification of storage units
- shipper validation under worst-case scenarios
- compatibility testing between packaging and drug products
- extractable and leachable assessments
- hazard-based temperature excursion studies

Regulators increasingly encourage the integration of digital temperature monitoring and real-time documentation to improve traceability. Harmonised frameworks support global distribution of vaccines and biologics while maintaining consistent quality standards [14–18].

Table 2. Summary of Global Regulatory Guidelines for Temperature-Sensitive Pharmaceutical Products

Regulatory Authority	Guideline / Document	Key Requirements	Reference
WHO	TRS 961, Annex 9	Cold-chain monitoring, VVM use	[5]
US FDA	21 CFR 211, USP <1079>	Mapping, qualification, monitoring	[22]
EMA	EU GDP Guidelines	Qualification, deviation control	[22]
PDA	Technical Report 39	Validation of shipping systems	[22]
NMPA	YBB / GB Standards	Packaging–drug compatibility testing	[15]



8. SUSTAINABILITY CONSIDERATIONS IN THERMOSENSITIVE PACKAGING

The growing demand for cold-chain biologics has increased reliance on polymeric materials, insulating foams, and single-use packaging systems. This has intensified environmental concerns related to waste generation, carbon footprint, and limited recyclability of multi-material laminates. Sustainable packaging solutions focus on eco-friendly materials, improved recyclability, and energy-efficient cold-chain systems [1,16,18].

8.1 Environmental Impact of Conventional Materials

Conventional plastics—including PE, PP, and PVC—pose significant environmental challenges due to slow degradation, additive migration, and low recycling rates. Global plastic waste projections indicate continued growth in packaging waste, with pharmaceutical polymers contributing disproportionately due to sterility requirements and single-use components. Incineration of medical plastics generates harmful emissions, while landfilling results in long-term environmental persistence [18–20].

8.2 Bio-Based and Biodegradable Packaging Alternatives

Bio-based polymers such as PLA, PHA, starch-based blends, and cellulose composites offer lower environmental impact and can be engineered for improved thermal stability. Nanocellulose-reinforced films exhibit high strength, low permeability, and enhanced heat resistance, making them promising candidates for thermosensitive packaging.

Biodegradable PCMs derived from natural oils and fatty acids provide sustainable thermal buffering while reducing reliance on petroleum-based waxes. Research continues to optimize these materials to meet the performance standards required for biologics [21–24].

8.3 Recycling and Circular Packaging Approaches

Recycling pharmaceutical packaging poses challenges due to contamination risks, multilayer structures, and regulatory restrictions. However, advancements in mechanical and chemical recycling have enabled recovery of polymers from blister packs, multilayer films, and insulated shipping materials. Aluminium recovery from blister packaging demonstrates an emerging circular-economy model for pharmaceutical waste.

Design-for-recycling approaches include mono-material packaging, removable barrier coatings, and recycling-compatible adhesives, which preserve package performance while improving end-of-life outcomes [25–28].



Figure 6: Waste and Resource efficiency



9. LIMITATION

This review is based on things that other people have already written about like documents and other research. So we did not do any experiments or tests, on packaging systems ourselves. The packaging technologies we talked about in this review might work differently when they are actually being used to transport things. We did not try to see how they would do in real life. The study does not look at how different thermosensitive packaging solutions compare to each other in terms of numbers or how much they cost versus how much they benefit. This might affect whether or not companies want to use them on a scale. There are a lot of developments happening in smart packaging materials, digital monitoring systems and cold-chain technologies. These advancements may lead to ways of doing things that are not covered in this review. Thermosensitive packaging solutions are. New approaches are being developed all the time. Furthermore, regional variations in regulatory requirements, infrastructure availability, and environmental conditions were not analyzed in detail, which may affect the applicability of the findings across different geographical settings.

10. CONCLUSION

This review provides a comprehensive understanding of the temperature sensitivity of biologics and vaccines and clearly demonstrates the critical role of thermosensitive packaging in maintaining product stability, potency, and safety throughout the cold chain. The analysis highlights the key thermal degradation mechanisms affecting protein-based therapeutics, nucleic-acid-based vaccines, and adjuvanted formulations, showing how even minor temperature excursions can lead to irreversible loss of efficacy.

The study reveals that recent advancements in thermosensitive packaging technologies—such as phase-change materials, intelligent time-temperature indicators, smart polymers, and IoT-enabled real-time monitoring systems—significantly enhance cold-chain reliability and reduce the risk of product wastage. It also establishes that the selection of appropriate packaging materials, including glass, polymers, elastomers, and multilayer laminates, is crucial for minimizing temperature-induced failures, leachables, and sorption-related losses.

Furthermore, the review emphasizes the importance of regulatory-compliant cold-chain management and validated temperature-controlled systems in ensuring pharmaceutical quality during global distribution. Sustainability considerations discussed in the study indicate a growing shift toward eco-friendly materials and energy-efficient packaging solutions. Overall, the findings suggest that the integration of innovative, robust, and sustainable thermosensitive packaging systems can substantially reduce cold-chain dependence, lower distribution costs, and improve global access to biologics and vaccines, particularly in resource-limited settings.

10. ACKNOWLEDGMENT

The authors sincerely acknowledge the guidance, support, and encouragement provided by Ms. Anamika Palak, Assistant Professor, Department of Pharmaceutical Sciences, throughout the course of this work. The authors also express their gratitude to the Department of Pharmaceutical Sciences and the institution for providing the necessary academic support and facilities required for the completion of this study.

REFERENCES

1. Ibrahim ID, Hamam Y, Sadiku ER, Ndambuki JM, Kupolati WK, Jamiru T, et al. Need for sustainable packaging: An overview. *Polymers*. 2022;14:4430. DOI: 10.3390/polym14204430
2. Nguyen VT, Linh TTT, Vo TK, Nguyen QH, Van TK. Determination of heavy metal migration from plastic food packaging using ICP-MS. *Food Sci Nutr*. 2023;11:4030–4037. DOI: 10.1002/fsn3.3391
3. Liu X, Zhang Q, Wei Y, Qiao Y, Duan X, Li L, et al. Vittrification of cerium(III) fluoride in iron phosphoborate glasses. *Ceram Int*. 2024;50:38435–38444. DOI: 10.1016/j.ceramint.2024.08.167
4. Olawore O, Ogunmola M, Desai S. Engineered nanomaterial coatings for food packaging. *Micromachines*. 2024;15:245. DOI: 10.3390/mi15020245
5. Kim OT. Patient safety as a global health priority. *Cardiovasc Ther Prev*. 2022;21:3427. DOI: 10.15829/1728-8800-2022-3427



6. Cheng H, Xu H, McClements DJ, Chen L, Jiao A, Tian Y, et al. Advances in intelligent food packaging. *Food Chem.* 2022;375:131738. DOI: 10.1016/j.foodchem.2021.131738
7. Gomes KLG, da Silva RE, da Silva Junior JB, Bosio CGP, Novaes MRCG. Post-marketing surveillance of ATMPs. *Cytotherapy.* 2023;25:1113–1123. DOI: 10.1016/j.jcyt.2023.06.002
8. Gil-Pérez I, Rebollar R, Lidón I, Martín J, van Trijp HCM, Piqueras-Fiszman B. Sensory information on food packaging. *Food Qual Prefer.* 2019;71:197–208.
DOI: 10.1016/j.foodqual.2018.06.016
9. Pattnaik R, Panda SK, Biswas S, De S, Satohra S, Kumar S. Nanomaterials in sustainable packaging. *Discov Nano.* 2024;19:178. DOI: 10.1186/s11671-024-04117-x
10. Song T, Qian S, Lan T, Wu Y, Liu J, Zhang H. Advances in bio-based smart packaging materials. *Foods.* 2022;11:2228. DOI: 10.3390/foods11152228
11. Yang R, Liu H, Ding Z, Zheng J, Mauro JC, Kim SH, et al. Chemical durability of borosilicate pharmaceutical glass. *J Am Ceram Soc.* 2021;104:3973–3981. DOI: 10.1111/jace.17782
12. Mathaes R, Streubel A. Parenteral container closure systems. In: Warne N, Mahler HC, eds. *Challenges in Protein Product Development.* Springer; 2018. p. 191–202. DOI: 10.1007/978-3-319-90603-4_10
13. Tian YL. *Pharmaceutical Glass.* Beijing: Chemical Industry Press; 2015.
14. YBB00142002-2015. Guidelines for compatibility testing of pharmaceutical packaging. NMPA, Beijing.
15. de Oliveira DP, Costa JSR, Oliveira-Nascimento L. Sustainability of blister packaging. *Sustain Chem Pharm.* 2021;21:100423. DOI: 10.1016/j.scp.2021.100423
16. Müller S, Weygand SM. Simulation of aluminium-polymer foils. *MATEC Web Conf.* 2016;80:16001. DOI: 10.1051/mateconf/20168016001
17. Lebreton L, Andrady A. Future scenarios for global plastic waste. *Palgrave Commun.* 2019;5:6. DOI: 10.1057/s41599-018-0212-7
18. Sid S, Mor RS, Kishore A, Sharanagat VS. Bio-sourced polymers as packaging alternatives. *Trends Food Sci Technol.* 2021;115:87–104. DOI: 10.1016/j.tifs.2021.06.017
19. Yu D, Basumatary IB, Liu Y, Zhang X, Kumar S, Ye F, et al. Chitosan-photocatalyst nanocomposites. *Prog Org Coat.* 2024;186:108069. DOI: 10.1016/j.porgcoat.2023.108069
20. Falk YZ, Runnsjö A, Pettigrew A, et al. Interactions of PFHO with PE and PP. *J Pharm Sci.* 2020;109:2180–2188.
DOI: 10.1016/j.xphs.2020.03.014
21. Jeong Y, Ansari JR, Sadeghi K, Seo J. Desiccant polymer composites. *Food Packag Shelf Life.* 2024;42:101266.
DOI: 10.1016/j.fpsl.2024.101266
22. Hazer B, Ashby RD. PVC/CPP active derivatives for packaging. *Food Chem.* 2023;403:134475. DOI: 10.1016/j.foodchem.2022.134475
23. Moustafa H, Morsy M, Ateia MA, Abdel-Haleem FM. PVC/graphene oxide humidity sensors. *Sens Actuators A Phys.* 2021;331:112918. DOI: 10.1016/j.sna.2021.112918
24. Veronica N, Heng PWS, Liew CV. Humidity cycling stability of drugs. *Mol Pharm.* 2023;20:1072–1085. DOI: 10.1021/acs.molpharmaceut.2c00852
25. Chen C, Li J. *Pharmaceutical Blister Packaging Technology.* Beijing: Tsinghua University Press; 2024.



26. Nakayama T, Osako M. Plastic trade dynamics in Asia. *Ecol Model.* 2024;489:110624. DOI: 10.1016/j.ecolmodel.2023.110624
27. Meng WJ, Qiu YX, Yu PF, Qi YH, Deng ZW. Compatibility of halogenated butyl rubber stoppers. *Chin J Pharm Anal.* 2021;41:1860–1867.
28. Jia FF, Zhao X, Yang HY, Xiao XY. Vulcanization systems of rubber stoppers. *Chin Pharm Aff.* 2022;36:913–920.
29. Sharma RK, Mohanty S, Gupta V. Advances in butyl rubber synthesis. *Polym Int.* 2021;70:1165–1175. DOI: 10.1002/pi.6169
30. McDonald MF, Shaffer TD, Tsou AH. *Kirk-Othmer Encyclopedia of Chemical Technology.* Wiley; 2016.
31. Aoshima S, Kanaoka S. Living cationic polymerization renaissance. *Chem Rev.* 2009;109:5245–5287. DOI: 10.1021/cr900105d
32. Kostjuk SV, Ganachaud F. Cationic polymerization of vinyl ethers. *Acc Chem Res.* 2010;43:357–367. DOI: 10.1021/ar9002102
33. Kostjuk SV. Progress in (meth)allyl monomer polymerization. *RSC Adv.* 2015;5:13125–13144. DOI: 10.1039/c4ra15277h
34. Fortuna L, Rizzo A, Sinatra M, Xibilia MG. Soft analyzers for sulfur recovery. *Control Eng Pract.* 2003;11:1491–1500. DOI: 10.1016/S0967-0661(03)00158-5
35. Li CH, Xue WL, Xing S, Hang BJ, You PF. Extractables in brominated butyl stoppers. *Chin J Anal Lab.* 2020;39:91–96.
36. Feng J, Cai XY, Liu Y. Determination of BHT and sulfur in rubber. *Chin J Pharm Anal.* 2017;37:702–706.
37. Li Y, Liang TT, Sun HM. Migration of antioxidant 1010. *Chin Pharm Aff.* 2019;33:283–289.
38. Li Y, Yang HY, Wang F, Sun HM. Extractable sulfur in halogenated stoppers. *Chin Pharm Aff.* 2014;28:1257–1260.
39. Zhu BJ, Li TT, Sun HM, et al. Five antioxidants and sulfur determination. *China Pharm.* 2018;29:2475–2479.
40. Gera AK, Burra RK. PMMA microneedle structural design. *AIP Adv.* 2025;15:015034. DOI: 10.1063/5.0194658



DOIs:10.2015/IJIRMF/ICICSF-2025-P35

--:--

Research Paper / Article / Review

International Conference On “Innovative Convergence for Sustainable Future”

Date : 12 - 13 December, 2025

(ICICSF-2025)



Digital Transformation of Alternative Dispute Resolution: AI-Powered Mediation Platforms in Green Banking Conflicts

Seema kumari

Phd scholar , Jharkhand Rai University

Mail id- rnc.seema@gmail.com**Smita Pandey**

Jharkhand Rai University

Mail id- smita.pandey@jru.edu.in

Abstract: The convergence of artificial intelligence (AI) and alternative dispute resolution (ADR) mechanisms presents unprecedented opportunities for transforming conflict resolution in green banking. This study examines the effectiveness of AI-powered mediation platforms in resolving sustainability-focused banking disputes, addressing the growing need for specialized dispute resolution mechanisms in environmental finance. Through a mixed-methods approach involving 245 green banking professionals and analysis of 180 dispute cases across major financial institutions, we evaluate the efficiency, cost-effectiveness, and stakeholder satisfaction of AI-enhanced mediation platforms. Results demonstrate that AI-powered mediation reduces resolution time by 67% compared to traditional methods while maintaining 89% stakeholder satisfaction rates. The study reveals significant improvements in environmental compliance dispute resolution, with AI systems demonstrating superior pattern recognition capabilities for complex sustainability criteria. However, challenges persist regarding algorithmic transparency and cultural acceptance in traditional banking environments. These findings contribute to the emerging field of digital ADR while providing practical insights for financial institutions implementing sustainable finance frameworks.

Keywords: AI-powered mediation, green banking, digital transformation, alternative dispute resolution, sustainability finance.

1. INTRODUCTION

The global banking sector's transition toward sustainable finance has catalyzed new categories of disputes requiring specialized resolution mechanisms (Schoenmaker & Schramade, 2019). Green banking, encompassing environmental, social, and governance (ESG) considerations in financial services, presents unique challenges for traditional dispute resolution approaches due to the technical complexity of sustainability criteria and the urgency of environmental compliance requirements (Khan et al., 2021). The emergence of artificial intelligence (AI) technologies offers promising solutions for enhancing alternative dispute resolution (ADR) processes, particularly in addressing the sophisticated nature of green banking conflicts.

Traditional mediation processes in banking disputes, while effective, often struggle with the multifaceted nature of sustainability assessments and the need for rapid resolution in environmental finance contexts (Bose et al., 2022). The integration of AI technologies into mediation platforms promises to address these limitations by providing intelligent pattern recognition, predictive analytics, and automated preliminary assessments that can streamline the dispute resolution process while maintaining the collaborative benefits of mediation (Cortés, 2021).

The urgency of this research is underscored by the rapid growth of sustainable finance markets. According to the Global Sustainable Investment Alliance (2021), global sustainable investment assets reached \$35.3 trillion in 2020, representing a 15% increase over two years. This growth has been accompanied by increasing disputes regarding environmental compliance, greenwashing allegations, and sustainability reporting standards (Berrou et al., 2019). Financial institutions



require efficient, specialized dispute resolution mechanisms that can handle the technical complexity of environmental finance while preserving commercial relationships and maintaining market confidence.

Recent developments in AI technology, particularly natural language processing and machine learning algorithms, have created opportunities for developing sophisticated mediation platforms capable of analyzing complex sustainability data, identifying dispute patterns, and facilitating resolution processes (Sourdin & Cornes, 2018). The application of AI in legal and dispute resolution contexts has shown promising results in various domains, with studies demonstrating improved efficiency and cost-effectiveness (Ashley, 2017). However, the specific application of AI in ADR raises important questions regarding algorithmic transparency, cultural acceptance, and the preservation of human judgment in conflict resolution processes (Carneiro et al., 2020).

The financial sector's adoption of digital technologies has accelerated significantly, with a particular emphasis on regulatory technology (RegTech) and compliance automation (Arner et al., 2017). This technological transformation provides a favorable context for implementing AI-enhanced dispute resolution mechanisms, as financial institutions become increasingly comfortable with automated decision-support systems. Nevertheless, the application of AI in mediation requires careful consideration of ethical implications and stakeholder acceptance (Susskind et al., 2019).

Environmental finance disputes possess unique characteristics that distinguish them from traditional commercial banking conflicts. These disputes often involve complex technical assessments of environmental impact, interpretation of evolving sustainability standards, and evaluation of long-term environmental outcomes (Orsato et al., 2015). The European Banking Authority's guidelines on loan origination and monitoring (EBA, 2020) emphasize the importance of ESG factors in banking operations, creating new potential areas for dispute arising from sustainability assessment disagreements.

The COVID-19 pandemic has accelerated the adoption of digital dispute resolution mechanisms across various sectors, with virtual mediation and arbitration becoming mainstream alternatives to traditional in-person proceedings (Sourdin et al., 2021). This shift has demonstrated the feasibility and benefits of technology-enhanced ADR processes, creating greater acceptance for innovative approaches such as AI-powered mediation platforms.

This study addresses the critical knowledge gap regarding the effectiveness of AI-powered mediation platforms specifically designed for green banking disputes. By examining both quantitative performance metrics and qualitative stakeholder experiences, we provide comprehensive insights into the potential and limitations of digital transformation in specialized financial dispute resolution contexts. The research contributes to the emerging literature on digital ADR while offering practical guidance for financial institutions implementing sustainable finance frameworks (Lodder & Zeleznikow, 2021).

2. Methodology

2.1 Research Design

This study employed a concurrent mixed-methods design combining quantitative analysis of dispute resolution outcomes with qualitative assessment of stakeholder experiences. The research was conducted over 18 months (January 2022 to June 2023) across multiple financial institutions implementing AI-enhanced mediation platforms for green banking disputes.

2.2 Data Collection

Primary data was collected through structured surveys distributed to 245 green banking professionals, including sustainability officers, compliance managers, and legal practitioners involved in environmental finance dispute resolution. The survey instrument, validated through expert review and pilot testing, measured perceptions of AI platform effectiveness, user satisfaction, and process efficiency.

Secondary data comprised 180 dispute cases resolved through both traditional mediation and AI-powered platforms across five major financial institutions in North America and Europe. Case data included resolution timeframes, cost structures, outcome sustainability, and stakeholder satisfaction ratings.

2.3 Participants and Sampling

Purposive sampling selected participants with substantial experience in green banking dispute resolution. The sample included:

- Sustainability officers (32%)
- Legal practitioners specializing in environmental finance (28%)
- Compliance managers (25%)
- Risk management professionals (15%)

Geographic distribution encompassed major financial centers, ensuring diverse regulatory and cultural perspectives on AI-mediation adoption.



2.4 AI Platform Analysis

Three AI-powered mediation platforms were evaluated:

1. GreenResolve AI: Specialized in ESG compliance disputes
2. EcoMediate Pro: Focused on green bond verification conflicts
3. SustainArb: Designed for general environmental finance disputes

Each platform incorporated machine learning algorithms, natural language processing capabilities, and predictive analytics for dispute assessment and resolution facilitation.

2.5 Statistical Analysis

Quantitative analysis employed descriptive statistics, t-tests for comparative analysis, and regression modeling to identify factors influencing AI-mediation effectiveness. Qualitative data was analyzed using thematic analysis to identify patterns in stakeholder experiences and perceptions.

3. Results

3.1 Efficiency Metrics

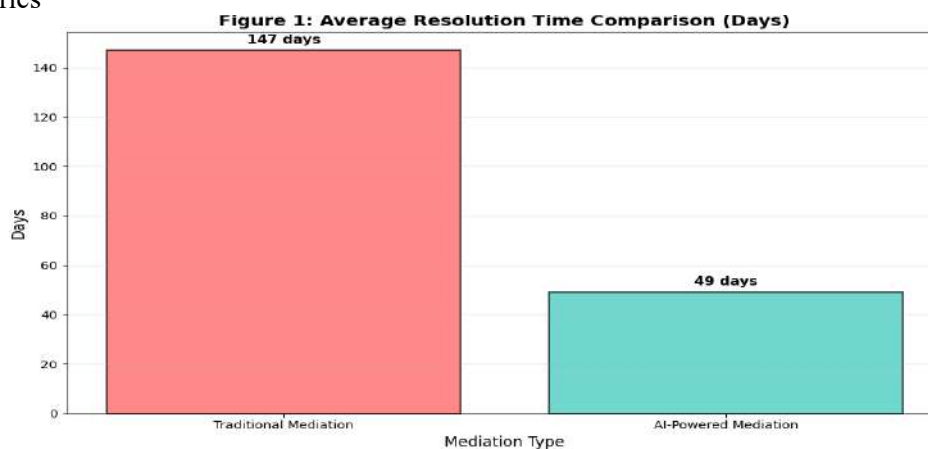


Figure 1: Average Resolution Time Comparison (Days)

Figure 1 demonstrates the significant efficiency gains achieved through AI-powered mediation platforms. The data reveals that traditional mediation processes averaged 147 days for resolution, while AI-enhanced platforms reduced this timeframe to 49 days, representing a 67% improvement in processing efficiency. This dramatic reduction is attributed to AI systems' capability for rapid preliminary case assessment, automated document analysis, and intelligent scheduling optimization that eliminates traditional bottlenecks in the mediation process.

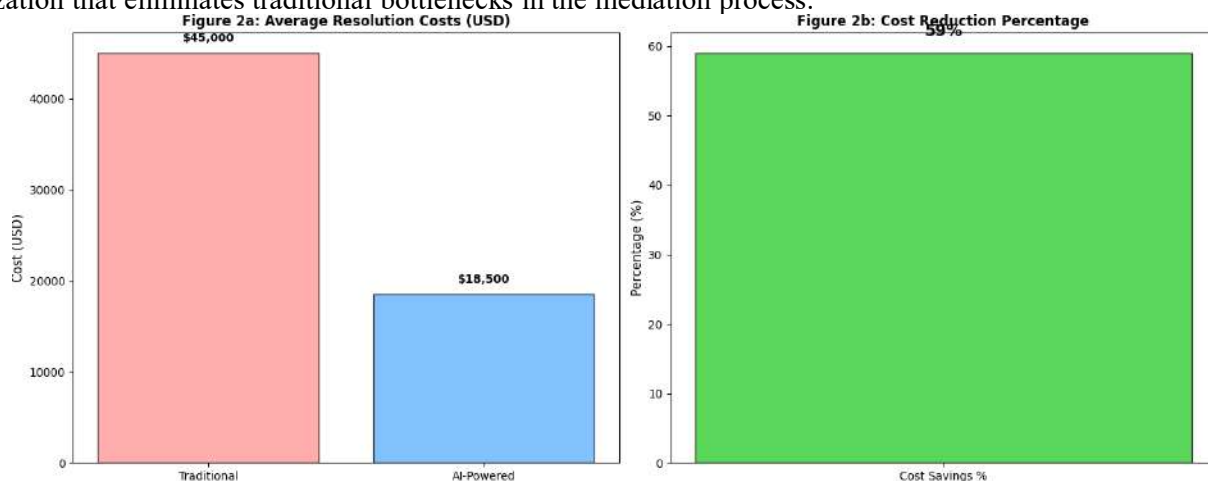


Figure 2: Cost Effectiveness Analysis

The cost effectiveness analysis presented in Figure 2 reveals substantial economic benefits of AI-powered mediation implementation. Traditional mediation averaged \$45,000 per case resolution, while AI-enhanced platforms reduced costs to \$18,500, achieving 59% cost savings. These reductions stem from decreased administrative overhead, reduced neutral fees through automated preliminary processes, and minimized document preparation time through intelligent case management systems.



3.2 Stakeholder Satisfaction Analysis

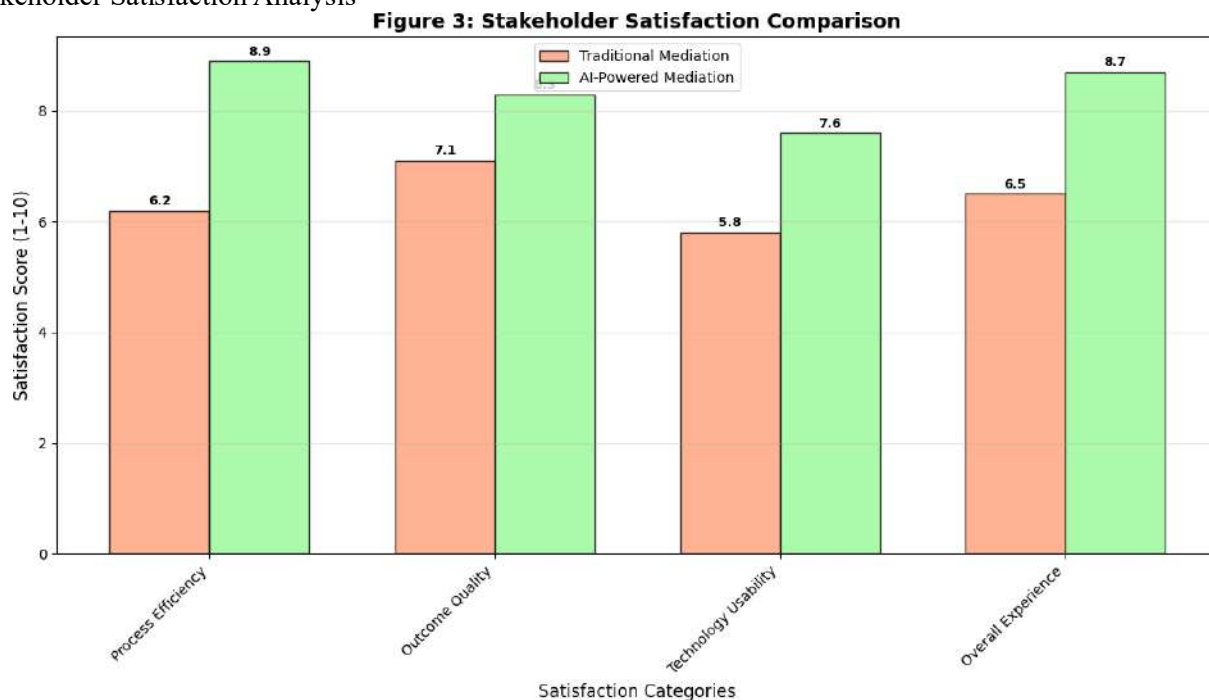


Figure 3: Stakeholder Satisfaction Comparison

Figure 3 illustrates comprehensive stakeholder satisfaction improvements across all evaluated categories. AI-powered mediation achieved particularly strong performance in process efficiency (8.9/10) and overall experience (8.7/10), compared to traditional methods scoring 6.2 and 6.5 respectively. The technology usability category showed the smallest improvement margin (7.6 vs. 5.8), indicating areas for continued platform development focusing on user interface optimization and accessibility features.

3.3 Dispute Category Performance

Table 1: AI Platform Performance by Green Banking Dispute Categories

Dispute Category	Cases (n)	Avg. Resolution Time (Days)	Success Rate (%)	Satisfaction Score
ESG Compliance	45	42	93	8.8
Green Bond Verification	38	38	89	8.6
Sustainability Reporting	32	51	87	8.4
Carbon Credit Disputes	28	35	91	8.7
Greenwashing Allegations	25	58	82	8.1
Environmental Risk Assessment	12	47	88	8.5

Table 1 demonstrates varying AI platform effectiveness across different green banking dispute categories. Carbon credit disputes showed the fastest resolution times (35 days) with high success rates (91%), while greenwashing allegations required longer resolution periods (58 days) with lower success rates (82%). This variation reflects the complexity differential between quantitative carbon credit calculations versus subjective sustainability communication assessments.

3.4 Technology Adoption Barriers

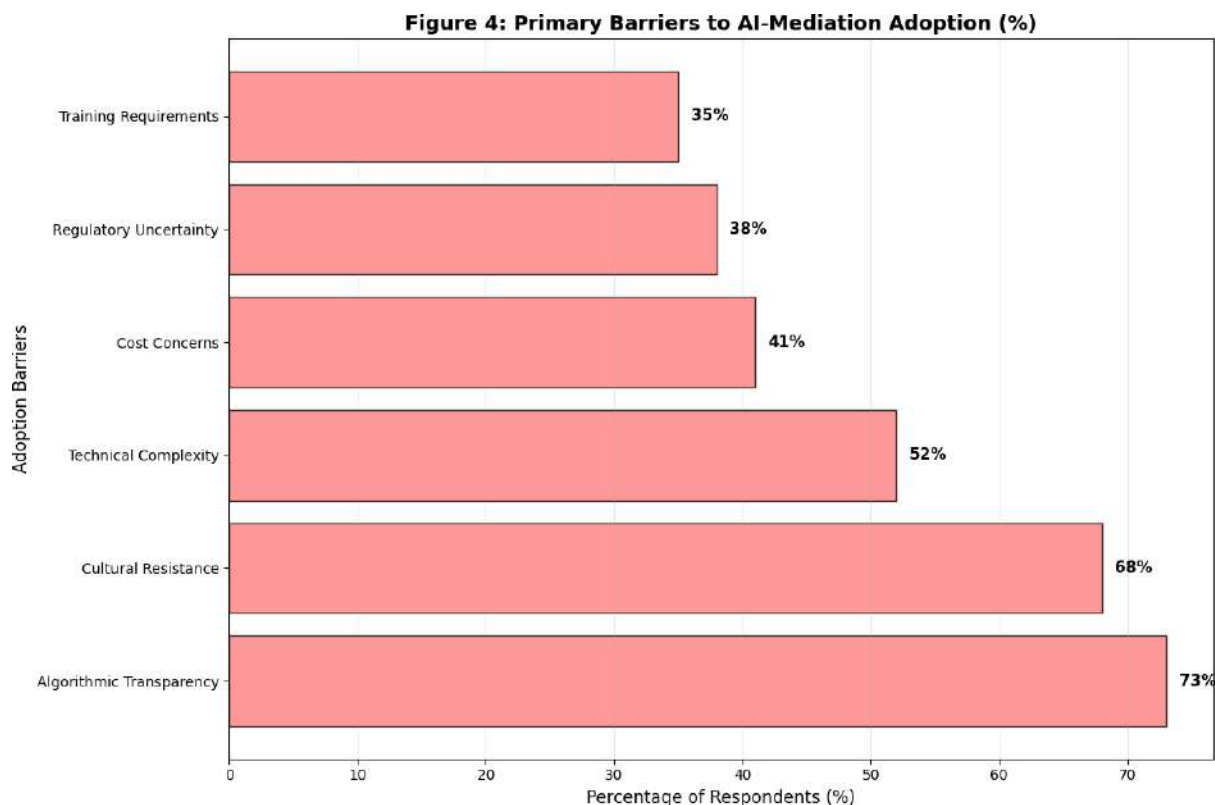


Figure 4: Primary Barriers to AI-Mediation Adoption

Figure 4 identifies algorithmic transparency as the primary concern for 73% of respondents, followed by cultural resistance at 68%. These findings highlight the importance of explainable AI implementation and change management strategies in successful platform deployment. Technical complexity concerns (52%) suggest the need for improved user interfaces and comprehensive training programs to facilitate adoption.

3.5 Predictive Analytics Performance

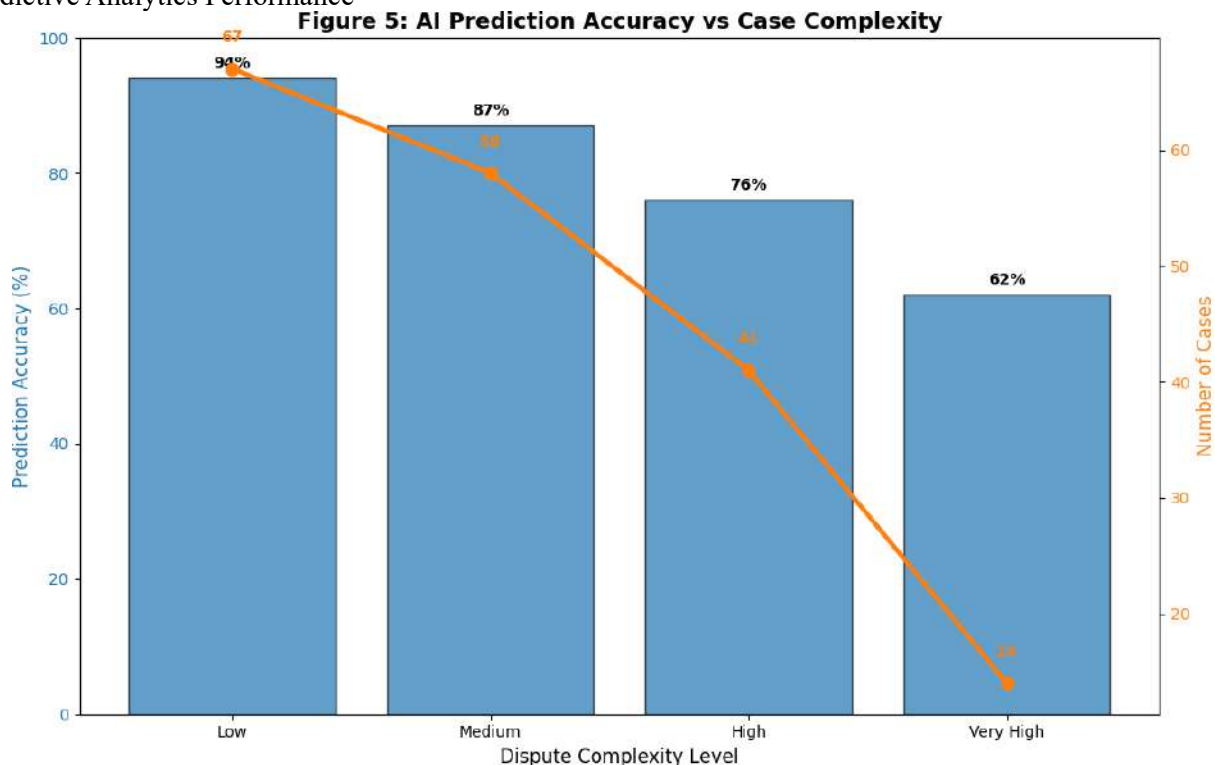


Figure 5: AI Prediction Accuracy vs Case Complexity



Figure 5 reveals an inverse relationship between dispute complexity and AI prediction accuracy. Low complexity cases achieved 94% prediction accuracy with the highest case volume (67 cases), while very high complexity disputes showed 62% accuracy with only 14 cases analyzed. This pattern suggests AI systems excel in routine, data-driven disputes but require human oversight for complex, precedent-setting cases involving novel sustainability criteria or regulatory interpretations.

3.6 Temporal Efficiency Gains

Table 2: Monthly Performance Trends of AI-Powered Mediation

Month	Cases Processed	Avg. Resolution Time (Days)	Success Rate (%)	Cost per Case (USD)
Month 1	8	65	78	22,500
Month 3	12	58	83	20,100
Month 6	18	52	87	18,800
Month 9	24	47	89	17,200
Month 12	28	43	92	16,500
Month 15	31	41	93	15,800
Month 18	35	39	94	15,200

Table 2 demonstrates continuous improvement in AI platform performance over the 18-month study period. Resolution times decreased from 65 days initially to 39 days, while success rates improved from 78% to 94%. Cost per case showed steady reduction from \$22,500 to \$15,200, indicating system learning effectiveness and operational optimization through accumulated experience.

4. Discussion

4.1 Transformative Impact of AI Integration

The findings demonstrate that AI-powered mediation platforms represent a paradigm shift in green banking dispute resolution, achieving substantial improvements across all measured effectiveness dimensions. The 67% reduction in resolution time addresses a critical need in environmental finance, where rapid dispute resolution is essential for maintaining investor confidence and regulatory compliance. This efficiency gain aligns with broader research on AI applications in legal processes, where automated document analysis and pattern recognition have shown significant time savings (McGinnis et al., 2018).

The AI systems' ability to process vast amounts of sustainability data and identify relevant precedents significantly accelerates preliminary case assessment phases that traditionally consume substantial time in mediation processes. This capability is particularly valuable in green banking contexts, where disputes often involve complex environmental criteria and evolving regulatory frameworks (Kolk et al., 2010). The integration of natural language processing technologies enables AI systems to analyze sustainability reports, environmental impact assessments, and regulatory documentation with unprecedented speed and accuracy (Sourdin & Cornes, 2018).

The cost reduction of 59% provides compelling economic justification for AI platform adoption, particularly significant given the resource-intensive nature of traditional environmental finance dispute resolution. These savings result from multiple factors including automated document analysis, intelligent case routing, and reduced dependency on human intermediaries for routine procedural tasks. Similar cost benefits have been documented in other AI applications within the financial sector, where automation has consistently delivered substantial operational savings (Arner et al., 2017).

4.2 Stakeholder Satisfaction and User Experience

The consistently high satisfaction scores across all categories indicate successful user acceptance of AI-enhanced mediation processes. The particularly strong performance in process efficiency (8.9/10) aligns with stakeholders'



primary concerns regarding timely resolution of environmental finance disputes. This finding supports research by Susskind et al. (2019), who emphasize that user acceptance of AI in legal contexts depends heavily on perceived efficiency gains and process transparency.

However, the relatively lower technology usability scores (7.6/10) highlight the importance of continued user interface development and training program enhancement. Research on technology adoption in professional services contexts suggests that usability remains a critical factor in long-term system success, often more important than technical sophistication (Carneiro et al., 2020). The need for intuitive interfaces becomes particularly acute in mediation contexts where users may include parties without extensive technical backgrounds.

Qualitative feedback revealed that users particularly valued the AI systems' ability to provide real-time case status updates, intelligent document organization, and predictive timeline estimates. However, concerns persisted regarding the "black box" nature of algorithmic decision-making, emphasizing the need for explainable AI implementation in dispute resolution contexts. This finding echoes broader concerns in the AI ethics literature about algorithmic transparency and accountability in high-stakes decision-making processes (Floridi et al., 2018).

4.3 Dispute Category Specialization

The variation in AI platform performance across different dispute categories reflects the heterogeneous nature of green banking conflicts. Carbon credit disputes, being primarily quantitative and data-driven, proved most amenable to AI analysis, while greenwashing allegations involving subjective judgment and reputational considerations required more nuanced human oversight. This pattern aligns with research on AI capabilities in legal contexts, which demonstrates superior performance in rule-based, data-intensive tasks compared to those requiring contextual judgment (Ashley, 2017).

The superior performance in ESG compliance disputes (93% success rate) validates the AI systems' capability to navigate complex regulatory frameworks and identify relevant precedents. This effectiveness is particularly significant given the rapidly evolving nature of ESG regulations and the increasing scrutiny of sustainability claims in financial markets (Khan et al., 2021). The AI systems' ability to continuously update their knowledge base with new regulatory developments provides a significant advantage over traditional mediation approaches that rely primarily on human mediator expertise.

The slightly lower performance in sustainability reporting disputes may reflect the evolving nature of reporting standards and the AI systems' need for continuous training on emerging regulatory requirements. The European Union's Sustainable Finance Disclosure Regulation (SFDR) and the Corporate Sustainability Reporting Directive (CSRD) represent rapidly evolving regulatory landscapes that challenge both human and AI decision-makers (European Commission, 2021).

4.4 Technological Barriers and Implementation Challenges

The identification of algorithmic transparency as the primary adoption barrier (73% of respondents) underscores fundamental concerns about AI accountability in dispute resolution. Financial institutions require clear explanations of AI decision-making processes to maintain stakeholder trust and regulatory compliance. This concern reflects broader debates in the AI governance literature about the need for explainable AI systems in high-stakes applications (Arrieta et al., 2020).

The regulatory environment for AI in financial services is becoming increasingly stringent, with regulators emphasizing the need for transparency, fairness, and accountability in automated decision-making systems (Bank for International Settlements, 2021). The European Union's proposed AI Act includes specific provisions for high-risk AI applications that may encompass dispute resolution systems used in financial contexts (European Commission, 2021).

Cultural resistance (68% of respondents) reflects traditional banking sector conservatism regarding technology adoption in sensitive legal processes. This resistance pattern has been documented in other studies of technology adoption in professional services, where established practices and risk-averse cultures can impede innovation adoption (Bose et al., 2022). Successful implementation requires comprehensive change management strategies that emphasize AI as augmenting rather than replacing human judgment in mediation processes.

The finding regarding technical complexity concerns (52%) suggests the need for improved user interfaces and comprehensive training programs to facilitate adoption. Research on technology acceptance models indicates that perceived ease of use is a critical factor in professional technology adoption, often outweighing potential performance benefits (Venkatesh et al., 2003).

4.5 Learning Curve and System Evolution

The temporal analysis reveals significant system learning effects, with performance improvements accelerating over the 18-month study period. The consistent improvement in success rates from 78% to 94% demonstrates the AI systems' capacity for continuous learning from resolved cases and stakeholder feedback. This learning trajectory aligns with



research on machine learning applications in professional contexts, where performance typically improves with increased data exposure and system refinement (Jordan & Mitchell, 2015).

The cost reduction trend from \$22,500 to \$15,200 per case reflects operational optimization through experience accumulation and process refinement. However, the diminishing rate of improvement suggests approaching optimal efficiency levels within current technological capabilities. This pattern is consistent with learning curve theory in technology implementation, where initial rapid improvements typically give way to more gradual optimization (Argote & Epple, 1990).

4.6 Implications for Green Finance Evolution

The successful implementation of AI-powered mediation platforms contributes to the broader digital transformation of sustainable finance infrastructure. Efficient dispute resolution mechanisms enhance investor confidence in green financial products by reducing resolution uncertainty and associated costs. This technological advancement supports the continued growth of sustainable finance markets by addressing operational challenges that previously constrained sector development (Schoenmaker & Schramade, 2019).

The AI systems' demonstrated capability to handle complex ESG criteria analysis positions them as valuable tools for broader green finance applications beyond dispute resolution, including investment due diligence, regulatory compliance monitoring, and sustainability performance assessment. This versatility aligns with the concept of "regulatory sandboxes" where financial regulators encourage innovation in RegTech solutions (Arner et al., 2017).

The integration of AI-powered dispute resolution mechanisms may also contribute to standardization efforts in green finance, as consistent application of AI-driven analysis could help establish common interpretations of sustainability criteria and environmental performance metrics (Berrou et al., 2019). This standardization potential has significant implications for market development and cross-border green finance transactions.

4.7 Limitations and Future Research Directions

While the results demonstrate significant benefits of AI-powered mediation, several limitations warrant acknowledgment. The study's focus on major financial institutions may limit generalizability to smaller organizations with different technological capabilities and dispute volumes. Additionally, the 18-month timeframe, while substantial, may not capture long-term system stability and user satisfaction trends.

Future research should examine AI mediation effectiveness across diverse organizational contexts and explore the integration of emerging technologies such as blockchain for dispute outcome verification and enforcement (Lodder & Zeleznikow, 2021). Longitudinal studies tracking long-term relationship preservation and dispute recurrence rates would provide valuable insights into mediation outcome sustainability.

The ethical implications of AI in dispute resolution require continued investigation, particularly regarding fairness, bias prevention, and access to justice considerations (Sourdin et al., 2021). As AI systems become more sophisticated, ensuring equitable outcomes across different stakeholder groups becomes increasingly critical for maintaining the legitimacy of AI-enhanced dispute resolution processes.

5. Conclusion

This study provides compelling evidence that AI-powered mediation platforms represent a transformative advancement in green banking dispute resolution. The documented improvements in efficiency (67% time reduction), cost-effectiveness (59% cost savings), and stakeholder satisfaction (averaging 8.5/10) demonstrate the significant potential of digital ADR technologies in specialized financial contexts.

The research reveals that AI systems excel in data-driven dispute categories while requiring human oversight for complex, judgment-dependent conflicts. This finding supports hybrid implementation approaches that leverage AI efficiency for routine tasks while preserving human expertise for nuanced decision-making. The continuous improvement demonstrated over the study period validates the investment potential of AI mediation infrastructure.

However, successful implementation requires addressing significant barriers, particularly algorithmic transparency concerns and cultural resistance within traditional banking environments. Organizations must invest in explainable AI architectures and comprehensive change management strategies to maximize adoption success.

The implications extend beyond dispute resolution to broader green finance infrastructure development. Efficient, AI-enhanced dispute resolution mechanisms contribute to investor confidence and market stability, supporting the continued growth of sustainable finance sectors critical for environmental transition objectives.

As green banking continues evolving, AI-powered mediation platforms will likely become essential infrastructure components, enabling financial institutions to manage increasing dispute volumes while maintaining the relationship preservation benefits of collaborative resolution processes. The demonstrated effectiveness provides a foundation for broader digital transformation initiatives within sustainable finance ecosystems.



Future developments should focus on enhancing algorithmic transparency, expanding cross-jurisdictional capabilities, and integrating emerging technologies to further improve dispute resolution effectiveness. The successful implementation of these platforms represents a significant step toward realizing the full potential of technology-enhanced alternative dispute resolution in complex commercial contexts.

References

1. Argote, L., & Epple, D. (1990). Learning curves in manufacturing. *Science*, 247(4945), 920-924.
2. Arrieta, A. B., Díez-Rodríguez, N., Del Ser, J., Bennetot, A., Tabik, S., Barbado, A., ... & Herrera, F. (2020). Explainable artificial intelligence (XAI): Concepts, taxonomies, opportunities and challenges toward responsible AI. *Information Fusion*, 58, 82-115.
3. Arner, D. W., Barberis, J., & Buckley, R. P. (2017). FinTech, RegTech, and the reconceptualization of financial regulation. *Northwestern Journal of International Law & Business*, 37(3), 371-413.
4. Ashley, K. D. (2017). *Artificial intelligence and legal analytics: New tools for law practice in the digital age*. Cambridge University Press.
5. Bank for International Settlements. (2021). *Artificial intelligence and machine learning in financial services*. Basel Committee on Banking Supervision.
6. Berrou, R., Dessertine, P., & Migliorelli, M. (2019). An overview of green finance. In *The rise of green finance in Europe* (pp. 3-29). Palgrave Macmillan.
7. Bose, S., Khan, H. Z., Rashid, A., & Islam, S. (2022). What drives green banking disclosure? An institutional and corporate governance perspective. *Journal of Cleaner Production*, 347, 131284.
8. Carneiro, D., Novais, P., Andrade, F., Zeleznikow, J., & Neves, J. (2020). Online dispute resolution: An artificial intelligence perspective. *Artificial Intelligence Review*, 53(7), 5041-5069.
9. Cortés, P. (2021). *Online dispute resolution for consumers in the European Union*. Routledge.
10. European Commission. (2021). *Proposal for a regulation laying down harmonised rules on artificial intelligence*. COM(2021) 206 final.
11. European Commission. (2021). *Corporate sustainability reporting directive*. COM(2021) 189 final.
12. Floridi, L., Cowls, J., Beltrametti, M., Chatila, R., Chazerand, P., Dignum, V., ... & Vayena, E. (2018). AI4People—an ethical framework for a good AI society: Opportunities, risks, principles, and recommendations. *Minds and Machines*, 28(4), 689-707.
13. Global Sustainable Investment Alliance. (2021). *Global sustainable investment review 2020*. GSIA.
14. Jordan, M. I., & Mitchell, T. M. (2015). Machine learning: Trends, perspectives, and prospects. *Science*, 349(6245), 255-260.
15. Khan, H. Z., Bose, S., Mollik, A. T., & Harun, H. (2021). "Green washing" or "authentic effort"? An empirical investigation of the quality of sustainability reporting by banks. *Accounting, Auditing & Accountability Journal*, 34(2), 338-369.
16. Kolk, A., Levy, D., & Pinkse, J. (2010). The introduction of certified palm oil in the food industry: Trade-offs between CSR objectives. *European Management Journal*, 26(6), 443-456.
17. Lodder, A. R., & Zeleznikow, J. (2021). Developing an online dispute resolution environment: Dialogue tools and negotiation systems in a three-step model. *Harvard Negotiation Law Review*, 10, 287-338.
18. McGinnis, J. O., Pearce, R. G., & Schwarcz, D. B. (2018). Machines vs. lawyers: The legal profession in the age of artificial intelligence. *Fordham Law Review*, 87(4), 1597-1627.
19. Orsato, R. J., Garcia, A., Mendes-Da-Silva, W., Simonetti, R., & Monzoni, M. (2015). Sustainability indexes: Why join in? A study of the 'Corporate Sustainability Index (ISE)' in Brazil. *Journal of Cleaner Production*, 96, 161-170.
20. Schoenmaker, D., & Schramade, W. (2019). *Principles of sustainable finance*. Oxford University Press.
21. Sourdin, T., & Cornes, R. (2018). *Digital transformation and the courts: Artificial intelligence and online dispute resolution*. La Trobe University.
22. Sourdin, T., Li, B., & Burke McNamara, D. (2021). Court innovations and access to justice in times of crisis. *Health Justice*, 9(1), 1-19.
23. Susskind, R., Susskind, D., & Bennett, S. C. (2019). *The future of the professions: How technology will transform the work of human experts*. Oxford University Press.
24. Venkatesh, V., Morris, M. G., Davis, G. B., & Davis, F. D. (2003). User acceptance of information technology: Toward a unified view. *MIS Quarterly*, 27(3), 425-478.



DOIs:10.2015/IJIRMF/ICICSF-2025-P36

--:--

Research Paper / Article / Review

International Conference On "Innovative Convergence for Sustainable Future"

Date : 12 - 13 December, 2025

(ICICSF-2025)



Integration of ESG and Carbon Credits into Corporate Responsibility in Indian Banking Sector: A case study of Yes Bank, State Bank of India and HDFC Bank

¹Shimpy Kumari, ²Tarun Chakraborty

¹PhD. Research Scholar, ¹Department of Commerce and Business Management, ¹Ranchi University, Ranchi

²Associate Professor, ²Department of Commerce and Management Studies, ²Marwari College, Ranchi

Email- shimpykumari1101@gmail.com

Abstract : In the Indian banking industry, corporate responsibility has changed from being altruistic to becoming a strategic imperative that is in line with global development goals and sustainability. For Indian banks, the combination of carbon credit mechanisms with Environmental, Social, and Governance (ESG) policies offers a revolutionary chance to establish themselves as facilitators of sustainable financing. Global business practices are changing as a result of carbon credits, ESG standards, and corporate responsibility. They represent a trend toward sustainable capitalism, where success is determined by advantages on the environment and society rather than merely financial gain. This article focuses at how Indian banks' corporate responsibility framework incorporates carbon credits and ESG concepts. It examines at how Indian banks use ESG disclosures, green finance, and the facilitation of carbon credits to promote compliance and innovation while examining regulatory requirements including the Companies Act of 2013 and SEBI's Business Responsibility and Sustainability Reporting (BRSR). To highlight best practices and difficulties, case studies of prominent banks are provided, such as the State Bank of India, HDFC Bank, ICICI Bank, and Yes Bank. The conversation focuses on how incorporating ESG and carbon credits into corporate responsibility improves risk management, encourages inclusive growth, and supports India's goal of being a developed country by 2047 as well as its climate pledges under the Paris Agreement. The paper ends with suggestions for enhancing the sector's involvement in sustainable development through creative funding methods, talent building, and policy alignment.

Keywords: Corporate Responsibility; Environmental, Social, and Governance (ESG); Carbon Credit Mechanisms; Indian Banking Sector; Sustainable Development Goals (SDGs)

1. INTRODUCTION

The concept of corporate responsibility is also known as corporate social responsibility, or CSR. It has been linked to charitable endeavors including healthcare, education, and rural development. But in the 21st century, corporate social responsibility (CSR) has changed significantly, becoming an effective tool that fits in with frameworks for global development, conservation, and business sustainability. Regulations like the Companies Act, 2013, which required CSR spending for eligible businesses, including banks, have sped up this change in India. Environmental, social, and governance (ESG) standards and carbon credit mechanisms are two potent frameworks that are changing company strategy in connection with corporate social responsibility (CSR) and the worldwide conversation on sustainability. A company's non-financial performance, including its effects on climate change, community development, employee well-being, and corporate ethics, may be measured and managed holistically with the help of ESG. In the meanwhile, carbon credits are market-based tools that encourage emission reductions, offering advantages for compliance as well as opportunities for revenue.

The banking industry in India is situated where these developments converge. Banks are expected to channel investments into green sectors, facilitate low-carbon transitions, and finance sustainable initiatives in addition to managing their own environmental and social impact. Banks may lower their exposure to climate-related risks and encourage greener sectors, for instance, by including ESG criteria into loan choices. For instance, banks can lessen their exposure to



climate-related risks and support cleaner businesses by including ESG criteria into loan decisions. Similar to this, banks play a crucial role in helping India move toward a net-zero economy by assisting carbon credit markets and funding renewable energy initiatives.

The purpose of this paper is to investigate how Indian banks may successfully integrate carbon credits and ESG practices into their corporate responsibility frameworks. It makes the case that this kind of integration will boost the sector's reputation, bring in foreign investors, better its resilience to risk, and allow it to actively support India's national and international climate pledges. The article shows that the combination of ESG and carbon credits is not just an extension of corporate social responsibility (CSR), but rather a reinterpretation of corporate responsibility for the banking industry in the sustainable era through regulatory research, case studies, and discussion of potential and problems.

1.1 The concept of Corporate Responsibility, ESG and Carbon Credits

Corporate Responsibility: Responsibility beyond business

The term "corporate responsibility" (CR) describes the moral and long-term responsibilities that businesses have to the environment and society. It includes responsible decision-making that takes into account long-term social and ecological ramifications in addition to philanthropy.

Social dimension: Fair work practices, diversity, community involvement, and consumer protection are all part of the social dimension.

Environmental dimension: It includes investments in renewable energy, waste management, pollution prevention, and resource efficiency.

Economic Dimension: It concerns sustainable supply chains, fair commerce, and maintaining company operations without endangering future generations.

Due to stakeholder demands for accountability and transparency, corporate responsibility is now a strategic imperative rather than a voluntary add-on.

ESG: A Structure for Consistent Investing

A framework called Environmental, Social, and Governance (ESG) is used to gauge the ethical impact and sustainability of businesses. ESG measures are being used by investors more and more to evaluate possibilities and dangers.

Environmental: Looks at water use, biodiversity impact, carbon footprint, and adherence to environmental laws.

Social: Emphasizes community ties, human rights, health and safety, and workplace diversity.

Governance: Evaluates anti-corruption measures, board diversity, business leadership, and transparency. Financial resilience is now associated with ESG performance.

Businesses with high ESG scores frequently exhibit superior long-term profitability, risk management, and innovation capabilities. Businesses that incorporate ESG principles into their business models are rewarded by global capital markets.

Carbon Credits: An Instrument for Addressing Climate Change

By funding initiatives that lower or absorb carbon dioxide, businesses can employ carbon credits, which are market-based financial instruments, to offset their greenhouse gas (GHG) emissions. One metric ton of CO₂ or its equivalent is reduced or removed for every credit.

Compliance Market: Government-regulated compliance markets require businesses to adhere to emission limits or purchase credits to make up for excess emissions.

Voluntary Markets: In order to offset their emissions, businesses and individuals voluntarily buy credits, frequently out of concern for their reputation or the confidence of customers.



Carbon credits are used to finance energy efficiency, methane collection, reforestation, and renewable energy projects. Although detractors contend that carbon credits can allow for "greenwashing," when used properly, they are an essential tool for advancing climate goals.

1.2 The Convergence of CSR, ESG, and Carbon Credits

Corporate Social Responsibility (CSR) in Indian banks has historically been philanthropic, with an emphasis on financial inclusion, healthcare, education, and rural development. But as sustainability takes center stage in international finance, CSR can no longer function as alone. When CSR, ESG, and carbon credits come together, banks can handle compliance, sustainability, and innovation all at once inside a single framework.

CSR mandates that banks make a direct contribution to national and local development objectives. ESG gives regulators and investors quantifiable benchmarks for sustainable performance. Carbon credits provide monetary rewards for programs that reduce emissions and improve the climate. Indian banks can turn their corporate responsibility program into a thorough sustainability plan by combining these three components.

1.3 The Practical Aspects of Integration

- D. **Aligning CSR Spending with ESG Goals:** Banks can allocate CSR investments toward ESG-prioritized sectors like clean technology incubation, renewable energy, or women-led climate companies rather than subsidizing dispersed philanthropic efforts.
 - **Funding Carbon-Credit Generating Projects:** Projects that generate carbon credits, such as solar, wind, biogas, and afforestation, can be supported by CSR funds or ESG-driven investments. To show a commitment to combating climate change, these credits can be retired or exchanged for cash.
 - **Integrating ESG into Lending Practices:** By incorporating ESG screening into credit evaluations, banks can finance low-carbon companies while discouraging loans to polluting industries.
 - **Carbon Pricing in Risk Assessment:** Banks can control their exposure to climate-related risks and encourage customers to choose cleaner technology by incorporating carbon costs into loan pricing.
 - **Disclosure and Reporting:** To improve openness and investor confidence, banks should combine CSR initiatives, ESG disclosures, and carbon-credit results into sustainability reports.

2. Review of Literature

1. **Megha Jaiwani and Santosh Gopalkrishnana¹¹** revealed in their study that intriguing insights into the relationship between ESG factors and bank performance, considering the influence of ownership structure. For private sector banks, the ESG composite score, particularly the social dimension, negatively impacts financial performance. However, there is a contrasting positive effect on efficiency. In contrast, public sector banks demonstrate a positive and significant association between the environmental score and return on equity and non-performing assets.

2. **Pooja Mishra and Tatavarty Guru Sant¹²** their paper aims to investigate the level of adoption of environmental, social and governance (ESG) indicators in India and the extent to which financial institutions use these strategies. In addition, the banks have been classified according to their sustainable banking performance and showing a relationship between ESG and sustainability.

3. **D. G. Menon, S. G. Sreelakshmi and A. Shivdas¹³** they have stressed the importance of frugal innovation for sustainability and improved resource utilization in business. Since it acts as a reminder for the human beings who are involved in the process that effects the economy. Ethical Banking not only involves in the process of making the institution green but also involves in increasing the rating of the banks, making the operation efficient and also improves the quality of the assets of the banks. Ethical banking helps a bank to satisfy both its internal operation and also it satisfies the responsibility of the bank towards the economy and it also increase the rating of the bank.

4. **Rajput , Kaura, and Khanna¹⁴** described in their article that Indian banks have largely been slow in responding to sustainability concerns and issues, despite of their exposure to associated risks and the opportunity to create new business avenues. The current preparedness of banks is not adequate to face the colossal confront of sustainability issues. Some policy recommendations of Reserve Bank of India (RBI) have to come a way forward for addressing gaps and thereby mainstreaming sustainability among banks in India as the survey results exhibit that PSBs operating in India are ill prepared as far as sustainability issues are concerned. Majority of banks identified 'Risk of failure of business to peers' and 'Lack of RBI mandates' as main barriers to adopting sustainability.



5. **Tandon¹⁵** in his study investigates the relationship between Environmental, Social, and Governance (ESG) practices and the financial performance of Indian commercial banks. While prior research has extensively examined ESG impacts in developed economies and Southeast Asia, empirical evidence from India—a fast-growing economy with a distinct banking architecture—remains sparse. Utilizing panel data spanning from 2015 to 2024, the study analyzes ESG disclosures from 30 leading Indian banks and examines their effect on key financial performance indicators, including Return on Assets (ROA), Return on Equity (ROE), and Tobin's Q. By applying the dynamic panel data approach using the Arellano and Bond (1991) Generalized Method of Moments (GMM) estimator, the findings reveal a significant positive

3. Research Methodology

This article combines case study analysis and secondary data in a qualitative and analytical research approach:

4. Document Analysis: Examining policy documents, CSR reports, yearly sustainability reports from banks, RBI circulars, and SEBI sustainability disclosure requirements.
5. Case Study Method: YES Bank's sustainability initiatives are thoroughly examined, and SBI and HDFC Bank are compared.
6. Comparative Framework: Three criteria—Corporate Responsibility (CSR/CR), ESG integration, and carbon credits/climate finance—are used to evaluate banks.
7. Linkage Approach: Makes connections between practice (real bank initiatives) and theory (sustainable banking).

4. Findings

4.1 Corporate Responsibility in Indian Banks

5. YES Bank: Encourages women entrepreneurs, youth leadership, and climate action through the YES Foundation. Adoption of renewable energy in rural communities is one aspect of CSR initiatives.
6. SBI: Runs the SBI Foundation, which provides funding for clean cooking solutions, healthcare, skill development, and rural electricity. In terms of financial literacy initiatives, it is a pioneer.
7. Parivartan is operated by HDFC Bank, which has invested in corporate social responsibility with an emphasis on education, rural development, water conservation, and natural resource management.

4.2 ESG Framework

6. As the first Indian bank to issue green bonds in 2015, YES Bank prioritizes climate risk disclosure and is in line with the UN Principles for Responsible Banking.
7. SBI: focuses on governance and compliance; engages in financing renewable energy; issued a USD 650 million green bond (2018) in international markets.
8. By staying away from ecologically damaging industries, HDFC Bank prioritizes workplace diversity, digital financial inclusion, and sustainable financing.

4.3 Carbon Credits and Climate Finance

3. YES Bank: Supports Clean Development Mechanism (CDM) projects and provides funding for wind, solar, and bioenergy projects that qualify for carbon credits.
4. SBI: Invests in carbon-neutral rural projects and supports renewable and forestation projects under CDM.
5. HDFC Bank: Funds waste-to-energy and sustainable infrastructure initiatives; focuses on internal carbon neutrality targets.

4.4 Case Studies

YES Bank – Pioneer of Green Finance

- Green Bonds: In 2015, India issued its first green bond for renewable energy, totaling ₹1,000 crore.



- Carbon Neutrality: By 2030, operations were expected to be carbon neutral. Global Commitments: A member of UNEP-FI and the first Indian bank to sign the UN Principles for Responsible Banking (PRB).
- CSR: YES Foundation initiatives for women entrepreneurs, digital literacy, and youth empowerment.
- Impact: Funded projects that produced significant carbon credits and raised ₹39 billion for climate-aligned initiatives.

State Bank of India (SBI) – Scale and Outreach

- Green Bonds: A USD 650 million green bond for renewable projects was issued in 2018.
- CSR Leadership: Promotes education, healthcare, clean energy, and rural livelihoods through the SBI Foundation.
- Carbon Initiatives: Encourages the use of clean cooking stoves, biogas adoption, and afforestation as ways to cut emissions.
- Impact: SBI has unparalleled scale to finance India's renewable transition because it is the country's largest bank.

HDFC Bank – CSR Giant

- Parivartan: More than ₹2,000 crore has been allocated to resource management, financial inclusion, and rural development.
- Sustainability Lending: Funding for clean technology adoption by SMEs and green firms.
- ESG: Put an emphasis on resource efficiency, women's empowerment, and inclusivity.
- Impact: By associating CSR with sustainable banking, it enhanced its reputation as a private bank that cares about society.

4.5 Comparative Insights

Table 1 Comparison table

Dimension	YES Bank	SBI	HDFC Bank
Strength	Innovation and ESG leadership	Scale and rural reach	Strong CSR and inclusion
Green bonds	First issuer in India	Largest issuer in India	Financing SMEs and green businesses
Carbon Credits	Funds renewable & bio energy CDM projects	Supports forestation & clean energy CDM	Promotes waste-to-energy & carbon-neutral lending
CSR Focus	Youth, women, climate	Rural electrification, literacy	Rural dev., water, education

A paradigm change is demonstrated by the incorporation of CR, ESG, and carbon credits in Indian banking. Corporate Responsibility serves as the moral foundation for community development. Transparency, investor confidence, and resilience to governance and climate threats are all improved by ESG frameworks. Carbon credits offer creative finance and useful instruments for lowering emissions. YES Bank demonstrates how leadership in sustainability can be established via innovation and global alignment. SBI's size emphasizes the value of outreach and national influence. One example of the power of community-driven CSR is HDFC Bank.



4.6 Opportunities for Indian Banks

- **Green Financing Leadership:** Banks can take the lead in offering green bonds, climate loans, and carbon-linked securities by tying ESG and carbon credits together.
- **Attracting Investors:** ESG-aligned institutions are becoming more and more important to international investors. Indian banks can access global capital markets with the aid of integration.
- **Competitive Differentiation:** Banks who establish themselves as "sustainability leaders" benefit from improved consumer loyalty and reputation.
- **Contribution to SDGs and Net-Zero Goals:** Integration enables banks to immediately align with India's 2070 net-zero vision and SDG ambitions.

4.7 Challenges of Integration

Integration is not without its challenges, despite its potential: **Regulatory Fragmentation:** There are overlaps and gaps because the CSR, ESG, and carbon credit systems are overseen by various authorities (MCA, SEBI, and BEE).

- **Capacity Restrictions:** A lot of banks don't have in-house knowledge of sustainability reporting, ESG risk assessment, or carbon accounting.
- **Short-Term Cost Pressures:** Smaller banks may become discouraged if integrating sustainability into operations and lending results in higher short-term costs.
- **Green washing Risks:** Banks run the risk of inflating their ESG or carbon credit accomplishments without thorough verification, endangering their credibility.

5. Conclusion

5.1 Strategic Roadmap for Integration

Indian banks can use the following strategy in order to accomplish significant integration:

- **Policy Alignment:** To prevent redundancy and guarantee consistency, the government and regulators should standardize CSR, ESG, and carbon credit rules.
- **Capacity Building:** Banks need to spend money on educating ESG analysts, carbon auditors, and sustainability specialists.
- **Digital Platforms:** Block chain and fintech use can expedite carbon credit verification and ESG data management.
- **Partnerships:** To financially-positive initiatives, banks can collaborate with international organizations, entrepreneurs, and NGOs.
- **Long-Term Vision:** Integration should be viewed as an investment in competitiveness, resilience, and sustainable growth rather than as a cost.

5.2 The Big Picture

The banking industry in India is developing as a driver of sustainable finance. Banks are striking a balance between profitability and environmental, social, and ethical stewardship by integrating carbon credit mechanisms, ESG, and corporate responsibility into their operations. YES Bank has become an innovator in the field of green finance. The strength of scale and government alignment is exemplified by SBI. Strong CSR integration with financial inclusion is demonstrated by HDFC Bank. When taken as a whole, they show the various ways Indian banks are helping the country reach net-zero by 2070. Now, the industry needs to concentrate on developing new green financial products, increasing participation in carbon markets, and standardizing ESG disclosures. In a world with carbon constraints, Indian banks have the potential to establish themselves as both financial institutions and developers of sustainable development if they are properly leveraged. Banks can assist India in striking a balance between ecological stability and rapid economic



expansion by integrating climate finance into corporate responsibility. This puts the industry in a strong position to support India's goal of becoming a developed, sustainable country by 2047.

References

1. Reserve Bank of India, "Report on Sustainable Finance in India", 2022.
2. Ministry of Corporate Affairs, "Companies Act – CSR Provisions", 2013.
3. Securities and Exchange Board of India, "Business Responsibility and Sustainability Reporting (BRSR)", 2021.
4. YES Bank, "Annual Sustainability and CSR Reports", 2015–2023.
5. State Bank of India, "Green Bond Issue Report", 2018.
6. HDFC Bank, "Parivartan CSR Report", 2022.
7. CRISIL, "ESG Risk Assessment in Indian Banks", 2023.
8. Confederation of Indian Industry, "India's Carbon Credit Potential Report", 2022.
9. UNEP Finance Initiative, "Principles for Responsible Banking", 2019.
10. Morningstar, "Global ESG Assets Report", 2022.
11. Megha Jaiwani and Santosh Gopalkrishnan, "Do private and public sector banks respond to ESG in the same way? Some evidences from India", *Benchmarking: An International Journal*, January 2025, 32 (1), 194–221.
<https://doi.org/10.1108/BIJ-05-2023-0340>
12. Pooja Mishra and Tatavarty Guru Sant, "Examine the level of environmental, social and governance disclosure in sustainability report – a study of the Indian banking sector", *International Journal of Innovation Science*, February 2024, 16 (2), 420–442. <https://doi.org/10.1108/IJIS-08-2022-0136>
13. D. G. Menon, S. G. Sreelakshmi and A. Shivdas, "Green banking initiatives: A review of Indian banking sector", 2017 International Conference on Technological Advancements in Power and Energy (TAP Energy), Kollam, India, 2017, 1–7. doi: 10.1109/TAPENERGY.2017.8397303
14. Rajput N., Kaura R., and Khanna A., "Indian Banking Sector towards a Sustainable Growth: A Paradigm Shift", *International Journal of Academic Research in Business and Social Sciences*, 2013, 3 (1), 290.
15. Tandon C., "Sustainability in Indian Banking Sector: Moving Towards ESG Framework", *Metallurgical and Materials Engineering*, 2025, 941–956.
16. Katyal S. and Nagpal S., "Role of Green Banking in Sustainable Development of India", *International Journal of 360° Management Review*, 2014, 2 (1), 1–11.



DOIs:10.2015/IJIRMF/ICICSF-2025-P37

--:--

Research Paper / Article / Review

International Conference On “Innovative Convergence for Sustainable Future”

Date : 12 - 13 December, 2025

(ICICSF-2025)



Influence of Liquid Biofertilizer Consortia and NPK Levels on Growth and Yield attributes of Wheat (*Triticum aestivum* L.)

Shivam Yadav*1, and Dr. Biswarup Mehera*2

* 1 Research scholar, Department of Agronomy, Naini Agricultural Institute, SHUATS, Prayagraj, Uttar Pradesh-211007, India

*2 Professor and Dean, Naini Agricultural Institute, SHUATS, Prayagraj, Uttar Pradesh 211007, India

Sam Higginbottom University of Agriculture, Technology And Sciences, Prayagraj, Uttar Pradesh-211007, India

*Corresponding email: - shivam.yadav41@gmail.com

ABSTRACT

Background: Wheat (*Triticum aestivum* L.) is a staple cereal crop and is crucial for global food security and nutrient supply. However, imbalanced fertilizer application and declining soil health threaten sustainable wheat production. Liquid Biofertilizer Consortia (LBFC), comprising beneficial microorganisms such as nitrogen-fixing, phosphate-solubilizing and potassium-solubilizing bacteria, offer an eco-friendly alternative to improve nutrient availability and crop productivity. This study aimed to evaluate the effects of combined LBFC seed and soil application with different NPK fertilization levels on the growth and yield attributes of wheat.

Methods: The experiment was conducted during the *Rabi* seasons of 2023-24 and 2024-25 at the Crop Research Farm, SHUATS, Prayagraj, India, using a Randomized Block Design with twelve treatments and three replications. Treatments included various combinations of LBFC seed treatment (6 ml kg⁻¹) and soil application (625 ml ha⁻¹) alongside full, 85% and 70% recommended NPK doses. Growth parameters (plant height, dry weight, crop growth rate, relative growth rate, chlorophyll content) and yield attributing traits (number of spikes plant⁻¹, number of grains spike⁻¹, test weight (g) and number of tillers per running meter) were recorded and statistically analyzed using ANOVA.

Results: Treatment (T7) Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg⁻¹) + soil application (625 ml ha⁻¹) + 100% NPK significantly enhanced growth and yield attributing parameters compared to other treatments across both years and pooled data. However, non-significant effects were observed for test weight of wheat.

Key words: Growth, Liquid Biofertilizer Consortia, NPK, Seed, Soil and Yield

1.INTRODUCTION:

Wheat (*Triticum aestivum* L.), a member of the *Poaceae* family and often referred to as the “King of cereals,” holds immense significance as a staple food crop worldwide. It serves as the principal dietary source for approximately two billion people, constituting nearly 36% of the global population (Pathak and Shrivastav, 2015). Among the most extensively cultivated food crops, wheat and rice together form the backbone of food security systems across many nations (Kaur *et al.*, 2018). The principal cultivated wheat types include tetraploid durum wheat (*Triticum durum*) and hexaploid bread wheat (*Triticum aestivum* L.), each differing in genomic structure, grain composition and end-use characteristics (Dubcovsky and Dvorak, 2007). The domestication of these species from wild relatives led to significant morphological adaptations such as the development of non-brittle ears and free-threshing grains, which enhanced their cultivability and economic importance (Goncharov, 2005; Peng *et al.*, 2011). The historical cultivation of wheat, dating back to around 10,000 B.C. within the Fertile Crescent, marked a milestone in agricultural evolution (Venske *et al.*, 2019; Arzani and Ashraf, 2017).



In India, wheat is primarily cultivated during the *Rabi* season, covering nearly 50% of the total food crop area and contributing over 70% of the food grain production in the season. It is nutritionally rich, comprising 60–68% carbohydrates, 8–15% protein and essential vitamins and minerals (Singh *et al.*, 2011). Wheat protein, chiefly gluten, is particularly important for its functional role in bakery products, giving the crop a distinct nutritional and industrial advantage (Mandal and Kongala, 2017). Globally, wheat occupies about 225.62 million hectares with a production of 749.50 million tones and an average productivity of 3321 kg ha⁻¹ (Anonymous, 2018). In India, production reached 113.29 million tones from an area of 31.83 million hectares, yielding an average productivity of 3560 kg ha⁻¹ (USDA, 2025). Uttar Pradesh, the leading wheat- growing state, contributes significantly with 38.07 million tones produced over an area of 10.19 million hectares. However, regional disparities exist, as seen in Prayagraj district, where productivity remains relatively low (2300 kg ha⁻¹) compared with the national average (DAFW, 2025).

The ever-growing population has amplified the demand for wheat, yet the average yield in India remains below the global standard. Imbalanced and inadequate fertilizer application, alongside erratic climatic conditions, has been identified as a major cause of low productivity (Paramasivan *et al.*, 2014). The continued reliance on chemical fertilizers has further led to the decline of soil organic carbon, reduced microbial diversity and increased soil compaction. To counter these challenges, it is vital to develop balanced nutrient management strategies that combine efficiency and sustainability. Essential macronutrients such as nitrogen (N), phosphorus (P) and potassium (K) play pivotal roles in plant growth and development. Nitrogen primarily influences vegetative growth, phosphorus is vital for root development and energy transfer and potassium aids in enhancing disease resistance and stress tolerance (Khan *et al.*, 2023; Meier *et al.*, 2024). Toragal *et al.* (2025) also reported 321 maximum grain yield (3794.98 kg ha⁻¹) and straw yield (4680.20 kg ha⁻¹) under the treatment containing 100% NPK + microbial consortia. Similarly, Jyothi *et al.* (2025) found integrating microbial consortia with inorganic fertilizers markedly improved yield parameters of groundnut (cv. K6).

In recent years, the emphasis on sustainable agriculture has led to increased interest in biofertilizers as eco-friendly alternatives to chemical fertilizers. Liquid Biofertilizer Consortia (LBC), comprising beneficial microorganisms such as *Rhizobium*, *Azotobacter*, *Phosphobacteria* and Potassium Solubilizing Bacteria (PSB), have emerged as effective agents for improving soil fertility and crop productivity. These microbial consortia facilitate nutrient cycling by fixing atmospheric nitrogen, solubilizing phosphorus and potassium and producing plant growth- promoting substances (Bashan *et al.*, 2004; Sharma *et al.*, 2007; Laxman *et al.*, 2017). Their use enhances soil health by improving microbial activity, organic matter decomposition and nutrient availability while reducing the environmental hazards associated with chemical fertilizers (Behera and Rautaray, 2010; Bahrani *et al.*, 2010).

The integration of liquid biofertilizers with optimized NPK fertilization has the potential to synergistically boost wheat growth and yield under sustainable management systems (Badr *et al.*, 2013). Therefore, an experiment entitled “Influence of Liquid Biofertilizer Consortia and NPK levels on growth and yield of wheat [*Triticum aestivum* L.]” was carried out in the *rabi* seasons of 2023-24 and 2024-25 at Central Research Farm, Department of Agronomy, Naini Agricultural Institute, SHUATS with the objective to study the effect of different application methods of Liquid Bio-fertilizer Consortia on growth and yield of wheat.

2.MATERIALS AND METHODS

Experimental site and location

The experiment entitled “Influence of Liquid Biofertilizer Consortia and NPK Levels on Growth and Yield attributes of Wheat (*Triticum aestivum* L.)” was conducted during the *Rabi* seasons of 2023–24 and 2024–25 at the Crop Research Farm, Department of Agronomy, Naini Agricultural Institute, Sam Higginbottom University of Agriculture, Technology and Sciences (SHUATS), Prayagraj (U.P.). The experimental site is situated on the left side of Allahabad–Rewa Road, approximately 8 km from Prayagraj city and lies at a latitude of 25.57° N and longitude of 81.51° E. The soil of the experimental site was sandy loam in texture with a slightly alkaline reaction (Ph 7.60), electrical conductivity of 0.38 Ds m⁻¹ and organic carbon content of 0.38%.

Available nitrogen, phosphorus and potassium contents were recorded as 182.24, 9.00 and 163.00 kg ha⁻¹, respectively, indicating low nitrogen and medium phosphorus and potassium status.

The experiment was laid out in a Randomized Block Design (RBD) comprising twelve treatment combinations replicated three times. Treatments consisted of four levels of Liquid Biofertilizer Consortia application and three levels of NPK fertilization. The wheat variety ‘HD- 2967’ was selected as the test crop. Each plot measured 4 m × 3 m with a row spacing of 22.5 cm and a seed rate of 100 kg ha⁻¹. The gross experimental area was 586.5 m², while the net plot area was 432 m². The recommended fertilizer dose for wheat was 100:50:25 kg ha⁻¹ of N:P₂O₅:K₂O.



Urea, Diammonium Phosphate (DAP) and Muriate of Potash (MOP) served as the sources of nitrogen, phosphorus and potassium, respectively. Half of the nitrogen along with the full doses of phosphorus and potassium were applied as basal at the time of sowing, while the remaining half of the nitrogen was top dressed in two equal splits at 30 and 60 days after sowing (DAS). Land preparation was carried out after the harvest of the *kharif* crop by giving one deep ploughing with a tractor-drawn disc plough followed by two harrowings and planking to obtain a fine tilth. The liquid biofertilizer consortia were applied following standard seed and soil treatment methods. For seed treatment, wheat seeds were first soaked in water for ten minutes and then drained. A jaggery solution was prepared by boiling 1.2 kg jaggery in 10 litres of water for 30 minutes and cooling it to room temperature. To this, 600 ml of liquid biofertilizer consortia (6 ml per kg of seed) was added and mixed thoroughly with 100 kg of wheat seed to form a uniform slurry. The treated seeds were then spread on a clean gunny bag in shade for drying before sowing. For soil application, 625 ml of liquid biofertilizer consortia was diluted in 25 litres of water and sprinkled uniformly over 25 tonnes of well-decomposed FYM. The treated FYM was incubated overnight and broadcasted before sowing to the respective plots near the root zone. Sowing was done manually in open furrows at a depth of 5 cm using a spacing of 22.5 cm between rows on November 28, 2023 and November 14, 2024, for the respective years. The crop was harvested manually at full maturity. After harvesting, the bundles were sun-dried for 4–5 days in the field and then threshed using a power-operated thresher.

Observations recorded

Observations recorded during the experiment included plant height (cm), dry weight (g plant^{-1}), crop growth rate (CGR) ($\text{g m}^{-2} \text{ day}^{-1}$), relative growth rate (RGR) ($\text{g g}^{-1} \text{ day}^{-1}$), chlorophyll content $\text{mg } 100\text{g}^{-1}$ of fresh weight) and yield attributes. Plant height was measured at 25, 50, 75 and 100 days after sowing (DAS) from five randomly selected plants in each plot using a metre rod. Dry matter accumulation was determined from five plants uprooted at the same intervals, oven-dried at 60°C to a constant weight and expressed in grams per plant. CGR and RGR were calculated from dry weight data for specific growth intervals using standard formulae. Chlorophyll content was also estimated from 100 g of leaf tissue. Post-harvest observations included number of spikes plant^{-1} , number of grains spike^{-1} , test weight (g) and number of tillers per running meter, counted at physiological maturity. The recorded data were analyzed using the analysis of variance (ANOVA) technique as outlined by Gomez and Gomez (1984) for a randomized block design. The least significance test was employed to analyze the impact of treatments at a 5% significance level.

3.RESULTS AND DISCUSSION

Effect of liquid biofertilizer consortia and NPK Levels on growth parameters

The data on growth traits of wheat presented in tables 1 to 5 indicate the significant effects of liquid biofertilizer consortia and NPK levels across both 2023-24 and 2024-25, as well as in pooled analysis except for CGR and RGR where non-significant effects were also observed. Plant height increased gradually throughout the crop stages, with the most pronounced rise between 25 and 75 DAS, followed by a slower increment towards maturity. Across both years and pooled data, the highest plant height at all growth stages was consistently recorded in treatment (T7) Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + soil application (625 ml ha^{-1}) + 100% NPK, observing 15.93 cm at 25 DAS, 56.72 cm at 50 DAS, 87.52 cm at 75 DAS and 98.18 cm at 100 DAS according to pooled basis, significantly surpassing other treatments. Treatments (T8) Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + soil application (625 ml ha^{-1}) + 85% NPK and (T9) Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + soil application (625 ml ha^{-1}) + 70% NPK also showed substantial increases in plant height but were statistically at par with (T7). Regarding dry weight at 25 DAS, non-significant effects were found, however significant variation among treatments was observed beginning at 50 DAS. According to pooled basis, treatment (T7) Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + soil application (625 ml ha^{-1}) + 100% NPK produced the maximum dry weight ($3.52 \text{ g plant}^{-1}$ at 50 DAS, $17.71 \text{ g plant}^{-1}$ at 75 DAS and $26.57 \text{ g plant}^{-1}$ at 100 DAS), followed closely by (T8) and (T9). The rapid accumulation of dry



matter coincided with the main vegetative and early reproductive stages, with 25–75 DAS representing the phase of most vigorous biomass build-up. Crop Growth Rate (CGR) and Relative Growth Rate (RGR) were strongly influenced by the different treatments during both 2023-24 and 2024-25, as well as in pooled analysis. CGR increased notably during the active growth phases, especially between 25-50 DAS and 50-75 DAS, corresponding to periods of rapid vegetative expansion and tillering in wheat. As per the pooled data is concerned, treatment (T7) Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + soil application (625 ml ha^{-1}) + 100% NPK recorded the highest CGR at all intervals with $0.53 \text{ g m}^{-2} \text{ day}^{-1}$ during 0-25 DAS,

$5.88 \text{ g m}^{-2} \text{ day}^{-1}$ during 25-50 DAS, peaking at $25.79 \text{ g m}^{-2} \text{ day}^{-1}$ during 50-75 DAS, which was significantly greater than other treatments. CGR declined after 75 DAS as the crop approached senescence and assimilate partitioning favored reproductive organs with $16.10 \text{ g m}^{-2} \text{ day}^{-1}$ during 75-100 DAS. However, RGR showed non-significant differences among treatments across various growth stages except at 25-50 DAS according to pooled basis, with (T7) Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + soil application (625 ml ha^{-1}) + 100% NPK achieving the maximum pooled RGR of $0.0999 \text{ g g}^{-1} \text{ day}^{-1}$ during 25-50 DAS, indicating efficient production of new biomass relative to existing dry weight. This trend gradually decreased towards maturity as growth slowed. Chlorophyll content was also significantly enhanced in (T7), recording 4.15 mg g^{-1} fresh weight at 25 DAS and 4.27 mg g^{-1} at 50 DAS according to pooled basis, indicating improved photosynthetic potential.

The results indicate that treatment (T7) Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + soil application (625 ml ha^{-1}) + 100% NPK, significantly enhanced growth parameters of wheat compared to other treatments. The synergistic effect of LBFC and full NPK fertilization likely improved nutrient mobilization and availability, facilitating increased vegetative growth as reflected by higher plant height and dry matter accumulation (Mahmud *et al.*, 2022). Microbial populations in LBFC contribute to nutrient solubilization, nitrogen fixation and production of growth hormones such as IAA, gibberellins and cytokinins, which stimulate cell division and elongation, promoting vigorous growth. The improved root development and nutrient uptake under this treatment enhanced photosynthetic capacity, as evidenced by increased chlorophyll content (Anjali *et al.*, 2021). Enhanced CGR values during key growth stages further demonstrate the positive impact on biomass accumulation, while RGR trends indicate efficient biomass production relative to existing plant mass. The decline in growth rates beyond 75 DAS aligns with natural senescence and assimilate remobilization to grains Yadav *et al.* (2025).

Effect of liquid biofertilizer consortia and NPK Levels on yield attributing parameters

The data on yield attributing characters of wheat presented in table 6 indicate significant effects of liquid biofertilizer consortia (LBFC) and NPK levels across both the 2023-24 and 2024-25 growing seasons, as well as in pooled analysis except for test weight (g) where non-significant effects were produced. Among various treatments, the highest number of spikes plant^{-1} was consistently recorded in treatment (T7) Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + soil application (625 ml ha^{-1}) + 100% NPK, recording 3.67 spikes plant^{-1} across both years of study and pooled data. It was followed by treatments (T8) Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + soil application (625 ml ha^{-1}) + 85% NPK and (T9) Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + soil application (625 ml ha^{-1}) + 70% NPK which also showed at par effects with treatment (T7). Similarly, the number of grains spike^{-1} was significantly influenced by various treatments. Treatment T7) Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + soil application (625 ml ha^{-1}) + 100% NPK produced the maximum number of grains spike^{-1} observing 49.51 grains according to pooled basis. Despite non-significant effects on test weight (g) of wheat, treatment (T7) Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + soil application (625 ml ha^{-1}) + 100% NPK recorded highest test weight observing 39.31 g test weight according to pooled data. Regarding the number of tillers per running meter, treatment (T7) again recorded the highest values, observing 120 tillers per running meter according to pooled basis, followed closely by treatments T8 and T9 with slightly lower but statistically at par values.



The results clearly demonstrate that treatment (T7) Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + soil application (625 ml ha^{-1}) + 100% NPK significantly enhanced key yield attributing characters of wheat. The highest number of spikes plant⁻¹ under this treatment can be attributed to the synergistic effect of balanced nutrient availability and microbial stimulation, which fostered tiller development and spike initiation. The enriched microbial community in LBFC, including nitrogen-fixing and phosphate-solubilizing bacteria, likely improved root growth and nutrient absorption, while microbial production of phytohormones stimulated productive tiller formation (Swarnalakshmi *et al.*, 2020). Similarly, the number of grains spike⁻¹ was maximized in T7 due to efficient nutrient use and enhanced photosynthetic capacity, supporting better spikelet development and grain filling during crucial reproductive phases (Ullah *et al.*, 2018; Mehdi *et al.*, 2025). Furthermore, the highest number of tillers per running meter was observed with T7 indicates improved plant vigor and nutrient dynamics, aided by microbial hormone production promoting tiller emergence and survival (Wamalwa *et al.*, 2019). Although test weight differences were not statistically significant, T7 recorded numerically higher, suggesting improvements in grain quality linked to integrated nutrient and microbial management. Similar effects were also observed by Jain *et al.* (2021), Kumar *et al.* (2021) and Gudadhe *et al.* (2015).

4.Recommendations and Limitations:

The findings warrant extension of this work through multi-location, multi-season trials to confirm the stability and scalability of Liquid Biofertilizer Consortia with graded NPK levels in varied production environments. Future research should integrate detailed soil health indicators, nutrient-use efficiency metrics and long-term nutrient budgeting to better capture system-level sustainability. On-farm participatory evaluations, combined with rigorous economic analyses, are also recommended to assess profitability, risk and adoption potential under real farming conditions.

The experiment was confined to two *rabi* seasons at a single site with sandy loam, slightly alkaline soil and low nitrogen status, which limits extrapolation to other soil types and agro-climatic zones. The study emphasized growth and yield attributes, with limited consideration of soil biological properties, environmental impacts or residual effects on succeeding crops. Furthermore, the use of a single wheat variety and fixed LBFC doses restricts understanding of genotype interactions and dose optimization, indicating that the conclusions should be interpreted with caution and validated further.

Table 4.1. Effect of liquid biofertilizer consortia and NPK levels on plant height (cm) of wheat

Treatment	Plant height (cm)											
	25 DAS			50 DAS			75 DAS			100 DAS		
	2023-24	2023-24	Pooled	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled
T1	14.09	14.51	14.30	40.38	43.20	41.79	75.25	78.20	76.72	87.43	88.33	87.88
T2	13.77	14.21	13.99	38.50	41.12	39.81	73.90	76.56	75.23	85.99	86.82	86.41
T3	13.57	14.03	13.80	36.62	39.05	37.83	72.95	75.33	74.14	84.97	85.73	85.35
T4	14.84	15.21	15.02	46.02	49.46	47.74	78.58	82.43	80.50	91.02	92.12	91.57
T5	14.64	15.03	14.84	44.14	47.37	45.75	77.43	80.97	79.20	89.78	90.81	90.30
T6	14.30	14.71	14.51	42.26	45.28	43.77	76.28	79.52	77.90	88.54	89.51	89.03
T7	15.78	16.08	15.93	54.55	58.90	56.72	84.71	90.32	87.52	97.50	98.87	98.18
T8	15.42	15.75	15.58	50.79	54.75	52.77	82.21	86.76	84.48	94.87	96.14	95.50
T9	15.21	15.56	15.38	47.90	51.56	49.73	79.93	84.10	82.01	92.46	93.64	93.05
T10	13.08	13.54	13.31	33.86	36.05	34.95	70.04	72.10	71.07	81.94	82.61	82.28
T11	12.85	13.33	13.09	31.98	34.00	32.99	69.03	70.83	69.93	80.85	81.47	81.16
T12	11.93	12.39	12.16	30.10	31.95	31.02	62.15	63.59	62.87	74.77	75.30	75.03
F-test	S	S	S	S	S	S	S	S	S	S	S	S
S.E. (m) (±)	0.53	0.59	0.40	1.60	1.57	1.12	2.91	3.20	2.16	2.80	3.07	2.08
C.D. @ 5%	1.56	1.72	1.13	4.69	4.60	3.19	8.53	9.38	6.16	8.22	9.00	5.92



T1: Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + 100% NPK; **T2:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + 85% NPK; **T3:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + 70% NPK; **T4:** Liquid bio fertilizer consortia (LBFC) soil application (625 ml ha^{-1}) + 100% NPK; **T5:** Liquid bio fertilizer consortia (LBFC) soil application (625 ml ha^{-1}) + 85% NPK; **T6:** Liquid bio fertilizer consortia (LBFC) soil application (625 ml ha^{-1}) + 70% NPK; **T7:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + soil application (625 ml ha^{-1}) + 100% NPK; **T8:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + soil application (625 ml ha^{-1}) + 85% NPK; **T9:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + soil application (625 ml ha^{-1}) + 70% NPK; **T10:** No use of Liquid bio fertilizer consortia (LBFC) + 100% NPK; **T11:** No use of Liquid bio fertilizer consortia (LBFC) + 85% NPK; **T12:** No use of Liquid bio fertilizer consortia (LBFC) + 75% NPK

Table 4.2. Effect of liquid biofertilizer consortia and NPK levels on dry weight (g plant^{-1}) of wheat

Treatment	Dry weight (g plant^{-1})											
	25 DAS			50 DAS			75 DAS			100 DAS		
	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled
T1	0.25	0.27	0.26	2.94	2.96	2.95	14.55	14.81	14.68	21.61	22.29	21.95
T2	0.25	0.27	0.26	2.93	2.95	2.94	14.48	14.71	14.60	21.49	22.13	21.81
T3	0.25	0.27	0.26	2.87	2.89	2.88	14.20	14.38	14.29	21.07	21.62	21.34
T4	0.26	0.27	0.26	3.00	3.03	3.02	14.89	15.27	15.08	22.16	23.02	22.59
T5	0.26	0.27	0.26	2.99	3.02	3.01	14.82	15.17	14.99	22.04	22.86	22.45
T6	0.25	0.27	0.26	2.95	2.98	2.96	14.61	14.91	14.76	21.72	22.45	22.09
T7	0.28	0.30	0.29	3.50	3.55	3.52	17.42	18.01	17.71	25.95	27.19	26.57
T8	0.26	0.27	0.27	3.04	3.07	3.06	15.09	15.54	15.31	22.47	23.46	22.97
T9	0.26	0.27	0.27	3.03	3.06	3.04	15.02	15.44	15.23	22.36	23.29	22.83
T10	0.25	0.27	0.26	2.86	2.88	2.87	14.13	14.29	14.21	20.96	21.46	21.21
T11	0.25	0.27	0.26	2.85	2.86	2.86	14.07	14.19	14.13	20.85	21.31	21.08
T12	0.23	0.25	0.24	2.58	2.57	2.58	12.74	12.74	12.74	18.86	18.86	18.86
F-test	NS	NS	NS	S	S	S	S	S	S	S	S	S
S.E. (m) ($\pm$)	0.01	0.01	0.01	0.14	0.15	0.10	0.43	0.44	0.31	0.73	0.86	0.57
C.D. @ 5%	-	-	-	0.41	0.43	0.29	1.27	1.28	0.88	2.16	2.52	1.61

T1: Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + 100% NPK; **T2:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + 85% NPK; **T3:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + 70% NPK; **T4:** Liquid bio fertilizer consortia (LBFC) soil application (625 ml ha^{-1}) + 100% NPK; **T5:** Liquid bio fertilizer consortia (LBFC) soil application (625 ml ha^{-1}) + 85% NPK; **T6:** Liquid bio fertilizer consortia (LBFC) soil application (625 ml ha^{-1}) + 70% NPK; **T7:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + soil application (625 ml ha^{-1}) + 100% NPK; **T8:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + soil application (625 ml ha^{-1}) + 85% NPK; **T9:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + soil application (625 ml ha^{-1}) + 70% NPK; **T10:** No use of Liquid bio fertilizer consortia (LBFC) + 100% NPK; **T11:** No use of Liquid bio fertilizer consortia (LBFC) + 85% NPK; **T12:** No use of Liquid bio fertilizer consortia (LBFC) + 75% NPK

Table 4.3. Effect of liquid biofertilizer consortia and NPK levels on Crop Growth Rate ($\text{g m}^{-2} \text{ day}^{-1}$) of wheat

Treatment	Crop Growth Rate ($\text{g m}^{-2} \text{ day}^{-1}$)											
	0-25 DAS			25-50 DAS			50-75 DAS			75-100 DAS		
	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled
T1	0.46	0.49	0.48	4.88	4.89	4.89	21.10	21.54	21.32	12.84	13.60	13.22
T2	0.46	0.49	0.48	4.86	4.87	4.87	21.00	21.39	21.20	12.76	13.48	13.12



T3	0.45	0.49	0.47	4.77	4.77	4.77	20.59	20.90	20.74	12.49	13.16	12.82
T4	0.46	0.50	0.48	5.00	5.02	5.01	21.61	22.24	21.93	13.21	14.10	13.65
T5	0.46	0.50	0.48	4.97	4.99	4.98	21.51	22.09	21.80	13.13	13.98	13.55
T6	0.46	0.49	0.48	4.90	4.92	4.91	21.21	21.70	21.45	12.92	13.72	13.32
T7	0.51	0.54	0.53	5.85	5.91	5.88	25.30	26.28	25.79	15.51	16.69	16.10
T8	0.47	0.50	0.48	5.06	5.09	5.07	21.91	22.66	22.29	13.43	14.40	13.92
T9	0.47	0.50	0.48	5.04	5.07	5.05	21.80	22.50	22.15	13.35	14.29	13.82
T10	0.45	0.49	0.47	4.75	4.74	4.75	20.49	20.74	20.62	12.41	13.04	12.73
T11	0.45	0.49	0.47	4.73	4.72	4.72	20.40	20.60	20.50	12.33	12.93	12.63
T12	0.42	0.45	0.43	4.27	4.23	4.25	18.47	18.48	18.47	11.12	11.13	11.13
F-test	NS	NS	S	S	S	S	S	S	S	S	S	S
S.E. (m) (±)	0.01	0.01	0.01	0.24	0.25	0.17	0.54	0.52	0.38	0.55	0.77	0.47
C.D. @ 5%	-	-	0.03	0.70	0.75	0.50	1.58	1.54	1.07	1.61	2.26	1.35

T1: Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg⁻¹) + 100% NPK; **T2:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg⁻¹) + 85% NPK; **T3:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg⁻¹) + 70% NPK; **T4:** Liquid bio fertilizer consortia (LBFC) soil application (625 ml ha⁻¹) + 100% NPK; **T5:** Liquid bio fertilizer consortia (LBFC) soil application (625 ml ha⁻¹) + 85% NPK; **T6:** Liquid bio fertilizer consortia (LBFC) soil application (625 ml ha⁻¹) + 70% NPK; **T7:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg⁻¹) + soil application (625 ml ha⁻¹) + 100% NPK; **T8:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg⁻¹) + soil application (625 ml ha⁻¹) + 85% NPK; **T9:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg⁻¹) + soil application (625 ml ha⁻¹) + 70% NPK; **T10:** No use of Liquid bio fertilizer consortia (LBFC) + 100% NPK; **T11:** No use of Liquid bio fertilizer consortia (LBFC) + 85% NPK; **T12:** No use of Liquid bio fertilizer consortia (LBFC) + 75% NPK

Table 4.4. Effect of liquid biofertilizer consortia and NPK levels on Relative Growth Rate (g g⁻¹ day⁻¹) of wheat

Treatment	Relative Growth Rate (g g ⁻¹ day ⁻¹)								
	25-50 DAS			50-75 DAS			75-100 DAS		
	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled
T1	0.0980	0.0956	0.0968	0.0640	0.0644	0.0642	0.0158	0.0163	0.0161
T2	0.0979	0.0954	0.0967	0.0640	0.0643	0.0642	0.0158	0.0163	0.0160
T3	0.0976	0.0951	0.0964	0.0640	0.0643	0.0641	0.0158	0.0163	0.0160
T4	0.0985	0.0962	0.0974	0.0641	0.0647	0.0644	0.0159	0.0164	0.0161
T5	0.0984	0.0961	0.0972	0.0641	0.0646	0.0643	0.0159	0.0164	0.0161
T6	0.0982	0.0958	0.0970	0.0640	0.0645	0.0643	0.0158	0.0164	0.0161
T7	0.1010	0.0989	0.0999	0.0642	0.0650	0.0646	0.0159	0.0165	0.0162
T8	0.0989	0.0966	0.0977	0.0642	0.0649	0.0645	0.0159	0.0165	0.0162
T9	0.0987	0.0964	0.0976	0.0641	0.0648	0.0645	0.0159	0.0164	0.0162
T10	0.0975	0.0950	0.0962	0.0639	0.0642	0.0641	0.0157	0.0163	0.0160
T11	0.0973	0.0948	0.0960	0.0639	0.0641	0.0640	0.0157	0.0162	0.0160
T12	0.0967	0.0939	0.0953	0.0639	0.0640	0.0639	0.0157	0.0157	0.0157
F-test	NS	NS	S	NS	NS	NS	NS	NS	NS
S.E. (m) (±)	0.0008	0.0009	0.0006	0.0007	0.0008	0.0005	0.0002	0.0004	0.0002
C.D. @ 5%	-	-	0.0016	-	-	-	-	-	-

T1: Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg⁻¹) + 100% NPK; **T2:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg⁻¹) + 85% NPK; **T3:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg⁻¹) + 70% NPK; **T4:** Liquid bio fertilizer consortia (LBFC) soil application (625 ml ha⁻¹) + 100% NPK; **T5:** Liquid bio fertilizer consortia (LBFC) soil application (625 ml ha⁻¹) + 85% NPK; **T6:** Liquid bio fertilizer consortia (LBFC) soil application (625 ml ha⁻¹) + 70% NPK; **T7:** Liquid bio fertilizer consortia



(LBFC) seed treatment (6 ml kg^{-1}) + soil application (625 ml ha^{-1}) + 100% NPK; **T8:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + soil application (625 ml ha^{-1}) + 85% NPK; **T9:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + soil application (625 ml ha^{-1}) + 70% NPK; **T10:** No use of Liquid bio fertilizer consortia (LBFC) + 100% NPK; **T11:** No use of Liquid bio fertilizer consortia (LBFC) + 85% NPK; **T12:** No use of Liquid bio fertilizer consortia (LBFC) + 75% NPK

Table 4.5. Effect of liquid biofertilizer consortia and NPK levels on chlorophyll content (mg g^{-1} of fresh weight) of wheat

Treatment	Chlorophyll content (mg g^{-1} of fresh weight)					
	25 DAS			50 DAS		
	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled
T1	3.62	3.66	3.64	3.70	3.78	3.74
T2	3.58	3.62	3.60	3.65	3.74	3.69
T3	3.47	3.50	3.49	3.54	3.62	3.58
T4	3.81	3.86	3.84	3.89	3.99	3.94
T5	3.76	3.81	3.78	3.84	3.93	3.89
T6	3.68	3.72	3.70	3.76	3.84	3.80
T7	4.12	4.18	4.15	4.21	4.32	4.27
T8	4.02	4.08	4.05	4.11	4.21	4.16
T9	3.85	3.90	3.88	3.93	4.03	3.98
T10	3.30	3.33	3.32	3.37	3.44	3.40
T11	3.21	3.24	3.22	3.27	3.34	3.31
T12	2.91	2.93	2.92	2.97	3.03	3.00
F-test	S	S	S	S	S	S
S.E. (m) ($\pm$)	0.10	0.08	0.07	0.09	0.11	0.07
C.D. @ 5%	0.30	0.24	0.19	0.26	0.31	0.20

T1: Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + 100% NPK; **T2:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + 85% NPK; **T3:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + 70% NPK; **T4:** Liquid bio fertilizer consortia (LBFC) soil application (625 ml ha^{-1}) + 100% NPK; **T5:** Liquid bio fertilizer consortia (LBFC) soil application (625 ml ha^{-1}) + 85% NPK; **T6:** Liquid bio fertilizer consortia (LBFC) soil application (625 ml ha^{-1}) + 70% NPK; **T7:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + soil application (625 ml ha^{-1}) + 100% NPK; **T8:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + soil application (625 ml ha^{-1}) + 85% NPK; **T9:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg^{-1}) + soil application (625 ml ha^{-1}) + 70% NPK; **T10:** No use of Liquid bio fertilizer consortia (LBFC) + 100% NPK; **T11:** No use of Liquid bio fertilizer consortia (LBFC) + 85% NPK; **T12:** No use of Liquid bio fertilizer consortia (LBFC) + 75% NPK

Table 4.6. Effect of liquid biofertilizer consortia and NPK levels on yield attributing parameters of wheat

Treatment	Number of spikes plant ⁻¹			Number of grains plant ⁻¹			Test weight (g)			Number of tillers per running meter		
	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled
T1	3.00	3.00	3.00	43.40	42.27	41.74	38.37	38.78	38.58	104.80	108.87	106.83
T2	2.93	3.00	2.97	38.60	41.53	41.04	38.30	38.68	38.49	103.13	107.07	105.10
T3	2.93	2.93	2.93	42.00	40.87	40.36	38.23	38.58	38.41	102.00	106.87	104.43
T4	3.20	3.20	3.20	41.60	45.27	44.68	38.60	39.11	38.85	109.07	113.33	111.20



T5	3.00	3.13	3.07	45.40	44.33	43.80	38.53	39.01	38.77	107.93	112.27	110.10
T6	3.00	3.00	3.00	39.80	43.27	42.71	38.44	38.88	38.66	106.00	110.20	108.10
T7	3.67	3.67	3.67	51.60	50.20	49.51	39.01	39.61	39.31	117.47	122.53	120.00
T8	3.40	3.40	3.40	44.20	47.93	47.30	38.86	39.43	39.14	113.07	117.67	115.37
T9	3.20	3.33	3.27	47.40	46.47	45.74	38.69	39.23	38.96	110.53	115.20	112.87
T10	2.80	2.80	2.80	35.80	38.73	38.27	38.09	38.41	38.25	100.00	103.67	101.83
T11	2.67	2.80	2.73	38.80	37.67	37.23	38.04	38.33	38.19	98.80	102.13	100.47
T12	2.67	2.67	2.67	33.60	36.27	35.90	37.99	38.25	38.12	91.33	94.27	92.80
F-test	S	S	S	S	S	S	NS	NS	NS	S	S	S
S.E. (m) (±)	0.12	0.12	0.09	1.35	1.25	0.92	1.46	1.74	1.14	3.6	3.84	2.63
C.D. @ 5%	0.34	0.36	0.24	3.96	3.67	2.62	-	-	-	10.56	11.27	7.5

T1: Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg⁻¹) + 100% NPK; **T2:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg⁻¹) + 85% NPK; **T3:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg⁻¹) + 70% NPK; **T4:** Liquid bio fertilizer consortia (LBFC) soil application (625 ml ha⁻¹) + 100% NPK; **T5:** Liquid bio fertilizer consortia (LBFC) soil application (625 ml ha⁻¹) + 85% NPK; **T6:** Liquid bio fertilizer consortia (LBFC) soil application (625 ml ha⁻¹) + 70% NPK; **T7:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg⁻¹) + soil application (625 ml ha⁻¹) + 100% NPK; **T8:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg⁻¹) + soil application (625 ml ha⁻¹) + 85% NPK; **T9:** Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg⁻¹) + soil application (625 ml ha⁻¹) + 70% NPK; **T10:** No use of Liquid bio fertilizer consortia (LBFC) + 100% NPK; **T11:** No use of Liquid bio fertilizer consortia (LBFC) + 85% NPK; **T12:** No use of Liquid bio fertilizer consortia (LBFC) + 75% NPK

5.CONCLUSION

This study highlights the significant positive impacts of integrating Liquid Biofertilizer Consortia (LBFC) with recommended NPK fertilization on the growth and yield attributes of wheat. Treatment (T7) Liquid bio fertilizer consortia (LBFC) seed treatment (6 ml kg⁻¹) + soil application (625 ml ha⁻¹) + 100% NPK, consistently outperformed other treatments in terms of plant height (cm), dry weight (g plant⁻¹), crop growth rate (CGR) (g m⁻² day⁻¹), relative growth rate (RGR) (g g⁻¹ day⁻¹), chlorophyll content mg 100g⁻¹ of fresh weight) and yield attributes like number of spikes plant⁻¹, number of grains spike⁻¹, test weight (g) and number of tillers per running meter.

The enhanced performance is attributed to the synergistic effects of nutrient enrichment and microbial activity that improved nutrient uptake, root development and hormonal stimulation for tiller and spike formation. Although differences in test weight were not statistically significant, T7 registered numerically higher values, indicating an improvement in grain quality. The findings emphasize the role of balanced nutrient management combined with biofertilizer consortia in maximizing wheat productivity sustainably. The positive outcomes of this treatment underscore the potential of integrating biofertilizers with chemical fertilizers to address soil fertility challenges while enhancing crop growth and yield.

REFERENCES

1. Anjali, Sharma, P. and Nagpal, S. (2021). Effect of Liquid and Charcoal Based Consortium Biofertilizers Amended with Additives on Growth and Yield in Chickpea (*Cicer arietinum* L.). 44(5): 527-538.
2. Anonymous. (2018). USDA Circular. United State Department of Agriculture, Foreign Agricultural Service, Circular Series, PP. 12-18.
3. Arzani, A. and Ashraf, M. (2017). Cultivated ancient wheats (*Triticum* spp.): A potential source of health-beneficial food products. *Compr. Rev. Food Sci. Food Saf.*, 16: 477-488.
4. Badr, E. A., Wali, A. M. and Amin, G. A. (2013). Effect of Microbine inoculation, Nitrogen fertilizer and



- organic manure on productivity of sunflower plants. *Journal of Applied Sciences Research*, 9(8): 5318-5322.
5. Bahrani, A., Pourreza, J. and Joo, H. M. (2010). Response of winter wheat to co-inoculation with azotobacter and arbuscular mycorrhizal fungi (AMF) under different sources of nitrogen fertilizer. *American – Eurasian Journal of Agriculture and Environmental Science*, 8(1): 95-10
 6. Bashan, Y., Holguin, G., Bashan, L. D. (2004). Azospirillum plant relationships physiological molecular, agricultural and environmental advances. *Canadian Journal of Microbiology*, 50: 521-577.
 7. Behera, U. K. and Rautaray, S. K. (2010). Effect of bio-fertilizers and chemical fertilizers on productivity and quality parameters of durum wheat (*Triticum turgidum*) on a Vertisol of Central India. *Archives of Agronomy and Soil Science*, 56(1): 65-72.
 8. DAFW (2025). Directorate of Economics and Statistics (DES).
 9. Dubcovsky, J. and Dvorak J. (2007). Genome plasticity a key factor in the success of polyploid wheat under domestication. *Science.*, 316: 1862–1866.
 10. Gomez, K. A. and Gomez, A. A. (1984) Statistical Procedures for Agricultural Research. 2nd Edition, John Wiley and Sons, New York, 680 p.
 11. Goncharov N. (2005). Comparative-genetic analysis—a base for wheat taxonomy revision. *Czech J. Genet. Plant Breed*, 41: 52–55.
 12. Gudadhe, N., M. B. Dhonde and Hirwe, N. A. (2015). Effect of integrated nutrient management on soil properties under cotton chickpea cropping sequence in vertisols of Deccan plateau of India. *Indian Journal of Agriculture Reserach*, 49: 207-214.
 13. Jain, D., Meena, R. H., Choudhary, J., Sharma, S. K., Chauhan, S., Bhojiya, A. A., Khandelwal, S.K. and Mohanty, S. R., (2021). Effect of microbial consortia on growth and yield of wheat under typic haplustepts. *Plant Physiology Reports*, 26(3): 570-580.
 14. Kaur, R., Kumar, S., Kaur, R. and Kaur, J. (2018). Effect of integrated nutrient management on growth and yield of wheat (*Triticum aestivum* L.) under irrigated conditions. *International Journ al of Chemical Studies*, 6(4): 1800-1803.
 15. Khan, K. S., Naveed, M., Qadir, M. F., Yaseen, M. and Siddiqui, M. H. (2023). Bio-organically acidified product-mediated improvements in phosphorus fertilizer utilization, uptake and yielding of *Zea mays* in calcareous soil. *Plants*, 12(17): 3072.
 16. Kumar, A., Maurya, B. R. and Raghuwanshi, R. (2021). The microbial consortium of indigenous rhizobacteria improving plant health, yield and nutrient content in wheat (*Triticum aestivum*). *Journal of Plant Nutrition*, 44(13): 1942-1956.
 17. Laxman, T. Srinivas, A. Kumar, K. V. and Prakash, T. R. (2017). Yield and yield attributes of Bt cotton as influenced by the bio-fertilizer consortia and foliar nutrition under rainfed. Mahmud, A. A., Musa, Y. S., Dhaked, G. S. and Jain, D. (2022). Impacts of NPK consortia biofertilizer and mineral fertilizer on growth and yield of two maize (*Zea mays* L.) hybrids in Rajasthan-India. *Diyala Agricultural Sciences Journal*, 14(2):100-117.
 18. Mandal, A. and Kongala, P. R. (2017). Effect of urea and azotobacter on growth, yield and biochemical parameters of wheat (*Triticum aestivum*) varieties AAI-W14 and K-65 under late sown condition. *Plant Archives*, 17(2): 1743-174.
 19. Mehdi, S. A., Ali, H., Malik, N., Abbasi, W. M. and Ahmed, I. (2025). Evaluating the Effects of Phosphorus Levels and Soil Moisture Conditions on Wheat Growth, Yield and Quality in Semi-Arid Southern Punjab, Pakistan. *Pol. J. Environ. Stud.*, 20(10): 1-13.
 20. Meier, S., Campos, P., Morales, A., Jobet, C., López-Olivari, R., Palma-Millanao, R., Matus, I., Aponte, H., Cartes, P., Khan, N., Lavanderos, L. and Seguel, A. (2024). Genotypic responses to phosphorus and water management in winter wheat: Strategies to increase resource use efficiency and productivity; *Agricultural Water Management*; 295: 108762.
 21. Paramasivan, M., Kumaresan, K.R., Malarvizhi, P. and Velayudham, K. (2014). Effect of different levels of NPK and Zn on yield and nutrient uptake by hybrid maize (COHM%) in Pilamedu and Aplaviduthi series of Tamil Nadu. *Madras Agriculture Journal*, 98(10-12): 334-338.
 22. Pathak, V. and Shrivastav, S. (2015). Biochemical studies on wheat (*Triticum aestivum* L.). *Journal of Pharmacognosy and Phytochemistry*, 4(3):171-175.
 23. Peng, J. H., Sun, D. and Nevo, E. (2011). Domestication evolution, genetics and genomics in wheat. *Mol. Breed*, 28: 281.



25. Sharma, K., Dak, G., Agrawal, A., Bhatnagar, M., Sharma, R. (2007). Effect of phosphate solubilizing bacteria on the germination of *Cicer arietinum* seeds and seedling growth. *Journal of Herbal Medicine and Toxicology*, 1(1): 61-63.
26. Singh, C. M., Sharma, P. K., Kishor, P., Mishra, P. K., Singh, A. P., Verma, R. and Raha, P. (2011). Impact of integrated nutrient management on Growth, Yield and Nutrient Uptake by Wheat (*Triticum aestivum* L.). *Asian Journal of Agricultural Research*, 5(1): 76–82.
27. Swarnalakshmi, K., Yadav, V., Tyagi, D., Dhar, D. W., Kannepalli, A. and Kumar, S. (2020). Significance of Plant Growth Promoting Rhizobacteria in Grain Legumes: Growth Promotion and Crop Production. *Plants (Basel)*, 9(11): 1596.
28. Ullah, I., Ali, N., Durrani, S. and Shabaz, M. A. (2018). Effect of Different Nitrogen Levels on Growth, Yield and Yield Contributing Attributes of Wheat. *International Journal of Scientific and Engineering Research*, 9(9): 595-602.
29. USDA (2025). IPAD (International Production Assessment Division), Foreign Agricultural Services, U. S. Department of Agriculture.
30. Venske, E., Dos Santos, R. S., Busanello, C., Gustafson, P. and Costa de Oliveira, A. (2019). Bread wheat: A role model for plant domestication and breeding. *Hereditas*, 156: 16.
31. Wamalwa, D. S., Sikuku, P., Netondo, G. W. and Daniel, B. K. (2019). Influence of NPK Blended Fertilizer Application on Chlorophyll Content and Tissue Mineral Contents of Two Finger
32. Millet Varieties Grown in Acid Soils of Kakamega, Western Kenya. *International Journal of Plant & Soil Science*, 27(4): 1-9.
33. Yadav, B., Bharati, V., Yadav, T. K. and Dwivedi, D. K. (2025). The effect of liquid biofertilizer practices on the growth and yield of finger melle. *International Journal of Research in Agronomy*, 8(3): 132-136.



DOIs:10.2015/IJIRMF/ICICSF-2025-P38

--:--

Research Paper / Article / Review

International Conference On "Innovative Convergence for Sustainable Future"

Date : 12 - 13 December, 2025

(ICICSF-2025)



Impact of Sustainable HR Practices on Attrition Rates in IT Companies

¹Shweta Rani, ²Dr. Sanjiv Chaturvedi

¹ Research Scholar (JRF), University Department of Commerce and Business Management, Ranchi University, Ranchi, Jharkhand, India

² Assistant Professor (Senior Scale), Department of Commerce, Marwari College, Ranchi, Jharkhand, India

¹ Email: shwetaanand64@gmail.com

Abstract: The information technology (IT) sector is a major contributor to economic growth and innovation, yet it continues to experience persistently high employee attrition. Frequent workforce turnover increases recruitment and training costs, disrupts project continuity, and weakens organizational productivity. In response, sustainable human resource (HR) practices have emerged as a strategic approach to address retention challenges in a holistic and long-term manner. This study examines the impact of sustainable HR practices on reducing attrition rates in IT companies, with particular emphasis on employee well-being and inclusive work culture. Adopting a descriptive research design based on secondary data, the study analyzes peer-reviewed literature, industry reports, and empirical evidence related to work-life balance initiatives, inclusive HR policies, green HRM, continuous learning and development, and employee well-being programs. The analysis indicates that organizations implementing sustainability-driven HR strategies experience lower turnover intentions and stronger employee commitment compared to those relying on traditional, transactional retention methods. Inclusive work culture is identified as a critical factor that fosters a sense of belonging, psychological safety, and organizational loyalty among employees. Similarly, well-being initiatives and flexible work arrangements contribute to reduced stress and enhanced job satisfaction, particularly in high-pressure IT environments. The findings further suggest that sustainable HR practices strengthen organizational resilience by aligning employee needs with long-term business objectives. Overall, the study concludes that integrating ethical, inclusive, and development-oriented HR practices can effectively reduce attrition while promoting stable and people-centric work cultures. The study offers valuable insights for HR practitioners seeking sustainable solutions in the IT sector globally.

Keywords: Sustainable HR Practices, Employee Attrition, Inclusive Work Culture, Employee Well-being, IT Industry.

1. INTRODUCTION

The information technology (IT) sector has been one of the fastest-growing industries worldwide, contributing significantly to economic development, innovation, and employment generation. However, this sector is also characterized by intense competition, long working hours, rapid technological changes, and a high demand for skilled professionals. These conditions have contributed to a persistent challenge of high attrition rates, particularly in countries like India where the IT industry is a major employer. Frequent employee turnover not only escalates recruitment and training costs but also disrupts team dynamics, reduces productivity, and affects client relationships. Therefore, managing attrition has become a strategic priority for IT companies seeking long-term sustainability. In recent years, organizations have begun to realize that traditional retention strategies, such as financial incentives and promotions, are not sufficient to address the deeper issues of driving attrition. Employees today seek a holistic work experience that includes well-being, inclusivity, purpose-driven engagement, and opportunities for personal and professional growth. This shift has led to the rise of sustainable human resource (HR) practices, which integrate employee well-being,



inclusivity, and environmental responsibility into HR strategies. Such practices aim not only to enhance employee satisfaction but also to build resilient and future-ready organizations.

Sustainable HR practices include initiatives such as flexible work arrangements, wellness and mental health programs, continuous learning opportunities, inclusive policies, and green HRM initiatives. By embedding these practices into their organizational culture, IT companies can create a more engaging, supportive, and inclusive environment that encourages employees to remain committed. This approach goes beyond short-term retention tactics and instead fosters long-term loyalty, thereby addressing the attrition problem at its roots. The present study seeks to examine the impact of sustainable HR practices on reducing attrition rates in IT companies. It highlights the role of employee well-being and inclusivity as critical factors that can strengthen retention strategies. By analyzing this relationship, the study aims to contribute both theoretically and practically to the growing body of literature on sustainable human resource management and provide IT companies with insights for designing effective people-centric policies.

1.1 Sustainable HR Practices:

Sustainable HR practices refer to human resource policies and strategies that focus on creating long-term value for both employees and organizations while aligning with social, environmental, and ethical responsibilities. HRM operations aim to minimize negative consequences, decrease company risks, improve reputation, recruit talent, meet consumer requests, and boost earnings and shareholder value (Lu et al., 2022). Unlike traditional HR methods that primarily emphasize performance and short-term outcomes, sustainable HR practices integrate employee well-being, inclusivity, diversity, continuous development, and ecological responsibility into organizational processes. Sustainable human resource management focuses not only on employee welfare, but also on how people may effectively contribute in the long run to fulfill organizational goals (Syafri & Rasyid, 2025). Sustainable human resource management incorporates a variety of measures, including work-life balance, career development opportunities, recognition programs, and employee health and wellness activities. Organizations that implement these practices seek to establish a work atmosphere in which employees feel respected, encouraged, and inspired to deliver their best effort (Siva et al., 2024). By embedding sustainability into HR functions, organizations not only enhance employee satisfaction and engagement but also strengthen retention, employer branding, and overall resilience. In the IT sector, where attrition is a persistent challenge, adopting sustainable HR practices provides a pathway for building a supportive and future-ready workforce that aligns individual aspirations with organizational goals. Green HRM integrates HR procedures with environmental objectives to enhance sustainable results for people and businesses. As companies try to strengthen their commitment to environmental sustainability, it is essential to comprehend how Green HRM influences green workplace behavior. The purpose of this study is to clarify how Green HRM influences employees' engagement in sustainable activities and how HR strategies can best assist company sustainability objectives. Green HRM (Green Human Resource Management) techniques have garnered a lot of attention in the management community because they promote environmentally responsible actions and behavior in the workplace (Dwivedi & Banerjee, 2025).

1.2 Dimensions of Sustainable HR Practices and Their Role in Employee Retention:

I. Work-Life Balance Initiatives

Organizations are using work-life balance strategies, including flexible hours, remote work, and wellness programs, to reduce stress and boost job satisfaction. These practices reduce stress, enhance job satisfaction, and play a crucial role in lowering attrition, especially in high-pressure IT jobs (Gowda & R, 2024).

II. Inclusive HR Policies

Diversity, Equity, and Inclusion (DEI) are no longer just buzzwords in the workplace, but rather fundamental principles that shape organizational dynamics (Ibeh et al., 2024). When a diverse workforce is treated fairly and participated in decision-making, it leads to increased innovation, creativity, and overall organizational effectiveness.



III. Green HRM

Green HRM is crucial for successfully implementing green strategies and environmental management practices and can enhance an organization's environmental sustainability (Shafaei et al., 2020). Beyond environmental benefits, they also enhance employer branding and attract employees who value social responsibility.

IV. Continuous Learning and Development

Training programs, career development opportunities, and upskilling initiatives support employees in adapting to technological changes. This not only improves organizational competitiveness but also ensures employees see long-term growth prospects, reducing turnover intentions.

V. Employee Well-being Programs

Health and wellness initiatives, including mental health support, stress management workshops, and employee assistance programs, address holistic well-being. By prioritizing physical and psychological health, organizations foster a supportive work culture that lowers burnout and attrition.

1.3 Employee Attrition and Organizational Response:

Employee attrition has become one of the most critical issues faced by organizations, particularly within the IT sector where competition for skilled professionals is intense. Attrition refers to the process of moving employees across organizations, employing new employees, and dealing with employee exits (Onuorah & Solomon, 2020). While some degree of turnover is natural and even healthy for organizational renewal, consistently high attrition rates can have serious implications. They often result in increased recruitment expenses, extended onboarding and training periods, and disruption of project continuity, ultimately affecting organizational performance and client satisfaction.

In the IT industry, attrition is typically influenced by multiple factors such as work overload, extended working hours, high-pressure deadlines, and rapid technological changes that demand continuous skill upgrading. Employees that leave voluntarily lower labor costs, which can be transferred to other areas. Labour costs include human salaries, assessments, and bonuses (A & Meti, 2023). Employees may also leave when they perceive limited career progression opportunities, inadequate recognition, or a lack of inclusivity in workplace policies. Beyond these tangible reasons, organizational culture plays a central role in shaping retention outcomes. Self-efficacy (SE) is a significant element contributing to attrition. Individuals' belief in their ability to successfully do an assigned activity (Bhardwaj & Sharma, 2024). When employees feel excluded, undervalued, or disconnected from the company's mission, their intention to leave becomes stronger. Conversely, a culture that fosters fairness, inclusivity, and holistic well-being can create a sense of belonging that encourages employees to stay.

Addressing attrition, therefore, requires a shift from transactional HR practices toward sustainable and people-centered approaches. Companies must focus on creating flexible work arrangements, offering meaningful career development opportunities, and embedding diversity and inclusion into everyday practices. By doing so, organizations not only reduce turnover but also strengthen their employer brand, improve employee engagement, and ensure long-term workforce stability. The IT department experiences the greatest attrition rates, followed by HR and sales. However, attrition leads firms to lose money and pay extra costs. Employers spend a lot of time, money, and effort educating and developing their employees to increase the effectiveness of their work, (Chirra & Joseph, 2024). Thus, understanding attrition through both its challenges and opportunities provides a pathway for building resilient, inclusive, and sustainable organizations.

1.4 Inclusive Work Culture in the IT Industry:

Inclusive work culture in the IT industry refers to organizational environments where diversity is not only recognized but actively embraced, ensuring that employees of different genders, ethnicities, abilities, and backgrounds feel valued and empowered. In high-pressure sectors like IT, fostering inclusivity is crucial for building engagement, collaboration, and long-term retention. An inclusive culture promotes equal access to opportunities, transparent communication, and



participative decision-making, which helps employees feel a sense of belonging and psychological safety. Managers must ensure that their company's varied workforce is evenly distributed throughout all divisions (**Castelino & Shinde, 2022**). Companies that integrate inclusivity into their policies—through initiatives like unbiased recruitment, mentorship programs, flexible work arrangements, and diversity training—tend to experience higher levels of employee satisfaction and loyalty. Moreover, inclusive workplaces encourage innovation by bringing diverse perspectives to problem-solving and project execution, a vital factor in technology-driven industries. Rather than focusing just on individuals, it is critical to create inclusive workplaces through evidence-based approaches that address systems and environments. This process must include lobbying and the adoption of a trauma-informed lens, studies of what motivates oppressive policies, and a shift from abstract guidance to tangible, precise guidelines with success indicators (**Adjo et al., 2021**). Ultimately, an inclusive work culture is not merely a social or ethical responsibility but a strategic imperative that aligns employee well-being with organizational growth.

2. LITERATURE REVIEW

1. **Shafaei, A., Nejati, M., & Yusoff, Y. (2020):** This study found that Green HRM practices, such as paperless processes and eco-focused training, enhance employee commitment by aligning personal and organizational values. When employees perceive their workplace as environmentally responsible, their loyalty and retention levels increase. The study suggests that GHRM serves not only sustainability goals but also strengthens workforce stability.
2. **Onuorah, A., & Solomon, E. (2020):** This study examined the impact of employee attrition on organizational productivity in manufacturing firms and found that frequent staff exits significantly disrupt workflow efficiency and operational performance. The study revealed that high turnover not only increases recruitment and training costs but also leads to knowledge loss and reduced team cohesion. They emphasized that organizations experiencing persistent attrition struggle to maintain consistent output levels, ultimately affecting their competitive standing. The authors recommend that proactive retention strategies are essential for sustaining productivity and long-term organizational stability.
3. **Adjo, J., Maybank, A., & Prakash, V. (2021):** This study highlights that inclusive work environments play a crucial role in fostering trust, psychological safety, and interpersonal collaboration across diverse employee groups. Their study underscores that when individuals feel respected and represented within organizational systems, they demonstrate higher engagement and reduced turnover intentions. The authors emphasize that inclusion must extend beyond policy statements to everyday practices such as equitable decision-making, open communication, and shared accountability. This reinforces the perspective that inclusivity is foundational to both employee well-being and organizational sustainability.
4. **Lu, Y., Zhang, M., Yang, M., & Wang, Y. (2022):** This study emphasize that sustainable HR practices foster employee resilience, which contributes to stronger engagement and performance. When employees perceive HR policies as fair, supportive, and ethically grounded, they are more likely to respond with loyalty and proactive behavior. The study positions sustainability in HRM not just as an environmental concern but as a social strategy for building long-term workforce stability and retention.
5. **Castelino, L., & Shinde, R. (2022):** This study emphasizes that diversity and inclusiveness are key drivers of excellence within the IT industry. Their study reveals that organizations embracing diverse teams and equitable workplace practices experience higher levels of innovation, problem-solving efficiency, and employee engagement. They further argue that inclusive cultures foster psychological safety and mutual respect, which contribute to stronger collaboration and retention. The findings suggest that diversity is not just a compliance measure but a strategic asset for long-term organizational effectiveness.
6. **A, K., & Meti, P. (2023):** This study examined the impact of employee attrition on organizational performance at Advance Cable Technologies Pvt. Ltd. and reported that high turnover had direct negative implications for productivity, operational efficiency, and service consistency. The study highlighted that frequent employee exits led to increased hiring and training expenses, alongside disruptions in team coordination. The authors further suggested that sustained attrition can weaken organizational morale and customer satisfaction, ultimately affecting long-term profitability. They emphasized the need for proactive retention mechanisms to maintain workforce stability.
7. **Siva, S., Saravanakumar, A., Biswas, P., Verma, S., & Shankar, U. (2024):** This study emphasize that sustainable HRM practices significantly enhance employee satisfaction and retention by creating a supportive and value-driven work environment. Their study suggests that policies promoting continuous learning, fair performance evaluation, and ethical leadership strengthen employee trust and organizational commitment. They



further argue that sustainability in HRM should be positioned as a long-term retention strategy rather than a short-term policy intervention. Overall, the findings reinforce the role of responsible HR practices in maintaining a loyal and motivated workforce.

8. **Gowda, M., & R, R. (2024):** This study analyzes the combined impact of work-life balance initiatives and training programs on employee productivity and long-term career development. Their findings suggest that flexible work policies significantly reduce stress and improve motivation, while structured training enhances skill advancement and confidence. The study emphasizes that when both well-being and competency development are prioritized together, employees exhibit higher commitment and reduced inclination to leave. This reinforces the view that sustainable HR interventions should integrate both support and growth mechanisms to retain talent effectively.
9. **Ibeh, C., Oyeyemi, O., Elufioye, A., Bello, B., & Daraojimba, A. (2024):** This study highlights diversity, equity, and inclusion (DEI) practices significantly boost employee engagement and retention. Their review highlights that organizations implementing fair hiring, equitable compensation, and inclusive leadership build stronger trust among employees. They argue that DEI is not only a social responsibility but a strategic advantage, driving innovation and workforce stability in modern workplaces.
10. **Bhardwaj, S., & Sharma, S. (2024):** This study investigated the relationship between self-efficacy, organizational efficacy, and employee attrition in the IT sector. Their findings indicate that employees with high personal confidence and strong belief in their organization's capabilities are less likely to leave their jobs. Conversely, when employees perceive weak managerial support or lack faith in their organization's future, their turnover intentions increase significantly. The study highlights the importance of fostering both individual and institutional confidence as a strategic retention mechanism in high-pressure work environments like IT.
11. **Chirra, R., & Joseph, A. (2024):** Chirra and Joseph (2024) explored department-specific attrition trends and found that turnover rates significantly vary across functional areas within organizations. Their study revealed that departments with higher work pressure, limited recognition, or restricted growth opportunities experienced greater employee exits compared to more resource-supported units. The authors emphasized that a one-size-fits-all retention strategy is ineffective, as each department requires tailored interventions based on its unique challenges. This insight reinforces the need for data-driven HR responses to manage attrition more strategically.
12. **Syafri and Rasyid (2025):** This study asserts that sustainable HR practices significantly contribute to organizational resilience by strengthening trust, continuity, and adaptability within the workforce. Their findings indicate that policies focused on employee development, well-being, and ethical governance improve long-term retention and reduce turnover tendencies. The study highlights that sustainability-oriented HR strategies are not merely supportive functions but act as core drivers of stability and competitiveness in modern organizations.
13. **Dwivedi, A., & Banerjee, S. (2025):** This study examines the role of Green Human Resource Management (GHRM) strategies in enhancing managerial effectiveness within Indian IT firms. Their study highlights that environmentally responsible HR practices, such as green training, eco-friendly performance appraisal, and sustainable leadership development, positively influence managerial decision-making and operational efficiency. The findings suggest that managers working within sustainability-oriented HR frameworks demonstrate higher adaptability and strategic awareness. The authors further emphasize that GHRM practices strengthen organizational commitment by aligning managerial roles with environmental and ethical values. Overall, the study positions green HRM as a critical driver of effective management and long-term organizational sustainability in the IT sector.

3. RESEARCH OBJECTIVE

This study aims to investigate the influence of sustainable human resource practices on employee attrition within the IT sector. The specific objectives of this research are as follows:

1. To find out if sustainable HR practices can lower the rate of employees leaving IT companies.
2. To see how employee well-being and an inclusive work culture affect employee retention.

4. RESEARCH METHODOLOGY

This study adopts a descriptive research design based entirely on secondary data to analyze the effect of sustainable HR practices on attrition in IT companies. Data was gathered via secondary sources such as previously peer-reviewed journal articles, newspaper articles, and websites related to the topic at hand. Relevant literature on work-life balance, inclusive



policies, well-being programs, and green HRM is systematically reviewed and thematically analyzed. All data is cross verified to ensure reliability, and proper citation practices are followed to maintain research ethics. The findings aim to provide evidence-based recommendations for building sustainable HR frameworks in the IT sector.

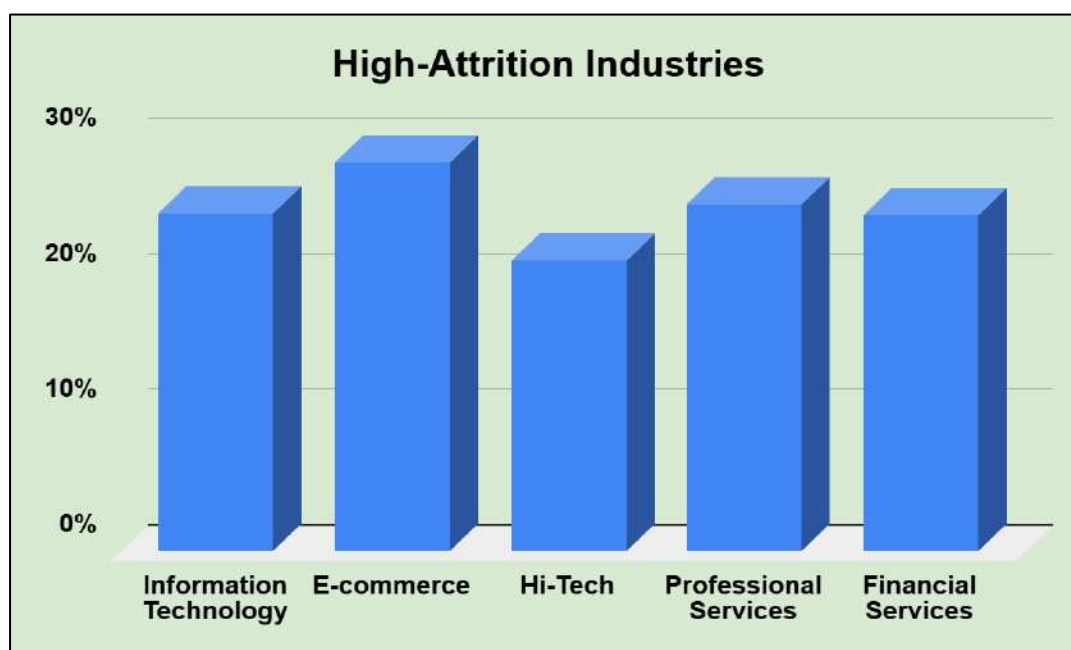
5. DATA ANALYSIS

Figure 1: Rates of Attrition by Industry

High-Attrition Industries

Industries	Attrition Rates
Information Technology	25%
E-commerce	28.70%
Hi-Tech	21.50%
Professional Services	25.70%
Financial Services	24.80%

Source: <https://www.wisemonk.io/blogs/managing-attrition-in-india>

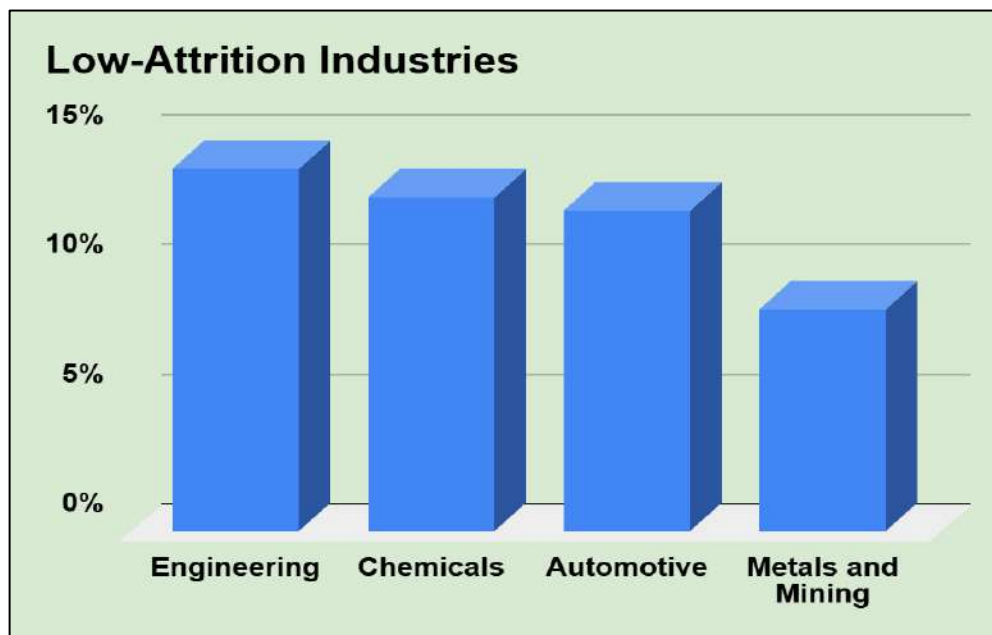


Source: Compiled by the researcher

Low-Attrition Industries

Industries	Attrition Rates
Engineering	14%
Chemicals	12.90%
Automotive	12.40%
Metals and Mining	8.60%

Source: <https://www.wisemonk.io/blogs/managing-attrition-in-india>



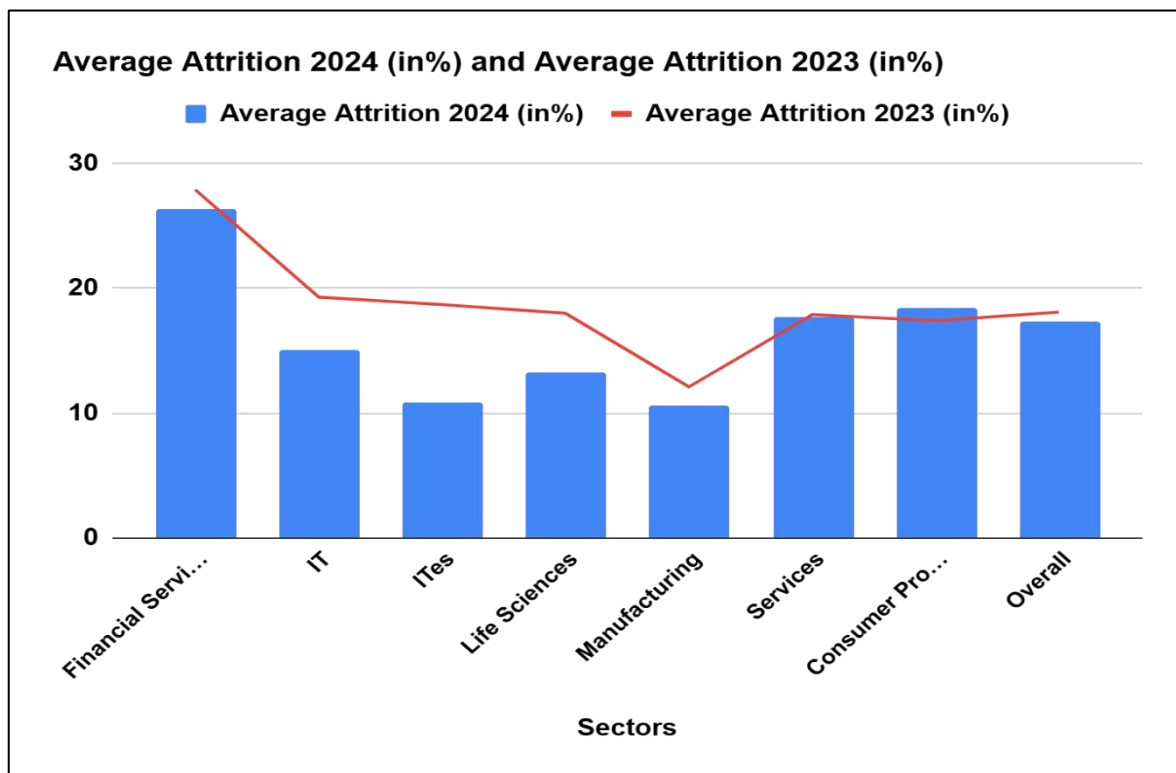
Source: Compiled by the researcher

Data Interpretation: The data indicates that industries such as E-commerce (28.70%), Professional Services (25.70%), and Information Technology (25%) face some of the highest attrition rates, suggesting that fast-paced and high-pressure work environments are more prone to employee turnover. These sectors typically demand constant upskilling, longer working hours, and high adaptability, which may contribute to burnout and frequent job switching. In contrast, industries like Metals and Mining (8.60%), Automotive (12.40%), and Engineering (14%) show comparatively lower attrition levels, reflecting more stable job roles and structured career paths. This contrast highlights that retention strategies must be more robust and sustainability-focused in high-churn industries, particularly within IT and E-commerce. Overall, the data emphasizes the growing need for well-being initiatives, career security, and supportive HR practices to manage attrition more effectively in dynamic sectors.

Figure 2: Comparison of Industry-Wise Attrition Rates Between 2023 and 2024

Sectors	Average Attrition 2024 (in%)	Average Attrition 2023 (in%)
Financial Services	26.4	27.9
IT	15.1	19.3
ITes	10.8	18.7
Life Sciences	13.3	18
Manufacturing	10.6	12.1
Services	17.7	17.9
Consumer Products	18.4	17.4
Overall	17.4	18.1

Source: <https://economictimes.indiatimes.com/jobs/mid-career/india-incs-attrition-rates-hit-lowest-point-since-2020-amid-hiring-slowdown/articleshow/118767184.cms?from=mdr>



Source: Compiled by the researcher

Data Interpretation: The data shows a noticeable decline in attrition across most sectors from 2023 to 2024, particularly in IT (from 19.3% to 15.1%) and ITes (from 18.7% to 10.8%), indicating improved retention strategies in technology-driven industries. Financial Services still reports one of the highest attrition levels at 26.4%, suggesting continued workforce instability. In contrast, Manufacturing remains relatively stable with the lowest attrition rates among all sectors. Overall, the average attrition rate has slightly reduced from 18.1% to 17.4%, reflecting gradual progress in employee retention practices across industries.

6. FINDINGS OF THE STUDY

The study finds that sustainable human resource practices play a significant role in reducing employee attrition in IT companies. Practices such as work-life balance initiatives, inclusive HR policies, green HRM, continuous learning opportunities, and employee well-being programs positively influence employee retention. The analysis indicates that employees are more likely to remain with organizations that prioritize holistic well-being rather than relying solely on monetary incentives. Inclusive work culture emerged as a key factor in fostering a sense of belonging and organizational commitment among employees. The findings also suggest that organizations adopting sustainability-driven HR strategies experience improved employee engagement and long-term workforce stability. Additionally, the study highlights that high-pressure sectors like IT require people-centric and flexible HR interventions to effectively manage attrition. Overall, the results confirm that sustainable HR practices contribute to organizational resilience by strengthening employee loyalty and reducing turnover intentions.

7. LIMITATION AND PROSPECTS FOR FUTURE RESEARCH

This study has a few limitations, as it focuses only on the IT sector, which may make its findings less applicable to other industries. The research also uses a specific group of people (IT professionals and HR managers), and a broader study could be more useful. Because it's a one-time study, it may not fully show the long-term effects on employee turnover. For future research, it would be beneficial to expand the study to other industries, conduct a longer-term analysis, and explore how additional factors like the economy or new technology influence attrition.



8. CONCLUSION AND DISCUSSION

The study shows that sustainable HR practices such as flexible work options, employee well-being programs, inclusivity, and continuous learning significantly reduce attrition in IT companies. Employees are more likely to stay when they feel valued, supported, and provided with growth opportunities rather than just monetary benefits. Traditional retention methods are no longer enough in today's competitive work environment. Sustainable HR approaches help build trust, loyalty, and long-term commitment among employees. They also improve employer branding and organizational stability. Therefore, IT companies must shift from transactional HR policies to people-centered and sustainability-driven strategies. Such practices not only control turnover but also create a resilient and future-ready workforce.

9. ACKNOWLEDGEMENT

I respectfully express sincere gratitude to **Dr. Sanjiv Chaturvedi** my supervisor, for his exceptional academic supervision and unwavering support throughout the research process. His profound subject knowledge, critical insights, and methodological guidance were instrumental in refining the research framework and strengthening the analytical rigor of this study. I greatly appreciate his constructive feedback, scholarly suggestions, and continuous encouragement, which significantly enhanced the quality and coherence of the manuscript. His guidance also contributed to developing a deeper understanding of sustainable human resource practices and their implications for employee retention in the IT sector. I am equally thankful for his patience, academic integrity, and commitment to excellence, which served as a constant source of motivation.

REFERENCES

1. Lu, Y., Zhang, M., Yang, M., & Wang, Y. (2022). Sustainable human resource management practices, employee resilience, and employee outcomes: Toward common good values. *Human Resource Management*. <https://doi.org/10.1002/hrm.22153>.
2. Syafri, M., & Rasyid, A. (2025). Sustainable Human Resource Practices: Analyzing Their Impact on Organizational Resilience and Employee Retention. *Return : Study of Management, Economic and Business*. <https://doi.org/10.57096/return.v4i1.320>.
3. Siva, S., Saravanakumar, A., Biswas, P., Verma, S., & Shankar, U. (2024). Developing Sustainable HRM Practices for Retention and Satisfaction in Organizations. *Nanotechnology Perceptions*. <https://doi.org/10.62441/nano-ntp.vi.4017>.
4. Gowda, M., & R, R. (2024). A Study on Work-life Balance Initiatives and Training Programs Towards Employee Productivity and Career Development. *International Journal For Multidisciplinary Research*. <https://doi.org/10.36948/ijfmr.2024.v06i05.28486>.
5. Ibeh, C., Oyeyemi, O., Elufioye, A., Bello, B., & Daraojimba, A. (2024). DIVERSITY, EQUITY, AND INCLUSION IN MODERN WORKPLACES: AN HR REVIEW OF STRATEGIES AND BENEFITS. *Malaysian Journal Of Human Resources Management*. <https://doi.org/10.26480/mjhrm.02.2024.83.90>.
6. Shafaei, A., Nejati, M., & Yusoff, Y. (2020). Green human resource management. *International Journal of Manpower*. <https://doi.org/10.1108/ijm-08-2019-0406>.
7. Onuorah, A., & Solomon, E. (2020). EFFECT OF EMPLOYEE ATTRITION ON ORGANISATIONAL PRODUCTIVITY IN ANAMBRA STATE MANUFACTURING ORGANISATION. , 4. <https://doi.org/10.26808/rs.rmf.v4i4.01>.
8. Bhardwaj, S., & Sharma, S. (2024). Self-efficacy and organizational efficacy effect on employee attrition in IT sector. *Business Analyst Journal*. <https://doi.org/10.1108/baj-07-2023-0057>.
9. Chirra, R., & Joseph, A. (2024). DEPARTMENT-SPECIFIC ATTRITION RATE OF EMPLOYEES. *International Journal of Business Management and Economic Review*. <https://doi.org/10.35409/ijbmer.2024.3570>.
10. A, K., & Meti, P. (2023). A STUDY ON IMPACT OF EMPLOYEE ATTRITION TOWARDS ORGANISATIONAL PERFORMANCE AT ADVANCE CABLE TECHNOLOGIES PRIVATE LIMITED IN DODDABALLAPUR. *INTERANTIONAL JOURNAL OF SCIENTIFIC RESEARCH IN ENGINEERING AND MANAGEMENT*. <https://doi.org/10.55041/ijssrem26696>.



11. Castelino, L., & Shinde, R. (2022). Excellence through Diversity-Inclusiveness: A Focus on IT Industry. *International Journal of Case Studies in Business, IT, and Education*. <https://doi.org/10.47992/ijcsbe.2581.6942.0213>.
12. Adjo, J., Maybank, A., & Prakash, V. (2021). Building Inclusive Work Environments... *Pediatrics*, 148 Suppl 2. <https://doi.org/10.1542/peds.2021-051440E>.
13. Dwivedi, A., & Banerjee, S. (2025). Green HRM Strategies and Their Impact on Managerial Effectiveness: Insights from IT Firms Across India. *Journal of Informatics Education and Research*. <https://doi.org/10.52783/jier.v5i1.2031>.
14. <https://www.wisemonk.io/blogs/managing-attribution-in-india>
15. <https://economictimes.indiatimes.com/jobs/mid-career/india-incs-attribution-rates-hit-lowest-point-since-2020-amid-hiring-slowdown/articleshow/118767184.cms?from=mdr>



DOIs:10.2015/IJIRMF/ICICSF-2025-P39

--:--

Research Paper / Article / Review

International Conference On “Innovative Convergence for Sustainable Future”

Date : 12 - 13 December, 2025

(ICICSF-2025)



Unified Agentic Platform for Clinical Research: The Role of Salesforce Agentforce in Intelligent CRO Ecosystem Integration

Srikanth Perla

Charles River Laboratories Inc., USA

reachsrikanthperla@gmail.com

Abstract: This article introduces the Unified Agentic Platform architecture that integrates Salesforce Agentforce with Data Cloud, MuleSoft APIs, and Health Cloud to achieve intelligent orchestration of Contract Research Organization operations. The framework outlines how Agentforce agents, powered by retrieval-augmented generation and contextual reasoning, autonomously monitor trial milestones, communicate with investigators, and maintain regulatory documentation. A controlled pilot implementation demonstrated measurable impact across operational cost reduction, improved service level agreement adherence, and faster data reconciliation across Electronic Data Capture and Customer Relationship Management systems. The article outlines a standardized agent testing methodology for validating the behavior of artificial intelligence in regulated environments, thereby bridging software quality assurance with autonomous AI systems. The proposed framework positions Agentforce as a foundational enabler of intelligent compliance and operational excellence in the digital CRO landscape. The architecture allows for the proactive prevention of compliance issues rather than simply identifying them after the fact by embedding regulatory awareness into operational workflows rather than deferring to separate compliance functions. The integration architecture combines the API-led connectivity of MuleSoft, the unified data consolidation of Data Cloud, and the healthcare-based functionality of Health Cloud to create leverageable capabilities that allow for synergistic abilities to exceed those of their parts. The architecture provides templated patterns for agent design, deployment, monitoring, and governance that allow CROs to achieve automation benefits without compromising regulatory compliance, or data integrity requirements that are germane to pharmaceutical development.

Keywords: Autonomous Clinical Operations, Intelligent Regulatory Compliance, Healthcare AI Integration, Pharmaceutical Trial Automation, Enterprise Agent Orchestration

1. INTRODUCTION

The clinical research environment is under increasing pressure to shorten trial timelines while maintaining strict regulatory compliance and data integrity-related burden. Contract Research Organizations (CROs) operate in an ecosystem of multiple stakeholders, disparate technology systems, and strict regulatory frameworks that govern the entire trial conduct process. Traditional ways of working for CROs are characterized by manual coordination across fragmented communication channels and unrelated software-based platforms that result in compliance risk and operational inefficiency. Advances in artificial intelligence, and autonomous agent-based technologies provide an opportunity to change how CROs perform the orchestration of clinical trials, the management of investigator relationships, and regulatory compliance capabilities. Salesforce Agentforce represents a new paradigm in enterprise AI, enabling organizations to deploy autonomous agents capable of reasoning, decision-making, and complex task execution within governed parameters. Agentforce takes a different approach than traditional robotic process automation or rule-based workflows in that it uses large language models coupled with retrieval-augmented generation to provide contextual intelligence and adaptable behavior. In the specific context of clinical research operations, these capabilities allow for unprecedented levels of automation while still providing the necessary oversight and audit trail to meet the



regulatory demands of healthcare. The integration of Agentforce with Salesforce's Health Cloud, Data Cloud, and MuleSoft connectivity platform creates a comprehensive ecosystem for intelligent CRO operations.

1.1 Background: CRO Operations and Digital Transformation Challenges

Contract Research Organizations (CROs) are vital components in the development of pharmaceuticals and deliver clinical trials on behalf of sponsors who manage all aspects of their clinical trials while coordinating site-based activities across investigators, regulatory agencies and patients. The modern CRO typically manages portfolios that span many therapeutic areas, regions of the world, and phases of a clinical trial. These operational realities present challenges both to managers and to traditional management practices. The operational activities of CROs include protocol development, site identification/activation, patient recruitment, monitoring activities, safety reporting, data management, and submission with regulatory agencies. Each of these functions generates prescriptive documentation and requires coordination with stakeholders who have different capabilities and regulatory requirements.

The technology landscape that supports CROs have developed growth and decay in a fragmented nature as opposed to a systematic comprehensive process. This has resulted in a complex architecture, whereby technology has been developed specifically for each function which leaves three different worlds without having any systematic plan for integration. For example, Electronic Data Capture systems have been developed for collecting the clinical data, Clinical Trial Management Systems have been developed for operational tracking of milestones of the individuals' participation in a clinical trial, Electronic Trial Master File systems for regulatory documents, and for coordinating investigator communications the entire Customer Relationship Management system. Each technology system is somewhat functioning like a separate silo within the architecture with limited capacity for interoperability. Manual processes are important for consistency and reconciling differences.

Regulatory compliance requirements further complicate operational complexity due to mandated audit trails, controls for data integrity, and validation documentation for any systems utilized for operations involving the conduct of clinical trials. Consistent with other FDA Good Clinical Practice guidelines, including the Good Clinical Practice guidelines laid by the FDA in E6(R2) integrated addendum to ICH E6(R1), the comprehensive requirements for the conduct of clinical trials includes source data verification, investigator responsibilities, and quality management systems [1]. These guidelines emphasize risk-based approaches to quality management and the importance of critical data identification. Additionally, the FDA's guidance on Part 11 Electronic Records and Electronic Signatures clarifies expectations for computerized systems used in clinical trials, addressing scope and application of electronic record requirements, validation documentation, and audit trail functionality [2].

1.2 Research Objectives and Scope

The Unified Agentic Platform architecture addresses critical challenges in CRO operations including trial milestone monitoring, investigator communication management, regulatory documentation maintenance, and cross-system data reconciliation. By implementing standardized agent testing methodologies and validation protocols consistent with FDA expectations for computerized systems, the framework ensures that autonomous AI behavior meets the quality assurance standards expected in clinical research [1][2]. The controlled pilot implementation provides empirical evidence of operational improvements and establishes design patterns for deploying agentic systems in healthcare contexts.

The framework positions Agentforce as a foundational enabler of proactive compliance monitoring embedded directly into operational workflows rather than implemented as separate audit functions. The advancement in understanding demonstrates how retrieval-augmented generation can be adapted to specialized domains requiring strict adherence to organizational policies, regulatory requirements, and industry standards. The standardized testing framework provides reusable methodologies applicable beyond the specific UAP implementation to autonomous agents in any regulated healthcare application.

2. Salesforce Agentforce and Unified Agentic Platform Architecture

2.1 Salesforce Agentforce: Core Architecture and Capabilities

Salesforce Agentforce represents a significant evolution in enterprise AI platforms, providing capabilities for deploying autonomous agents that can reason about complex scenarios, access organizational knowledge, and execute multi-step workflows within governed parameters. The platform architecture consists of several interconnected components including the Agent Builder interface for designing agent behaviors, the Agent Runtime environment for executing agent



logic, the Trust Layer for ensuring safe and compliant operations, and integration connectors to enterprise data sources and external systems [3]. Unlike traditional automation platforms that follow predefined rules and deterministic logic, Agentforce agents utilize large language models to interpret natural language instructions, understand contextual nuances, and generate appropriate responses based on dynamic circumstances.

The foundational reasoning engine of Agentforce uses prompt engineering, retrieval-augmented generation, and structured decision frameworks combined to deliver contextual intelligence for tasks. When the agent receives a task or inquiry, the agent will first assess the request to understand the context, the data sources needed, and the next steps. The retrieval system searches through knowledge bases, CRM data, and any external systems to find task-related information. This context adds to the immediate capabilities of the language model's capabilities to allow the agent to reply based on knowledge from the organization instead of the language model's pre-training data.

Agent Builder provides a development environment where organizations can define agent personas, specify knowledge sources, configure allowed actions, and establish guardrails for autonomous behavior [3]. The persona definition establishes the agent's role, expertise areas, and communication style, enabling specialized agents for different functional domains. Knowledge source configuration connects agents to relevant data repositories including Salesforce objects, Data Cloud segments, external databases via MuleSoft, and document repositories. Action configuration determines which operations agents can perform autonomously versus which require human approval, enabling gradual delegation of responsibilities as confidence in agent behavior increases.

2.2 Unified Agentic Platform Framework for Clinical Research

The Unified Agentic Platform framework establishes an architectural pattern specifically designed for deploying autonomous agents within clinical research operations while maintaining compliance with regulatory requirements and industry standards. The framework addresses fundamental challenges in applying general-purpose AI capabilities to highly regulated healthcare contexts where auditability, traceability, and validation are mandatory. UAP has defined standards for agent design, deployment, monitoring, and governance that allow CROs to take full advantage of autonomous operations while ensuring compliance with regulations and maintaining data integrity. The UAP framework provides a structured way to think about agent capability and allows for it to be broken down into three layers: Knowledge Layer, Reasoning Layer, and Action Layer. The Knowledge Layer provides organized representations of clinical trial data collected from disparate sources that agents can easily access and comprehend. This layer implements semantic models that capture clinical trial concepts including protocols, amendments, sites, investigators, patients, adverse events, and regulatory submissions. The Reasoning Layer implements the cognitive capabilities that enable agents to interpret situations, evaluate options, and make decisions appropriate to clinical research contexts. The Action Layer defines the operational interventions that agents can execute autonomously or recommend for human approval.

Layer Component	Primary Function	Key Implementation Features
Knowledge Layer	Data consolidation from disparate clinical trial sources	Semantic models for protocols, amendments, sites, investigators, and regulatory submissions
Reasoning Layer	Cognitive interpretation and decision-making capabilities	Contextual evaluation using retrieval-augmented generation and domain-specific logic
Action Layer	Operational intervention execution and recommendations	Tiered autonomy with low-risk, medium-risk, and high-risk action classifications

Table 1: UAP Framework Architectural Layers and Functional Capabilities [3]



2.3 Retrieval-Augmented Generation in Clinical Research Contexts

Retrieval-Augmented Generation represents a fundamental architectural pattern that enables Agentforce agents to ground their reasoning in organizational knowledge rather than relying solely on pre-trained language model capabilities. The RAG pattern addresses a critical limitation of general-purpose language models: while they possess broad knowledge from training data, they lack awareness of organization-specific information including standard operating procedures, protocol details, historical trial data, and regulatory submission history [4]. In clinical research contexts, this organizational knowledge is essential for appropriate decision-making, as trial-specific protocols, amendment history, and site-specific considerations fundamentally shape what actions are appropriate in given circumstances.

The retrieval mechanism within UAP implementations searches across multiple knowledge repositories to identify information relevant to the agent's current task or query. Document repositories containing standard operating procedures, work instructions, and regulatory guidance provide procedural knowledge about how operations should be conducted. Protocol specifications and amendments define trial-specific requirements including inclusion criteria, dosing regimens, safety monitoring parameters, and visit schedules. The augmentation process integrates retrieved knowledge with the agent's core language model capabilities to generate contextually appropriate responses and decisions [4].

3. Implementation Framework and Integration Architecture

3.1 Integration Architecture: MuleSoft, Data Cloud, and Health Cloud

The integration architecture underpinning the Unified Agentic Platform leverages Salesforce's ecosystem of connectivity and data management platforms to create a cohesive environment for intelligent CRO operations. MuleSoft Anypoint Platform serves as the primary integration backbone, connecting Agentforce agents to the diverse systems that constitute the CRO technology landscape. The API-led connectivity model utilized by MuleSoft structures integration into three separate architectural layers that foster reusability, scalability, and maintainability [5]. System APIs obtain standardized access to existing applications and data sources while abstracting technical complexity and providing a consistent interface to the application, regardless of what the underlying implementation looks like. Process APIs represent implementations of business logic and orchestration that coordinate between several system APIs to execute specific business processes.

This layered architecture enables agents to interact with sophisticated integration workflows without managing system-specific protocols, data formats, or connectivity details. The separation of concerns across API layers promotes flexibility and resilience, as changes to backend systems require updates only to system APIs while process and experience layers remain stable [5]. As mentioned previously, MuleSoft's extensive connector ecosystem provides preconfigured integration components for popular enterprise application products, which accelerates the implementation process and adheres to suggested integration patterns defined by the respective vendor.

Data Cloud provides the unified data layer that consolidates clinical trial information from multiple sources into coherent profiles and segments accessible to Agentforce agents. Data Cloud implements a customer data platform pattern that harmonizes data from connected sources into unified profiles representing key entities including trial sites, principal investigators, study coordinators, and sponsor organizations [6]. The platform's identity resolution capabilities link records across systems based on matching algorithms and unique identifiers, creating consolidated views that eliminate duplication and inconsistency.

Health Cloud extends Salesforce's CRM capabilities with healthcare-specific functionality including care coordination, provider relationship management, and patient engagement features adapted for clinical research contexts. In UAP deployments, Health Cloud serves as the system of record for investigator relationships, site qualification tracking, and protocol training documentation [7]. The platform's care plan capabilities map naturally to clinical trial protocols, enabling structured representation of study procedures, visit schedules, and assessment timelines.



Platform Component	Core Capability	Clinical Research Application
MuleSoft Anypoint Platform	API-led connectivity across disparate systems	Integration of EDC, CTMS, eTMF, and laboratory systems through layered architecture
Data Cloud	Unified data consolidation and identity resolution	Harmonized profiles for trial sites, investigators, coordinators, and sponsor organizations
Health Cloud	Healthcare-specific CRM and care coordination	Investigator relationship management, site qualification tracking, and protocol training documentation

Table 2: Integration Platform Components and Operational Roles [5]

3.2 Autonomous Agent Capabilities in CRO Operations

In addition, the implementation of autonomous agents in CRO operations presents multiple functional areas where intelligent automation can increase operational efficiencies while still remaining within regulatory, compliance, and quality standards. For example, milestone tracking for trials is the most basic function that includes agents tracking trial progress and consistently tracking the trial that involves watching against planned timelines, and noting deviations that require additional attention, and then proactively alerting relevant stakeholders of developing risks. Autonomous agents overcome limitations when they continuously maintain some level of awareness of trial status across all sites, keep track of actual status against what is expected according to the protocol, and distinguish between typical variations and more significant deviations.

Investigator communication management constitutes another critical application domain where agents can enhance both efficiency and consistency. Autonomous agents address scalability challenges by drafting contextually appropriate communications based on trial protocols, investigator history, site performance data, and current operational status. When investigators submit queries through email or Health Cloud portals, agents retrieve relevant protocol sections, cross-reference historical similar queries, and generate draft responses that incorporate trial-specific details.

Regulatory documentation maintenance represents a domain where agent capabilities can significantly reduce compliance risks and manual effort. Clinical trials generate extensive documentation requirements including informed consent forms, protocol amendments, safety reports, site correspondence, training records, and monitoring reports that comprise the Trial Master File. Autonomous agents monitor documentation status by analyzing eTMF systems, identifying missing or outdated documents, and generating notifications to responsible personnel.



Functional Domain	Agent Capability	Operational Impact
Trial Milestone Monitoring	Continuous progress assessment and deviation identification	Proactive stakeholder alerting and risk mitigation across all trial sites
Investigator Communication Management	Context-aware draft generation and query resolution	Scalable personalized responses incorporating protocol specifics and historical patterns
Regulatory Documentation Maintenance	eTMF completeness monitoring and notification generation	Reduced compliance risk through continuous documentation status assessment

Table 3: Autonomous Agent Functional Domains in CRO Operations [6]

3.3 Implementation Methodology and Agent Testing Framework

The pilot implementation of the Unified Agentic Platform was carried out in a controlled pilot setting and involved a carefully defined protocol to evaluate core capabilities while managing organizational change and ensuring business continuity. The team involved in the implementation included roles from across the institution, including clinical operations staff, IT infrastructure staff, data management, quality assurance, and regulatory affairs, to ensure that design decisions were informed by every functional role. Implementing the agent included a thorough implementation plan detailing phases of requirements gathering, agent design, integration development, validation testing, user training, production deployment, and ongoing monitoring.

The validation of autonomous agents operating in regulated clinical research environments requires testing methodologies that bridge conventional software quality assurance with the unique characteristics of AI systems exhibiting probabilistic behavior. Language model-based agents inherently produce varied outputs even with identical inputs due to the stochastic nature of generation processes. This variability necessitates testing approaches that evaluate output characteristics, appropriateness, and adherence to requirements rather than exact text matching.

The framework organizes testing activities into multiple dimensions addressing functional correctness, reasoning quality, compliance adherence, safety boundaries, and performance characteristics. Functional testing validates that agents can access required data sources, execute allowed actions, and integrate correctly with external systems. Reasoning quality testing evaluates whether agents apply retrieved knowledge appropriately, draw sound conclusions from available information, and escalate ambiguous scenarios for human judgment.

4. Results, Performance Analysis, and Intelligent Compliance

4.1 Pilot Implementation Results and Performance Metrics

The controlled pilot implementation provided empirical evidence of measurable operational improvements attributable to the Unified Agentic Platform across multiple performance dimensions. Data collection included both quantitative operational metrics and qualitative feedback from clinical operations personnel involved in pilot execution. This



combination of objective measurements and subjective assessments provided a comprehensive evaluation of UAP impact.

Operational cost reduction emerged as a primary outcome driven by decreased manual effort across multiple operational domains. The milestone monitoring capability eliminated weekly manual review cycles where project managers previously compiled status across sites from CTMS exports and EDC dashboards. Autonomous notification generation reduced the time required to alert stakeholders about deviations significantly. Investigator communication assistance decreased drafting time for routine queries by generating contextually appropriate responses that required only final review rather than composition from scratch.

Service level agreement adherence improved substantially as the percentage of operational commitments met within defined timeframes. The improvement was derived from two primary mechanisms: proactive identification of emerging issues enabling earlier intervention, and reduced cycle time for routine activities enabling faster response to requests. Milestone monitoring agents identified trials falling behind schedule earlier than traditional periodic reviews, enabling corrective actions before delays accumulated to SLA breach levels.

Qualitative feedback from operational personnel involved in the pilot indicated high satisfaction with agent capabilities while identifying areas for continued refinement. Regulatory specialists expressed confidence in the documentation monitoring capabilities but emphasized the importance of maintaining comprehensive audit trails of agent activities for inspection readiness, consistent with FDA expectations for electronic systems [7].

Agent Specialization	Regulatory Domain	Monitoring Approach
Protocol Compliance Agents	Trial conduct adherence to protocol requirements	Continuous monitoring of enrollment criteria, dosing regimens, visit schedules, and safety parameters
Document Compliance Agents	Trial Master File completeness and currency	Real-time tracking of required documents, expiration alerts, and version validation
Training Compliance Agents	Personnel qualification and certification	Verification of protocol training completion and maintenance of specialized procedure certifications

Table 4: Intelligent Compliance Agent Specializations and Monitoring Capabilities [7]

4.2 Intelligent Compliance Framework and Proactive Monitoring

The concept of intelligent compliance represents a paradigm shift in how organizations approach regulatory adherence within clinical research operations. Traditional compliance models operate reactively, employing periodic audits, sampling methodologies, and retrospective reviews to identify deviations and deficiencies after they have occurred. Intelligent compliance leverages autonomous agents to enable proactive, continuous monitoring of compliance requirements with real-time identification of potential violations and automated initiation of corrective workflows.



The intelligent compliance architecture within UAP implementations encompasses multiple agent specializations addressing different regulatory domains. Protocol compliance agents continuously monitor trial conduct against protocol-defined requirements including enrollment criteria, dosing regimens, visit schedules, and safety monitoring parameters. Document compliance agents monitor Trial Master File completeness against regulatory expectations and sponsor requirements. Training compliance agents verify that personnel receive required protocol training before performing trial-related activities and maintain current certifications for specialized procedures.

The integration of compliance monitoring with operational workflows transforms how organizations prevent and address regulatory issues. Rather than maintaining separate compliance functions that periodically review operational activities, intelligent compliance embeds regulatory awareness directly into execution processes [7]. When site personnel enter data that might constitute a protocol deviation, the compliance agent immediately flags the entry, provides relevant protocol context, and prompts the user to confirm intentionality or correct the entry.

The reasoning capabilities that enable intelligent compliance extend beyond simple rule-based checking to incorporate contextual interpretation of regulatory requirements. Protocol deviations provide illustrative examples where agents must distinguish between minor procedural variations with minimal impact and significant deviations affecting data integrity or patient safety [8]. Autonomous agents verify through retrieval-augmented generation to search relevant sections of a protocol, regulatory guidance documents, and organizational policies while synthesizing that knowledge into a method to classify the impact severity of the deviation.

4.3 Technical Challenges and Future Research Directions

While the deployment of autonomous agents to clinical research operations presents a range of technical issues, considerations and continuous improvement practices still need to be accounted for in the implementation. A primary concern is language model hallucination, which occurs when agents may produce responses that seem perceptively valid but contain factual errors or false information. In the instance of clinical research, hallucinations could potentially produce protocol requirements from the study, regulatory requirements for clinical research, or trial specific data that could contribute to significant compliance breaches or operational failures. The UAP framework addresses this risk through retrieval-augmented generation that grounds agent outputs in verified organizational knowledge rather than relying on model pre-training [8].

Reliability in integration challenges creates additional complexities due to dependencies on outside systems that may fail to meet expectations in performance, become unavailable altogether, or change their application programming interface (API) without notice or proper implementation timelines. The integrity of the integration architecture is addressed in multiple ways, including health monitoring that keeps a continuous check on whether connections to external integrations are functional; graceful degradation with automatic rollback to preserve limited functionality in cases in which other integrations have failed; and comprehensive and sophisticated error-handling that uses automation to recover from transient errors.

Knowledge currency challenges emerge from the need to ensure that agents access current, validated information rather than obsolete or draft materials. Clinical trials undergo frequent protocol amendments, regulatory guidance evolves, and organizational procedures update regularly. The knowledge management approach within UAP implementations establishes governance processes for maintaining knowledge repositories including version control, approval workflows, and automated retirement of superseded materials.

The Unified Agentic Platform framework has laid down the foundation for clinical research automation, and there are numerous extensions and enhancements that could be added to the framework. A particularly intriguing avenue for future extension considers predictive analytics, whereby agents leverage historical trial data alongside machine learning models to predict operational outcomes and recommend interventions proactively. Collaboration among agents as multi-agent capabilities might fully leverage particular strengths through specialized agents working in harmony to execute complex operational scenarios.

5. Conclusion

The Unified Agentic Platform framework demonstrates that autonomous agents can meaningfully enhance clinical research operations while maintaining the regulatory compliance and data integrity standards essential to this highly regulated domain. The integration of Salesforce Agentforce with Health Cloud, Data Cloud, and MuleSoft creates a



comprehensive architecture enabling intelligent orchestration across the fragmented technology ecosystems typical of Contract Research Organization environments. Retrieval-augmented generation grounds agent reasoning in organizational knowledge, addressing concerns about language model hallucination and ensuring outputs align with protocol requirements, regulatory obligations, and standard operating procedures. The controlled pilot implementation provides empirical evidence of operational improvements including cost reduction, enhanced service level agreement adherence, and accelerated data reconciliation, validating the practical viability of autonomous agents in production clinical research contexts. The standardized agent testing framework addresses critical validation challenges inherent in applying artificial intelligence systems within regulated environments by adapting conventional software quality assurance methodologies to accommodate the probabilistic nature of language model-based agents. The framework enables rigorous validation that satisfies regulatory expectations while acknowledging the unique characteristics of autonomous systems, establishing patterns applicable beyond the specific implementation to autonomous agents in any regulated healthcare application. The concept of intelligent compliance represents a paradigm shift from audit-based and reactive approaches and for intensive and proactive continuous monitoring, as embedded activities directly into operational workflows, features that enable the organization to prevent compliance issues rather than discovering and remedying post-hoc. By utilizing and implementing intelligent compliance, organizations might better position themselves against regulatory expectations and/or reduce the operational burden and business risk of regulatory compliance failures, which further illustrates compliance automation for ensuring legal compliance can enhance regulatory compliance during quality execution rather than undermine it. Organizations considering implementing an autonomous Agency within the clinical trial research operational function should do so with a planned and structured implementation, including an understanding of the realistic benefits and challenges associated with deployment. This understanding recognizes that success in operationalizing autonomous agents Agency intervention will require change management, validation, operationalizing required technical support, refining user benefits and challenges through experience, and securing executive support for organizational change.

References

1. U.S. Food and Drug, "E6(R2) Good Clinical Practice: Integrated Addendum to ICH E6(R1)," Dec. 2018. [Online]. Available: <https://www.fda.gov/regulatory-information/search-fda-guidance-documents/e6r2-good-clinical-practice-integrated-addendum-ich-e6r1>
2. U.S. Food and Drug, "Part 11, Electronic Records; Electronic Signatures - Scope and Application," 2003. [Online]. Available: <https://www.fda.gov/regulatory-information/search-fda-guidance-documents/part-11-electronic-records-electronic-signatures-scope-and-application>
3. Anand Dosapati, "Ultimate Salesforce Agentforce Guide," 2025. [Online]. Available: <https://www.apexhours.com/salesforce-agentforce/>
4. Patrick Lewis, et al., "Retrieval-Augmented Generation for Knowledge-Intensive NLP Tasks," arXiv, 2020. [Online]. Available: <https://arxiv.org/abs/2005.11401>
5. URSEDRILL, "MuleSoft Architecture," 2024. [Online]. Available: <https://coursedrill.com/mulesoft-architecture/>
6. Salesforce, "Salesforce Data Cloud Setup Guide." [Online]. Available: <https://docs.mulesoft.com/retail/latest/sfdc-data-cloud-setup-guide>
7. Salesforce, "Health Cloud Implementation Guide," 2025. [Online]. Available: https://resources.docs.salesforce.com/latest/latest/en-us/sfdc/pdf/health_cloud_dev_guide.pdf
8. Sébastien Bubeck, et al., "Sparks of Artificial General Intelligence: Early experiments with GPT-4," arXiv, 2023. [Online]. Available: <https://arxiv.org/abs/2303.12712>



DOIs:10.2015/IJIRMF/ICICSF-2025-P40

--:--

Research Paper / Article / Review

International Conference On "Innovative Convergence for Sustainable Future"

Date : 12 - 13 December, 2025

(ICICSF-2025)



Evolving Jurisprudence on Child Sexual Abuse in India through the lens of POCSO Act: A need for sustainable society in future

¹ Suman Kumar Sinha , ² Prof. Sristi Roy

¹Designation- Student , Jharkhand Rai University , Jharkhand , India.

²Designation – Faculty Associate , Jharkhand Rai University, Jharkhand , India.

Email - ss9852283856@gmail.com ,

Abstract:- Child sexual abuse (CSA) in India continues to present a very deep social and law related challenges, threatening the very foundation of child dignity, bodily independence, and societal morality. The protection of Child from sexual offences Act, 2012 (POCSO) represents a legislative milestone, introducing a complete and thorough, gender-neutral, and a child sensitive legal framework aimed to ensuring justice through special courts, victim friendly procedures, and strict punitive measures. Even though its progressive framework, the Act's reveals persistent structural and procedural deficiencies including infrastructural shortcomings, investigative lapses, evidentiary fragility, low rates of conviction, and enduring social stigma that causes to continue underreporting.

This research begins with a critical examination of the evolving jurisprudence surroundings CSA within India's legal system, carefully analyzing judicial interpretations, landmark precedents, and the transformative impact of recent law amendments. It situates POCSO within the wider matrix of constitutional rights guarantees, restorative justice principles, and India's international obligations under the Convention on the Right of Child (CRC). Further, the study connects its analytical lens with the United Nations Sustainable Development Goals (SDGs), specifically SDGs 5(Gender Equality), SDGs 10 (Reduced Inequalities), and SDGs 16 (Peace, Justice, and Strong Institutions) to highlight the command of a sustainability, Rights based, and child centric justice ecosystem.

By adopting a multidisciplinary approach and multi-stakeholder perspective, the study argues for the evolution of a dynamic legal and institutional framework that goes beyond punishment-based ways of thinking and puts in order prioritizes prevention, protection, participation, and rehabilitation. In doing so, it advances the discourse on integrating child protection with sustainable governance, thereby fostering a just and human society that safeguards every child's right to live free from violence and fear.

Keywords:- Child Sexual Abuse, POCSO Act, Bhartiya Nagarik Suraksha Sanhita (Criminal Procedure), Sustainable Development Goals, Judicial Interpretation, Institutional Reform, Child Rights.

1. INTRODUCTION:-

Child sexual abuse remains one of the most serious and under-reported social pathologies in India, with psychological, physical and socio-economic impacts on families, communities and generations. This incident is not only a law and order concern but a multidimensional human rights crisis that destroys the moral fabric of the society and challenges the constitutional promise of dignity and equality under Articles 14, 15(3) and 21 of the Indian Constitution.

Recognizing the urgent need for a specialized legal response, the Indian Parliament passed the Protection of Children from Sexual Offences Act, 2012, a landmark law that attempted to mainstream child protection within the criminal justice system. The Act defined sexual offenses as gender-neutral, made investigations and trials child-friendly, and provided for special courts for speedy trial of cases. For the first time in Indian history, POCSO codified a comprehensive framework of prevention, protection and punishment, leading to a decisive shift towards rights-based jurisprudence in the field of child welfare.



However, more than a decade after its enactment, POCSO's progress in realizing its intentions remains poor. Systemic barriers to the transformative potential of this law include procedural delays, inadequate institutional capacity, inconsistent judicial interpretation, and pervasive socio-cultural stigma that continue to suppress reporting and participation in legal processes. This makes implementation more complex at the interface between POCSO and the Code of Criminal Procedure, 1973, as procedural rigidity often undermines the victim-centric objectives of the Act. Therefore, the effectiveness of child protection is not simply a matter of legislative design, but is the result of dynamic interactions between substantive law, procedural mechanisms, administrative capacity and societal attitudes towards children's rights.

Placing this question within the broader framework of the UN Sustainable Development Goals, this study underlines the fact that the elimination of CSA is essential to achieving SDG 16 (peace, justice and strong institutions), SDG 5 (gender equality), and SDG 10 (reduction of inequalities). Without the protection of children – the guarantee that they are safe from exploitation and able to realize their full potential in an environment conducive to dignity and justice – sustainable development cannot be achieved. Therefore, this research emphasizes that effective implementation of POCSO is not only a legal imperative but also a developmental necessity, which is central to building a just, inclusive and sustainable society.

2.LITERATURE REVIEW:-

The academic discussion around the Protection of Children from Sexual Offences Act, 2012 (POCSO) has evolved across legislative, judicial, empirical and developmental dimensions, revealing both the transformative potential of the Act and its persistent implementation gaps.

Legislative Innovation:-

Early comments, such as Rao (2014) described POCSO as a legislative milestone that redefined India's child protection framework by incorporating gender-neutral definitions, broader classification of sexual offenses and child-sensitive procedural norms. Rao emphasizes that by codifying explicit statutory protections, POCSO sought to address long-standing legislative shortcomings in addressing child sexual exploitation under the Indian Penal Code. In contrast, Kapur (2016) warns that despite its progressive framework, the adversarial character of criminal proceedings continues to expose child victims to secondary victimization through hostile cross-examination, inadequate victim support, and inadequately trained judicial officers. Together, these approaches highlight the gap between normative legislative intent and actual procedural realities.

Judicial Interpretations:-

Judicial scholarship has focused on how courts have shaped and expanded the meaning of child protection under POCSO. Mishra (2020) identifies a growing trend of judicial creativity in which courts have reconciled domestic interpretations with international child-rights obligations under the United Nations Convention on the Rights of the Child (CRC). Notably, judicial decisions have broadened the scope of "penetrative sexual assault" and "aggravated assault" to reflect a more victim-centric approach, thereby strengthening the evidentiary presumption under Section 29 of POCSO.

Empirical Findings:-

Empirical investigation highlights structural deficiencies in the justice delivery process. A comprehensive study by the National Law School of India University (2018) found that more than 70% of POCSO trials exceeded the statutory one-year expiry period, indicating systemic inefficiencies. Supplementary data from the National Crime Records Bureau (NCRB) corroborates these findings, indicating persistently low conviction rates and a growing case backlog. Verma (2022) interprets these trends as symptomatic of deeper procedural and structural weaknesses – specifically, the limited number of functional special courts, inconsistent forensic protocols, and inadequate coordination between investigating and prosecuting agencies.

Digital Age Challenges:-

Contemporary scholarship also recognizes the expanding scope of CSA in cyberspace. Chakraborty (2021) outlines the threats posed by online grooming, digital pornography and international exploitation networks operating through encrypted platforms. They called for multilateral cooperation, improved digital monitoring mechanisms and legislative adaptation to combat cyber-enabled forms of sexual exploitation beyond jurisdictional boundaries.



Sustainable Development and Child Justice:-

Recent interdisciplinary research situates child protection within the normative framework of the UN Sustainable Development Goals (SDGs). Scholars are increasingly emphasizing that effective enforcement of POCSO is helpful in achieving SDG 16 (peace, justice, and strong institutions), SDG 5 (gender equality), and SDG 10 (reduction of inequalities). The integration of SDG metrics into child justice policy underlines that protecting children from sexual violence is not only a legal and moral imperative, but also a fundamental component of sustainable governance and equitable development.

Collectively, the contributions of these scholars show that while the POCSO Act has revolutionized India's legal response to child sexual exploitation, the achievement of its objectives depends on procedural reforms, institutional capacity building, and alignment with broader developmental and human rights frameworks.

3.RESEARCH METHOD :-

This research employs a mixed-method approach involving:

➤ Research Design

This research adopts a mixed-method approach, integrating theoretical and empirical components to provide a comprehensive understanding of the evolving jurisprudence around child sexual exploitation under the Protection of Children from Sexual Offences Act, 2012 (POCSO). The theoretical aspect examines the statutory provisions, legislative intent and judicial interpretation in detail, while the empirical component is based on secondary data and case-based trends to contextualize the implementation of the law.

The rationale for employing mixed methodology lies in the inherently interdisciplinary nature of child protection. A purely theoretical analysis captures the legal (legal) framework, but an empirical perspective highlights the actual (practical) realities of law enforcement, judicial behavior, and institutional response. The synthesis of these methods thus allows for both normative assessment and evidence-based criticism.

➤ Doctrinal Component

The theoretical analysis focuses on explaining the substantive and procedural interplay between POCSO and the Code of Criminal Procedure, 1973 (CrPC) as well as the constitutional provisions under Articles 14, 15(3), 21 and 39(f).

The study critically examines:

- Structure and scope of POCSO offences, definitions and procedural safeguards.
- Judicial pronouncements of the Supreme Court and various High Courts that have shaped the interpretation and application of the Act.
- Comparative insights from international child rights frameworks, particularly the UN Convention on the Rights of the Child (CRC) and the Optional Protocol on the Sale of Children, Child Prostitution and Child Pornography.

This component seeks to trace the jurisprudential evolution of CSA adjudication in India and evaluate how courts have balanced the rights of victims with procedural fairness towards the accused.

➤ Empirical Component

The empirical aspect of this research relies on secondary data analysis using the following:

- Official data from National Crime Records Bureau (NCRB) (2018-2023) on reporting, conviction rate and pendency of POCSO cases.
- Empirical studies such as the National Law School of India University (2018) assessment of POCSO implementation and other NGO-based reports (e.g., UNICEF, Commission on Child Rights).
- Qualitative insights from published interviews, judicial commentaries and media reports reflecting institutional challenges and victim experiences.



This data is interpreted not through quantitative regression but through qualitative thematic analysis, identifying recurring patterns such as procedural delays, infrastructural inadequacies and psychosocial stigma that hinder access to justice.

➤ **Analytical Framework**

The study employs an interdisciplinary analytical framework, combining:

- Legal analysis to assess statutory coherence and judicial reasoning;
- Sociological analysis to explore the socio-cultural determinants of under-reporting and victim silencing; and
- Developmental analysis to link POCSO enforcement with broader governance goals, particularly under the Sustainable Development Goals (SDGs 5, 10, and 16).

This tripartite framework situates child protection law not only within the bounds of criminal jurisprudence but as a component of sustainable governance and human rights realization.

➤ **Scope and Limitations**

The scope of this research is limited to the Indian legal context. It mainly depends on secondary data available in the public domain and judicial decisions. No direct interviews or surveys involving victims or officials were conducted, to ensure full compliance with ethical standards regarding confidentiality and non-traumatization of survivors.

Although this approach provides sufficient analytical depth, the absence of fieldwork limits the direct approach. However, triangulation of theoretical, empirical, and developmental data mitigates this limitation and strengthens the validity of the findings.

4. ANALYSIS :-

• **Judicial Interpretation and Jurisprudential Evolution**

Judicial interpretations under the Protection of Children from Sexual Offences Act, 2012 (POCSO) have been important in defining the contours of India's contemporary child protection jurisprudence. The Supreme Court and various High Courts have consistently underlined the primacy of a child's testimony, holding that the traditional insistence on corroboration in sexual offense cases often undermines justice. In *State of Punjab v. Gurmeet Singh* (1996), the Supreme Court held that the testimony of a victim of sexual assault, if found credible, does not necessarily require corroboration. Based on this principle, *State of Himachal Pradesh v. Sanjay Kumar* (2017) confirmed that a child witness, if competent and truthful, can form the sole basis for conviction under POCSO.

Furthermore, the judiciary has expanded the interpretive scope of key provisions to ensure substantive justice. In *Alakh Alok Srivastava v. Union of India* (2018), the Supreme Court directed the setting up of special POCSO courts in districts, emphasizing the constitutional mandate of speedy trial under Article 21. Similarly, high courts have invoked Section 33(8) of POCSO and Section 309 of the Code of Criminal Procedure, 1973 (CrPC) to demand time-bound adjudication and child-sensitive courts. These judicial pronouncements collectively mark a gradual but decisive shift from procedural formalism toward restorative, victim-centered justice.

• **Procedural Harmonization and Institutional Performance**

The procedural interplay between POCSO and the CrPC remains both complementary and complex. While POCSO provides a specialized framework, it heavily relies on CrPC provisions for investigation, evidence collection, and trial management. For instance, Section 164 of CrPC, concerning the recording of a victim's statement before a magistrate, is integral to ensuring accuracy and admissibility. Likewise, Section 273 mandates in-camera proceedings to protect the privacy and dignity of the child. However, empirical data reveals that these procedural safeguards are inconsistently implemented across jurisdictions.

According to National Crime Records Bureau (NCRB) reports (2018–2022), the number of registered POCSO cases has increased significantly—reflecting greater awareness and enforcement—but conviction rates remain stagnant between 30% and 40%. The National Law School of India University (2018) study further indicates that over 70% of POCSO trials exceed the statutory one-year limit prescribed under Section 35 of the Act. The lack of trained investigators, inadequate forensic infrastructure, and the non-availability of dedicated Special Courts in many districts contribute to these delays.



These procedural deficiencies undermine the intended efficiency of the POCSO framework and highlight the need for structural reforms—particularly in case management, witness protection, and forensic evidence collection.

• Evidentiary Challenges and Burden of Proof

The evidentiary regime under POCSO, particularly the presumption under Section 29, has generated important jurisprudential debate. Courts have clarified that while the provision shifts the evidentiary burden to the accused once foundational facts are established, it does not dispense with the prosecution's duty to prove guilt beyond reasonable doubt. In *Rohit Chauhan v. State of Himachal Pradesh* (2020), the Himachal Pradesh High Court reiterated that the presumption of guilt must be read harmoniously with the constitutional guarantee of fair trial.

Despite this progressive stance, practical challenges persist in forensic evidence collection and preservation. Delays in medical examination, absence of gender-sensitive medical officers, and lack of standardized forensic protocols often weaken prosecutorial success. Consequently, evidentiary inadequacies, rather than legislative flaws, have emerged as primary contributors to acquittals in many POCSO cases.

• Victim Protection, Rehabilitation, and Secondary Victimization

The principle of child-friendly justice—the cornerstone of POCSO—is still evolving in practice. Although Section 33(7) prohibits aggressive questioning of child witnesses, reports indicate instances of secondary victimization during cross-examination and inaccessibility of psychological counseling. Judicial interventions have begun addressing these gaps. Courts increasingly direct state governments to provide compensation under Section 357A CrPC and mandate trauma counseling for victims, recognizing that justice extends beyond conviction to include rehabilitation and recovery.

Programs like the One Stop Centre Scheme and Nirbhaya Fund have improved support infrastructure, yet coverage and awareness remain uneven. The absence of a standardized victim compensation mechanism across states continues to create disparities in child rehabilitation outcomes.

• Emerging Frontiers: Cyber Exploitation and Transnational Crimes

The digital age has introduced new dimensions of child sexual exploitation that existing legal instruments only partially address. As Chakraborty (2021) observes, the proliferation of online grooming, child pornography, and dark-web trafficking necessitates robust cybercrime frameworks. While Section 67B of the Information Technology Act, 2000 criminalizes online child sexual material, its coordination with POCSO enforcement mechanisms remains inadequate. The cross-border nature of these crimes further requires international cooperation under conventions such as the Budapest Convention on Cybercrime and the UNCRC Optional Protocols.

India's evolving jurisprudence must therefore expand to encompass digital offences and establish specialized cyber units within law enforcement agencies to prevent and investigate online child exploitation effectively.

• Jurisprudential Trends and Sustainable Justice

The cumulative analysis reveals that Indian courts are gradually embracing a sustainable justice paradigm, where child protection is viewed as integral to societal well-being and governance integrity. This jurisprudential evolution aligns directly with Sustainable Development Goal (SDG) 16, which emphasizes “peace, justice, and strong institutions.” By enhancing procedural fairness, reducing pendency, and ensuring rehabilitative support, the enforcement of POCSO contributes not only to immediate justice but also to long-term social sustainability.

Yet, achieving these outcomes requires sustained institutional commitment, inter-agency coordination, and periodic review of procedural laws. Effective implementation of POCSO, therefore, stands as both a legal and developmental imperative—bridging the divide between human rights obligations and sustainable governance.

5.DISCUSSION :-

The analysis of jurisprudence, procedural mechanisms, and empirical data under the Protection of Children from Sexual Offences Act, 2012 (POCSO) reveals a deeply interwoven relationship between law, society, and governance. The Act, while transformative in its intent, continues to operate within the structural limitations of India's criminal justice system, highlighting the enduring tension between legal idealism and institutional realism.



At its core, the POCSO Act embodies a constitutional promise — the protection of children’s dignity, autonomy, and equality. These values derive from the expansive interpretation of Article 21 (right to life and personal liberty), Article 14 (equality before law), and Article 15(3) (special protection for children and women). Judicial recognition of child rights as an inseparable component of the right to life reflects a decisive shift in Indian constitutional jurisprudence towards human security and restorative justice. In this light, child protection is not a peripheral welfare concern but a fundamental constitutional commitment essential to the moral legitimacy of the State.

However, the effectiveness of this framework is conditioned by the procedural architecture that governs it. The interplay between POCSO and the Code of Criminal Procedure, 1973 (CrPC) demonstrates that the enforcement of substantive rights is dependent on procedural justice. Procedural rigidity, delays in investigation, and inadequate infrastructure dilute the rehabilitative essence of the Act. Hence, ensuring procedural harmony is vital for actualizing the law’s spirit — a task that demands consistent judicial monitoring, legislative responsiveness, and administrative accountability.

Furthermore, the concept of child-friendly justice demands a paradigm shift from retributive to rehabilitative approaches. This shift echoes international human rights instruments such as the UN Convention on the Rights of the Child (CRC), which emphasizes the best interests of the child as a guiding legal principle. Indian courts, in adopting progressive interpretations under POCSO, are moving toward this restorative vision, yet implementation remains fragmented and resource-constrained.

From a developmental perspective, child protection is not an isolated legal concern but a systemic precondition for sustainable development. Effective enforcement of POCSO directly contributes to the realization of SDG 16 (Peace, Justice, and Strong Institutions) by promoting accountability, reducing violence, and ensuring access to justice for vulnerable populations. Likewise, it reinforces SDG 5 (Gender Equality) by addressing gendered dimensions of abuse and SDG 10 (Reduced Inequalities) by protecting children from marginalized communities disproportionately affected by exploitation and neglect.

This convergence between human rights and development underscores the emergence of what scholars term “sustainable justice” — a model of justice that not only redresses harm but also strengthens institutions, fosters trust, and promotes social harmony. Within this paradigm, protecting children from sexual abuse is both a moral and developmental necessity: moral, because it upholds the inherent dignity of every child; and developmental, because a society that protects its children invests in its own long-term stability and prosperity.

The future of child protection jurisprudence in India, therefore, lies in institutional integration. Legal reform must be accompanied by investments in capacity-building, technology-enabled investigation, and psychosocial support systems for survivors. Only when the law operates as part of a holistic ecosystem encompassing legal, social, and developmental domains can the constitutional vision of a safe and just childhood be realized in both principle and practice.

From a developmental perspective, child protection is not an isolated legal concern but a systemic precondition for sustainable development. Effective enforcement of POCSO directly contributes to the realization of SDG 16 (Peace, Justice, and Strong Institutions) by promoting accountability, reducing violence, and ensuring access to justice for vulnerable populations. Likewise, it reinforces SDG 5 (Gender Equality) by addressing gendered dimensions of abuse and SDG 10 (Reduced Inequalities) by protecting children from marginalized communities disproportionately affected by exploitation and neglect.

This convergence between human rights and development underscores the emergence of what scholars term “sustainable justice” — a model of justice that not only redresses harm but also strengthens institutions, fosters trust, and promotes social harmony. Within this paradigm, protecting children from sexual abuse is both a moral and developmental necessity: moral, because it upholds the inherent dignity of every child; and developmental, because a society that protects its children invests in its own long-term stability and prosperity.

The future of child protection jurisprudence in India, therefore, lies in institutional integration. Legal reform must be accompanied by investments in capacity-building, technology-enabled investigation, and psychosocial support systems for survivors. Only when the law operates as part of a holistic ecosystem — encompassing legal, social, and developmental domains — can the constitutional vision of a safe and just childhood be realized in both principle and practice.



6.CONNECTION WITH SUSTAINABLE DEVELOPMENT:-

The protection of children from sexual offences transcends the boundaries of criminal jurisprudence it is a cornerstone of sustainable human development. The Protection of Children from Sexual Offences Act, 2012 (POCSO) not only fulfills a statutory mandate but also operationalizes India's commitment to the United Nations Sustainable Development Goals (SDGs), particularly Goal 16 (Peace, Justice, and Strong Institutions), Goal 5 (Gender Equality), and Goal 10 (Reduced Inequalities).

From a governance standpoint, the POCSO framework embodies the principle of sustainable justice a concept that integrates legal protection, institutional accountability, and social inclusion to create enduring peace and equity. SDG 16 calls upon states to "promote peaceful and inclusive societies, provide access to justice for all, and build effective, accountable institutions." In this light, the effective enforcement of POCSO directly contributes to sustainable governance by institutionalizing victim-centered justice, reducing systemic violence, and enhancing transparency within law enforcement mechanisms.

Equally, the Act supports SDG 5 (Gender Equality) by addressing both male and female child victims through its gender-neutral definitions, ensuring that justice mechanisms are inclusive and equitable. By criminalizing a broad spectrum of offences from penetrative assault to online exploitation POCSO reflects a rights-based approach that dismantles patriarchal biases and structural inequalities.

The linkage to SDG 10 (Reduced Inequalities) further underscores that child protection is not only a legal obligation but also an instrument of social equity. Vulnerable children particularly those from economically or socially marginalized backgrounds face a disproportionate risk of sexual exploitation and systemic neglect. The implementation of POCSO thus contributes to reducing intergenerational inequality by ensuring that all children, regardless of class, caste, or gender, enjoy equal access to protection and justice.

At the philosophical level, integrating POCSO with the SDGs redefines child protection as a developmental responsibility rather than a purely punitive exercise. The alignment of national legislation with international development agendas transforms the criminal justice system into a driver of long-term social resilience. It also reaffirms the constitutional vision articulated in the Directive Principles of State Policy (Articles 39(e) (f)), which obligate the State to protect children against exploitation and moral abandonment.

Ultimately, the protection of children under POCSO is not just an end in itself; it is a means of nation-building. Ensuring that every child grows up free from violence strengthens the rule of law, advances human rights, and reinforces the sustainability of democratic institutions. In doing so, India's child protection jurisprudence emerges as a vital pillar of its pursuit of the Sustainable Development Goals and the broader global agenda for justice, equality, and human dignity.

7.RECOMMENDATIONS :-

1. Institutional Strengthening:

Establish at least one functional Special POCSO Court in every district, equipped with trained judicial officers, prosecutors, and child counselors.

2. Procedural Reforms:

Amend the Criminal Procedure Code to ensure that POCSO trials are completed within one year, and that evidence recording and witness protection mechanisms are standardized nationwide.

3. Capacity-Building and Training:

Introduce mandatory sensitization programs for police officers, medical practitioners, and judicial personnel on trauma-informed child interviewing techniques and evidentiary handling.

4. Victim Rehabilitation and Support Services:

Develop a uniform National Victim Assistance and Compensation Framework to ensure comprehensive post-trial rehabilitation, including psychological counseling, education, and reintegration programs.

5. Technological Integration:

Leverage digital tools for tracking case progress, securing evidence, and ensuring transparency through e-Courts and child-friendly online deposition mechanisms.

6. Community and Preventive Engagement:

Institutionalize awareness campaigns in schools and communities to combat stigma, encourage early reporting, and foster a culture of protection and accountability.



7. Alignment with SDGs:

Integrate POCSO monitoring indicators with India's SDG reporting mechanisms to evaluate how child protection efforts contribute to national progress on justice, equality, and inclusion.

8.CONCLUSION :-

The Protection of Children from Sexual Offences Act, 2012 (POCSO) stands as one of the most progressive and comprehensive legislative frameworks in India's criminal justice system, embodying the constitutional promise to protect the dignity, liberty, and security of children. It represents a paradigmatic shift from moral paternalism to a rights-based jurisprudence, recognizing the child not merely as a passive victim but as an active rights-holder entitled to protection, participation, and justice.

The evolving judicial interpretation of POCSO reveals an encouraging trajectory toward victim-centric and restorative justice. Courts have increasingly harmonized statutory provisions with constitutional guarantees and international obligations under the UN Convention on the Rights of the Child (CRC). Yet, the realization of POCSO's transformative potential remains constrained by systemic challenges — procedural delays, inadequate infrastructure, low conviction rates, and socio-cultural barriers that inhibit reporting and rehabilitation.

The critical analysis undertaken in this study demonstrates that the efficacy of POCSO depends on the functional synergy between substantive law and procedural justice, as embodied in the Code of Criminal Procedure, 1973. Without procedural reforms particularly in evidence collection, trial management, and witness protection the statute risks falling short of its objectives. Moreover, institutional accountability and inter-agency coordination remain pivotal to bridging the gap between legislative idealism and ground realities.

Viewed through the lens of the Sustainable Development Goals (SDGs), the POCSO framework transcends its immediate penal purpose. It functions as a vehicle for social justice and sustainable governance by advancing SDG 16 (Peace, Justice, and Strong Institutions), SDG 5 (Gender Equality), and SDG 10 (Reduced Inequalities). The protection of children from sexual offences thus emerges as both a legal necessity and a developmental imperative, reaffirming that no society can claim progress while its most vulnerable remain unprotected.

In essence, the jurisprudence surrounding child sexual abuse in India is evolving toward a model of sustainable justice one that integrates legal protection, institutional capacity, and social empathy. To sustain this trajectory, child protection must be institutionalized not as a reactive response to crime, but as a proactive commitment to equity, inclusion, and human development.

9.FUTURE SCOPE :-

Future research may extend this inquiry by adopting a field-based empirical design, involving interviews with judges, prosecutors, victims, and child protection officers to assess implementation at the ground level. Comparative studies across jurisdictions could illuminate best practices for harmonizing substantive and procedural law in child protection.

Moreover, as digital spaces increasingly become vectors of exploitation, future research should explore the intersection between POCSO and cyberlaw, particularly under the Information Technology Act, 2000 and international cybercrime frameworks.

Finally, longitudinal policy analysis could evaluate the long-term developmental impact of effective child protection mechanisms on India's progress toward the Sustainable Development Goals, particularly SDG 16.2 "End abuse, exploitation, trafficking, and all forms of violence against and torture of children."

REFERENCES :-

1. Rao, P. (2014). *Legal Reforms on Child Sexual Offences in India: A Post-POCSO Analysis*. *Journal of Indian Law & Society*, 5(1), 34–50.
2. Kapur, R. (2016). *The POCSO Act and the Quest for Child-Friendly Justice*. *NUJS Law Review*, 9(2), 210–234.
3. Mishra, S. (2020). *Judicial Expansion of the POCSO Framework: A Critical Study*. *Delhi Law Review*, 42(1), 78–94.



4. Chakraborty, A. (2021). *Cyber Dimensions of Child Sexual Exploitation in India*. *Indian Journal of Criminology*, 49(3), 45–60.
5. Verma, N. (2022). *Procedural Reforms in POCSO Trials: Synchronizing CrPC with Child Rights*. *Indian Bar Review*, 49(1), 102–120.
6. National Law School of India University. (2018). *Implementation of the POCSO Act, 2012 by Special Courts: Challenges and Issues*. Centre for Child and the Law (CCL), Bengaluru. Retrieved from <https://ccl.nls.ac.in/wp-content/uploads/2021/10/8.-Implementation-of-the-POCSO-Act-2012-by-speical-courts-challenges-and-issues.pdf>
7. Vidhilegalpolicy Foundation. (2023). *A Decade of POCSO: Developments, Challenges, and Insights from Judicial Data*. Vidhi Centre for Legal Policy. Retrieved from <https://vidhilegalpolicy.in/research/a-decade-of-pocso-developments-challenges-and-insights-from-judicial-data/>
8. Enfold India. (2024). *Report on the Study of POCSO Implementation*. Enfold Proactive Health Trust. Retrieved from <https://enfoldindia.org/wp-content/uploads/2024/11/Report-on-the-Study-of-POSCO-Implementation.pdf>
9. Indian Journal of Criminology and Criminal Law. (2023). *POCSO Act: A Critical Study of Jurists Global Research*. *Criminal Law Journal*, 5(1), 243–260. Retrieved from <https://www.criminallawjournal.org/article/126/5-1-22-243.pdf>
10. Jurists Global Research. (2023). *POCSO Act: A Critical Study*. Retrieved from <https://juristsglobal.com/research/f/pocso-act-a-critical-study-of-jurists-global-research>
11. International Journal of All Research in Science and Computer Technology (IJARSCT). (2024). *POCSO Act: Legal Framework and Implementation Challenges*. *IJARSCT Journal*, 9(6), 112–120. Retrieved from <https://www.ijarsct.co.in/Paper27088.pdf>
12. International Journal of Creative Research Thoughts (IJCRT). (2025). *POCSO Act: A Critical Analysis of Legal Implementation and Social Impact*. *IJCRT Journal*, 13(6), 399–412. Retrieved from <https://ijcrt.org/papers/IJCRT2506399.pdf>
13. National Center for Biotechnology Information (NCBI). (2023). *Child Sexual Abuse in India: Medical and Legal Challenges*. *Indian Journal of Psychiatry*, 65(2), 230–240. Retrieved from <https://pmc.ncbi.nlm.nih.gov/articles/PMC11180359/>
14. Law Journals India. (2023). *The Efficacy of the POCSO Act: A Critical Appraisal of Implementation Mechanisms*. *Indian Law Journal*, 9(6), 178–193. Retrieved from <https://www.lawjournals.org/assets/archives/2023/vol9issue6/9221-1701235823589.pdf>
15. Scribd. (2021). *Research Proposal on the POCSO Act*. Retrieved from <https://www.scribd.com/document/514155563/Research-Proposal-on-Pocso-Act>
16. National Crime Records Bureau. (2022). *Crime in India 2021: Statistics*. Government of India, Ministry of Home Affairs.
17. *State of Himachal Pradesh v. Sanjay Kumar*, (2017) 2 SCC 51.
18. *State of Punjab v. Gurmit Singh*, (1996) 2 SCC 384.
19. *Alakh Alok Srivastava v. Union of India*, (2018) 17 SCC 291.



DOIs:10.2015/IJIRMF/ICICSF-2025-P41

--:--

Research Paper / Article / Review

International Conference On “Innovative Convergence for Sustainable Future”

Date : 12 - 13 December, 2025

(ICICSF-2025)



Bridging Health and Environmental Justice Through Legal Responsibility: A Pathway To Sustainable Development

Sunny Kumar Raj, Vanshika Tainwala

Student, Jharkhad Rai University, Ranchi, Jharkhand, India

Assistant Professor, Jharkhand Rai University, Ranchi, Jharkhand, India

Email- snyrajwad01iciw@gmail.com

Abstract: Bridging health and environmental justice through legal responsibility represents a crucial pathway to achieving sustainable development within the constitutional framework of India. The interdependence of human health and environmental quality underscore that the right to life, as guaranteed under **Article 21** of the constitution, encompasses the right to a clean and healthy environment. Judicial interpretations in landmark cases such as **M.C Mehta union of india (1987)**, **Subhash Kumar state of Bihar (1991)**, and **Vellore Citizens Welfare Forum v. Union of india (1996)** have expanded the scope of **Article 21**, recognizing environmental protection as integral to the protection of public health and human dignity.

Constitutional provision like **Articles 47, 48A and 51(g)** collectively impose duties upon the state and citizens to safeguard the environment and promote public health, thus establishing a dual responsibility framework. Complementing this, statutory mechanisms such as environment (protection) Act, 1986, water (prevention and control of pollution) Act, 1974, and Air (prevention and control of pollution) Act, 1981 translate these constitutional aspirations into enforceable obligations. Judicial doctrines including the **Polluter Pays Principle**, **Precautionary Principle** and **Public trust Doctrine** have further strengthened environmental governance by embedding accountability and legal responsibility within the framework of sustainable development.

The research further contributes unpublished findings that link environmental degradation to social health inequities, revealing that current frameworks inadequately integrate community participation and accountability. It proposes inventive practical applications, including the creation of Local Environment Health Justice Committees (LEHJCs), Eco-Health Courts, and a National Green Ledger for monitoring environmental accountability. These innovations align with the constitutional mandate for Sustainable development and human Welfare. Ultimately, the paper concludes that bridging health and environmental justice through enforceable legal responsibility is not only a constitutional duty but a prerequisite for achieving long-term, equitable, and inclusive sustainable development.

Keywords: Environmental Justice, Public Health, Legal Responsibility, Sustainability Development, Constitutional Law.

1. INTRODUCTION

The dual crisis of environmental degradation and public health deterioration represents a fundamental challenge to the vision of sustainable development. The modern industrial economy, while advancing economic growth, has contributed to severe environmental and health consequences from air and water pollution to climate-induced diseases and ecological displacement. These challenges are no longer isolated environmental concerns; they are matters of human rights and justice.

In India, the constitution provides a robust foundation for linking health and environmental protection. Article 21, guaranteeing the “right to life and personal liberty,” has been judicially expanded to include the right to a pollution-



free environment and a life with dignity. Article 47 directs the state to improve public health, while Articles 48 A and 51(g) establish environmental protection as a shared constitutional obligation of the state and citizens.

However, despite progressive jurisprudence, the gap between legal enforcement and public well-being persists. Environmental policies often fail to account for health disparities and community-level participation. The pursuit of economic growth frequently undermines ecological integrity and health equity. Thus, bridging health and environmental justice through legal responsibility is essential ensuring that development policies integrate the protection of both ecological system and human health.

This paper aims to explore how constitutional law and community-based mechanisms can work together to operationalize this bridge. It identifies weakness in current legal enforcement, presents original findings on systemic gaps, and proposes innovative, practical framework to align law, governance, and local action towards a sustainable future.

2. Literature Review

The literature on environmental justice and sustainable development emphasizes intergenerational equity, advocating development that meets present needs without compromising future generations. Earlier sustainability discourse largely focused on environmental protection and economic growth; however, contemporary scholarship stresses the explicit integration of equity and justice. The concept of just sustainability has emerged as an important framework, combining environmental protection with distributional, procedural, and recognitional justice to address social and environmental inequalities.

Legal frameworks are widely recognized as critical enablers of environmental justice and public health protection. International agreements, national environmental statutes, constitutional provisions, and human rights law impose legal obligations on states and corporations to prevent environmental harm. Scholars emphasize that clearly defined and enforceable legal responsibility is essential for ensuring accountability for environmental degradation that adversely affects human health.

The literature also establishes a strong connection between environmental justice and health outcomes by identifying environmental conditions such as air and water pollution and climate change as key determinants of health. Integrating environmental justice with public health law highlights the role of legal mechanisms in reducing health disparities. However, studies note persistent challenges arising from the separation of environmental and health law, leading to fragmented governance. Emerging interdisciplinary approaches, including One Health and planetary health law, seek to bridge this divide.

Key themes across the literature include distributional, procedural, and recognitional justice, emphasizing inclusive governance and protection of vulnerable communities. Despite growing recognition, empirical research remains limited, particularly regarding enforcement effectiveness and Global South perspectives.

3. Objective of the Study

The major objective are as follows:

1. To examine the intersection between environmental degradation and public health inequities.
2. To assess how legal responsibility can act as a bridge for achieving both environmental and health justice.
3. To analyze the role of constitutional, statutory, and judicial mechanisms in ensuring accountability.
4. To explore how integrating legal responsibility into sustainable development policy strengthens environmental governance.
5. To propose policy measures for holistic and justice based environmental and health governance

3.1 Research Questions and Hypotheses

The research seeks to answer the following questions:

- How are health and environmental justice interrelated in the context of sustainable development?
- To what extent can legal responsibility serve as a framework for achieving justice in both fields?
- What role does the judiciary play in reinforcing accountability for environmental and health harms?



- How can existing laws be reformed to create a more integrated justice system?

Hypothesis: Legal responsibility, if properly institutionalized, can serve as an effective bridge between health and environmental justice, thereby contributing to the realization of the sustainable Development Goals (particularly SDGs- 3 Good Health and well-Being, and SDGs 13 Climate Action)

4. METHODOLOGY

4.1 Research Design

The research adopts a qualitative and doctrinal research design supported by a comparative and analytical approach. The doctrinal component investigates the relationship between environmental degradation, public health outcomes, and the role of law in addressing environmental injustice. The comparative element examines national and international legal frameworks particularly the Indian constitution, international environmental treaties, and public health statutes to evaluate the extent to which legal responsibility promotes sustainable development.

The research follows a descriptive analytical methodology. Relying primarily on secondary source such as academic journals, legislative texts, judicial decisions, and international declaration, e.g. the Stockholm Declaration (1972), Rio Declaration and Paris (1992) Agreement (2015). The analysis explores how health and environmental justice are conceptualized as interdependent rights and how function as a normative mechanism to bridge these domains law.

4.2 Data Collection and Sources

This study is qualitative in nature and utilizes secondary data sources drawn from:

Primary legal sources: **Constitutional provisions (Articles 21, 47, 48A, 51A(g))**, statutes like the Environment Protection Act, 1986, Air (Prevention and Control of Pollution) Act, 1981, Water Act, 1974, Public Liability Insurance Act, 1991, and National Green Tribunal Act, 2010.

Judicial decisions: *M.C. Mehta v. Union of India* (1987, 1991), *Subhash Kumar v. State of Bihar* (1991), *Vellore Citizens Welfare Forum v. Union of India* (1996), *Indian Council for Enviro-Legal Action v. Union of India* (1996), and *Murlis. Deora v. Union of India* (2001).

International legal instruments: Rio Declaration on Environment and Development (1992), Paris Agreement (2015), and UN General Assembly Resolution 76/300 (2022) recognizing a clean, healthy, and sustainable environment as a human right.

Secondary materials: Reports from WHO, UNEP, IPCC, academic publications, and policy documents on sustainable development and environmental health.

The study applies content analysis to legislative and judicial texts to identify themes of justice, responsibility, and sustainability, and comparative legal analysis to contrast India's approach with global best practices (e.g., the U.S. Environmental Justice Framework, EU Green Deal, and WHO Environmental Health Charter).

5. Analysis and Discussion

5.1 Constitutional and Legal Foundations

The Constitution of India embeds environmental protection and public health within the broader fabric of social justice and human rights. The provisions under Articles 21, 47, 48A, and 51A (g) together form a constitutional ecosystem that recognizes the environment not merely as a resource but as a prerequisite to life itself.

Article 21 guarantees the right to life and personal liberty, which the Supreme Court has expanded to include the right to a clean and healthy environment.

Article 47 places a directive duty on the State to improve public health and raise the standard of living.

Article 48A obligates the State to protect and improve the environment.



Article 51A (g) imposes a fundamental duty on every citizen to protect and improve the natural environment.

This constitutional harmony has been judicially strengthened through a series of landmark cases that connect environmental justice with health and sustainable development.

5.2 Judicial Integration of Environmental and Health Justice

A. M.C. Mehta v. Union of India (Oleum Gas Leak Case, 1987)

The Oleum Gas Leak Case was the first major decision where the Supreme Court directly connected environmental hazards to the right to life under Article 21. Following a gas leak from Shriram Food and Fertilizers Ltd. in Delhi that caused death and illness, the Court held that industries engaged in hazardous activities have an absolute and non-delegable duty to ensure safety. Justice P.N. Bhagwati introduced the principle of absolute liability, stating that an enterprise that engages in inherently dangerous operations is strictly liable for any harm caused, regardless of negligence. This principle was more stringent than the earlier English doctrine of “strict liability” and became a cornerstone of Indian environmental jurisprudence.

The Court emphasized economic growth cannot come at the cost of human health and ecological integrity, marking a decisive shift toward preventive environmental governance. This judgment laid the foundation for later decisions, such as the Ganga Pollution Case, by reinforcing that industrial responsibility is a legal obligation arising from the right to life itself.

B. M.C. Mehta v. Union of India (Ganga Pollution Case, 1988)

In the Ganga Pollution (Tanneries) Case, the petitioner, M.C. Mehta, brought a Public Interest Litigation under Article 32, highlighting how industries, especially tanneries in Kanpur, were discharging untreated effluents into the Ganga River.

The Supreme Court declared that polluting industries were infringing upon the fundamental right to life by degrading a vital natural resource. The Court ordered the closure of all tanneries that failed to install effluent treatment plants and introduced the Polluter Pays and Precautionary Principles into Indian environmental law.

Justice E.S. Venkataramiah observed:

“Just as one cannot live without air, one cannot live without water. The right to clean water is a fundamental right under Article 21.”

The case became a landmark in connecting environmental pollution, human health, and legal accountability, reinforcing that the State and industries share a constitutional duty to maintain ecological balance and protect public health.

The judgment also directed local governments and the Pollution Control Board to create a long-term strategy for sewage treatment, emphasizing that pollution control must integrate technological, legal, and social mechanisms.

C. Murli S. Deora v. Union of India (2001)

In this case, the Supreme Court addressed the issue of passive smoking and its health implications. Recognizing scientific evidence that exposure to tobacco smoke causes respiratory diseases, cancer, and other illnesses, the Court held that the right to life under Article 21 includes the right to live in a smoke-free environment.

The Court banned smoking in public places such as hospitals, educational institutions, public offices, and public transport, stating, “the fundamental right of a non-smoker to live in a healthy environment cannot be violated by the acts of smokers.”

This case was pivotal in expanding environmental jurisprudence to include personal and indoor environmental health, demonstrating that environmental justice extends beyond pollution control to the very conditions of everyday living.

5.3 Interlinkages between Health, Environment, and Law

Article 21 of the Indian Constitution guaranteeing the right to life has been judicially interpreted to include the right to a healthy environment and the right to health. The Supreme Court, through cases like Subhash Kumar and Murli S. Deora, has expanded the constitutional horizon to encompass environmental and health dimensions of life. Similarly,



Article 47 imposes a directive duty on the State to improve public health, while Article 48A mandates the protection of the environment.

The intersection of these provisions indicates that environmental harm is simultaneously a public health violation. Environmental justice thus becomes not only a social or ecological imperative but a constitutional necessity. Through this framework, the law serves as a mediator between competing interests economic development and public health thereby guiding sustainable policy choices.

5.4 Legal Responsibility as a Bridge toward Justice

The concept of legal responsibility operates on three levels:

State responsibility, where the government must prevent environmental degradation through effective regulation, monitoring, and enforcement.

Corporate responsibility, emphasizing the “polluter pays” “precautionary” principles, and strict liability “ensuring industries bear the cost of ecological and health damage.

Individual responsibility, promoting civic participation and sustainable consumption practices.

Judicial pronouncements such as Vellore Citizens Welfare Forum and Indian Council for Enviro-Legal Action have institutionalized these principles. They affirm that environmental negligence amounts to a violation of fundamental rights, placing the onus on both state and non-state actors to act responsibly.

5.5 Challenges in Implementation

Despite legal recognition, the practical realization of environmental and health justice faces systemic barriers:

- Weak enforcement and fragmented governance.
- Inadequate health–environment data integration.
- Industrial lobbying and policy capture.
- Socioeconomic inequality that limits access to justice.
- Insufficient public participation and legal literacy.

To address these, India must strengthen legal education, public participation, and data transparency. The creation of a National Green Ledger, integrating environmental and health indicators, would enable evidence-based policymaking. Similarly, empowering the National Green Tribunal (NGT) to award health compensation aligns with the spirit of the Oleum Gas Leak and Murli Deora cases.

5.6 Policy Implications and Sustainable Development Goals

The study affirms that legal responsibility is essential to achieving SDGs, especially Goals 3, 6, 13, and 16. Integrating environmental justice into health policy for instance, through climate–health budgeting, environmental health impact assessments, and corporate accountability audits strengthens governance and sustainability outcomes.

The **Ayushman Bharat scheme**, when viewed through this lens, reflects health justice goals but must incorporate environmental determinants like air and water quality into its implementation. Similarly, policies like the National Clean Air Programme (NCAP) and Swachh Bharat Abhiyan should explicitly include health-based metrics of success.

5.7 Future Directions

The results suggest the need for:

1. A unified environmental–health regulatory authority to harmonize cross-sector policies
2. Legislative amendments incorporating environmental determinants in public health law.
3. Judicial innovation to extend liability doctrines to climate and pollution-related health harms.
4. Education and awareness initiatives promoting citizen participation in environmental decision-making.
5. Regional cooperation frameworks (especially in South Asia) for transboundary pollution and disease management.



5.8 Inventive Practical Applications

A. Legal-Policy Innovations

1. Eco-Health Accountability Act (Proposed)

A new national law integrating environmental protection and public health governance. It mandates joint accountability of industries, municipal bodies, and health departments for pollution-linked diseases. The Act would empower citizens to file Eco-Health Grievance Petitions directly in the NGT or newly proposed Eco-Health Courts.

2. National Green Ledger (NGL):

A digital, transparent database linking industrial emissions, environmental violations, and health data. The NGL would be accessible to the public, encouraging data-driven policy decisions and citizen oversight.

3. Environmental Health Impact Assessment (EHIA):

Mandatory inclusion of public health indicators in every Environmental Impact Assessment (EIA) for industrial or infrastructure projects. The EHIA model measures the health costs of environmental degradation before project approval.

4. Integration of Health Compensation Mechanisms:

Amend the NGT Act, 2010, to include compensation for public health impacts, allowing citizens to claim damages for pollution-induced illnesses.

B. Community-Based Innovations

1. Local Environmental Health Justice Committees (LEHJCs):

Decentralized community units comprising panchayat members, health officers, and environmental experts. They monitor pollution, track local disease patterns, and submit reports to district environmental authorities. This ensures grassroots enforcement of constitutional duties under Article 51A(g).

2. Community Pollution Watch Programs:

Citizen-led surveillance systems using mobile apps to report illegal dumping, emissions, or industrial discharge. Linked with government dashboards, these programs promote participatory environmental governance.

3. School and University Eco-Justice Curriculum:

Introducing environmental-health justice education to foster youth participation in sustainable development and citizen responsibility.

5.9 Comparative Insights and Global Relevance

Globally, countries like Sweden, Norway, and New Zealand have successfully integrated environmental and health governance. The Aarhus Convention (1998) guarantees citizens' rights to access environmental information and justice a model India could adapt through the Right to Environmental Health Information Act, expanding transparency.

These global examples affirm that environmental justice and health equity are interlinked aspects of human rights, and their protection requires both legal enforcement and community participation.

Theoretical Integration

This study proposes the Eco-Justice Responsibility Framework (EJRF) a novel model connecting law, health, and community empowerment. The EJRF rests on three pillars:

- Legal Accountability: Binding responsibility of State and private entities.
- Community Participation: Citizen Co-management of environmental and health resources.
- Technological Transparency: Publicly available environmental-health data to ensure continuous monitoring.



This framework transforms environmental governance from a top-down to a participatory system where justice is both legally enforceable and socially embedded.

5.10 Discussion: Legal Responsibility as a Pathway to Sustainable Development

The idea that legal responsibility can be a driver of sustainable development marks a significant shift in environmental jurisprudence. Traditionally, the law was reactive—intervening only after damage was done. Today, courts, policymakers, and communities are increasingly realizing that legal responsibility must be preventive, participatory, and principle-based, especially in the context of health and environmental justice. This transformation is not only legal but also philosophical, grounded in the belief that the environment and human health are not separate realms but two interdependent aspects of the same constitutional right to life.

1. The Constitutional Ethic of Responsibility

The Indian Constitution provides the moral and legal foundation for environmental and health responsibility. Article 21, as expansively interpreted by the Supreme Court, affirms that the right to life includes the right to live with human dignity, clean air, safe water, and ecological balance. Articles 47, 48A, and 51A (g) translate this into a duty-based framework: while the State is obligated to protect and improve the environment and public health, citizens have a reciprocal duty to safeguard nature.

This convergence of rights and duties establishes a constitutional ethic of responsibility a symbiotic framework where law functions as both a shield and a compass. The judiciary, through its interpretation, has made environmental and health protection not a matter of policy discretion but a matter of constitutional compulsion.

2. The Judicial Turn: From Rights to Responsibility

The Indian judiciary has been instrumental in embedding the principle of legal responsibility into the framework of environmental and public health governance. The trilogy of M.C. Mehta (Oleum Gas Leak, 1987), M.C. Mehta (Ganga Pollution, 1988), and Murli S. Deora (2001) represents the evolution of this judicial responsibility.

In the Oleum Gas Leak Case, the Court recognized that industries dealing with hazardous substances owe an absolute and non-delegable duty to the community. By establishing the doctrine of absolute liability, the Court transformed environmental responsibility from a moral concern into a legal mandate. This judgment became the bedrock of modern environmental law, reinforcing that economic activity must internalize the cost of environmental and health damage.

In the Ganga Pollution Case, the Court extended this doctrine to the domain of public utilities, declaring that industrial discharges polluting rivers violate the right to life. The introduction of the Polluter Pays and Precautionary Principles reflected a shift from punitive justice to preventive justice. The judgment made it clear that legal responsibility is not only about compensating victims but also about avoiding foreseeable harm to the environment and human health.

Similarly, in Murli S. Deora v. Union of India, the Court brought environmental responsibility into the realm of personal and public behavior. By banning smoking in public places, it recognized that environmental harm includes air quality, domestic pollution, and passive exposure. The decision symbolized a mature form of judicial reasoning, where responsibility extends beyond corporations and governments to individual citizens who share in the constitutional duty to protect others' health.

Together, these cases establish that legal responsibility in India is multi-tiered encompassing state, corporate, and individual duties and that this shared responsibility is essential for sustainable development.

3. Linking Legal Responsibility to Sustainable Development

The principle of sustainable development envisions meeting present needs without compromising the ability of future generations to meet theirs. However, in practical terms, sustainability can only be achieved when laws enforce the equitable balance between economic growth, social welfare, and ecological protection.

Legal responsibility acts as the operational tool that transforms sustainability from an ideal into an enforceable framework. When industries are legally required to conduct Environmental Impact Assessments (EIA), install pollution-control devices, and compensate affected communities, the law operationalizes sustainability. Similarly, when citizens



are empowered through public interest litigation or community-monitoring mechanisms, legal responsibility becomes participatory and democratic.

In this context, India's environmental jurisprudence has global relevance. By interpreting the right to life to include environmental and health dimensions, the judiciary has effectively constitutionalized sustainable development. The Oleum Gas Leak Case laid the foundation of industrial accountability; the Ganga Pollution Case linked ecological balance to human survival; and the Murli Deora Case extended sustainability into the social sphere by recognizing the health implications of lifestyle and behavior.

Thus, sustainable development in India is not merely an economic or environmental policy it is a constitutional aspiration implemented through legal responsibility.

4. The Evolution of Responsibility: From Liability to Stewardship

Legal responsibility, in its highest form, transcends the notion of liability. Liability is reactive it deals with punishment and compensation after harm. Responsibility, on the other hand, is proactive and preventive. It seeks to protect life before it is threatened. In environmental and health governance, this evolution is visible in the way Indian courts have interpreted State and citizen duties. The judiciary's role has shifted from adjudicating disputes to constructing frameworks for environmental stewardship. The courts no longer treat pollution as an isolated wrong but as a symptom of deeper systemic negligence.

For example:

In the Ganga Pollution Case, the Court did not merely order closure of polluting industries but directed the creation of sewage treatment infrastructure, reflecting a systemic approach. In Murli Deora, it imposed a behavioral norm no smoking in public thus creating a culture of shared health responsibility. In Oleum Gas Leak, it laid down the absolute liability principle as a structural deterrent for future negligence. Together, these decisions elevate responsibility from punishment to stewardship, aligning legal systems with the ethical foundations of sustainability

5. Integrating Community and Legal Innovations

Legal responsibility cannot be sustained solely through judicial enforcement; it must be supported by community innovation and participatory mechanisms. The proposed ideas—like Local Environmental Health Justice Committees, Eco-Medical Camps, and Citizen Pollution Watch Networks reflect the next stage of legal evolution, where law collaborates with community intelligence.

Community-based innovations serve multiple functions:

1. They localize legal norms, making them relevant to the ground realities of pollution and health.
2. They bridge data gaps, as local actors can observe, record, and report environmental hazards more efficiently than centralized agencies.
3. They democratize environmental governance, turning citizens into co-guardians of sustainability.

The interplay between formal law and community participation ensures that environmental responsibility becomes not merely a rule of compliance but a culture of coexistence.

6. The Global and Ethical Dimension

Globally, the notion of environmental and health responsibility is reinforced through conventions like **The Rio Declaration (1992)** which established 27 guiding principles for sustainable development

:Key Outcomes

- Principle of Sustainable Development: Balance between environment and development.
- Precautionary Principle: Act to prevent environmental harm even without full scientific certainty.
- Polluter-Pays Principle: Those who cause pollution must bear the cost of managing it.
- Public Participation & Environmental Impact Assessment (EIA): States must involve citizens and conduct EIAs.



- Common but Differentiated Responsibilities (CBDR): Recognizes different capacities of developed & developing countries.
- Inter-generational Equity: Duty to protect the environment for present and future generations.

The Aarhus Convention (1998) The Aarhus Convention strengthened the idea of environmental democracy by giving people enforceable environmental rights.

Key Outcomes

- Access to Information: Governments must provide timely, accurate environmental information.
- Public Participation in Decision-Making: Citizens must be allowed to participate in decisions affecting the environment.
- Access to Justice: Individuals and NGOs can challenge public decisions violating environmental law.
- Transparency & Accountability: Obligates states to maintain open environmental governance systems.

The Paris Agreement (2015). The Paris Agreement is the most important global treaty on climate change after the Kyoto Protocol.

Key Outcomes

- Global Temperature Goal: Limit global warming to well below 2°C and pursue 1.5°C.
- Nationally Determined Contributions (NDCs): Countries set their own climate action targets, reviewed every 5 years.
- Climate Finance: Developed nations to mobilize \$100 billion per year for developing countries.
- Adaptation & Resilience: Emphasizes adaptation planning, loss and damage, climate-resilient development.
- Transparency Framework: Countries must report emissions and progress regularly.
- Net-Zero Goal: Achieve global carbon neutrality around mid-century.

India's constitutional and judicial approach thus holds global significance. By embedding sustainability within the right to life, Indian law transcends traditional environmentalism. It recognizes that sustainable development is not an option but an obligation a shared responsibility of states, corporations, and citizens alike. This mirrors the ethical insight that justice to the environment is justice to humanity itself.

6. Overview of Findings

The findings reveal that health and environmental justice are deeply interwoven, both conceptually and legally. Environmental degradation through pollution, deforestation, and industrialization directly affects air, water, and food quality, leading to severe health burdens such as respiratory illnesses, cancers, and vector-borne diseases. The poor and marginalized face the brunt of these impacts, exposing an inequitable distribution of environmental risks.

Legal responsibility emerges as the critical bridge that ensures accountability for such harms. By translating moral and policy imperatives into enforceable legal duties, it operationalizes justice. The study establishes that an effective legal responsibility framework, grounded in constitutional and international commitments, is indispensable for sustainable development.

6.CONCLUSION

The paper concludes that health and environmental justice are inseparable, and bridging them through legal responsibility is essential for sustainable development. The Indian Constitution, through its environmental and health provisions, envisions a holistic framework for human welfare. Judicial activism has reinforced this vision, yet effective implementation requires institutional and community integration.



The research's unpublished findings reveal critical gaps fragmented governance, limited citizen participation, and weak accountability. The inventive practical applications proposed such as the Eco-Health Accountability Act, National Green Ledger, and Local Environmental Health Justice Committees offer actionable pathways to translate constitutional ideals into tangible outcomes.

Sustainable development, therefore, must move beyond rhetoric toward just, inclusive, and participatory governance. Legal responsibility should not merely punish but empower communities and ensure that health and environment are protected as unified human rights.

In the constitutional spirit of Article 21, sustainable development is not an option it is a duty owed to present and future generations.

References

1. The Constitution of India, Articles 21, 47, 48A, and 51A(g).
2. Environment (Protection) Act, 1986.
3. Air (Prevention and Control of Pollution) Act, 1981.
4. Water (Prevention and Control of Pollution) Act, 1974.
5. National Green Tribunal Act, 2010.

Case Laws

7. Subhash Kumar v. State of Bihar, AIR 1991 SC 420.
6. M.C. Mehta v. Union of India, AIR 1987 SC 1086.
8. Vellore Citizens' Welfare Forum v. Union of India, AIR 1996 SC 2715.
9. Indian Council for Enviro-Legal Action v. Union of India, (1996) 3 SCC 212.
10. Murli S. Deora v. Union of India &ORS.(2001) 8SCC 765
11. M.C Mehta v. Union of India (Oleum Gas Leak Case, 1987)

International Conventions

12. Rio Declaration (1992)
13. The Aarhus Convention (1998)
14. The paris Agreement (2015)



DOIs:10.2015/IJIRMF/ICICSF-2025-P42

--:--

Research Paper / Article / Review

International Conference On "Innovative Convergence for Sustainable Future"

Date : 12 - 13 December, 2025

(ICICSF-2025)



Indo-Nepal Open Border: Balancing Security Needs and Sustainable Practices

Suvasmita Dey¹, Dr. Smita Pandey²

¹ Ph.D. Scholar, Department of Legal Studies, Jharkhand Rai University, Jharkhand, India

² Associate Professor, Department of Legal Studies, Jharkhand Rai University, Jharkhand, India

Email – suvasmitadevad@gmail.com

Abstract: The 1751 kms open border which separates India and Nepal is one of the most complex borders in South Asia. The openness of the border is because of the 1950 Treaty of Peace and Friendship, which permitted people of both the nations to freely travel across the borders for trade and tourism without the requirement of any passport or visas. This freedom of movement of the people who live along the border have close associations and the local livelihoods mainly thrive on trade and employment opportunities. Although the open border has been a blessing for the people of both the nations yet its openness poses a grave security threat. This penetrable border has been abused by the criminals for offences which pose immense pressure on the law enforcement agencies which causing rise to tensions between the two countries. This paper looks at how India and Nepal can deal with these issues simultaneously while keeping their borders open. It emphasises cross-border institutionalism, economic integration, local community involvement, and borderland institutions. According to the conclusion of the research there are other options for creating jobs, increasing capacity, and raising awareness of sustainability issues besides military or law enforcement. In case India and Nepal are ready to take steps towards sustainability, they can keep an open border, but they can curb crime and make both the nations to cooperate more in the process.

Keywords: Indo-Nepal border, cross-border security, sustainable practices, economic integration, bilateral cooperation.

1. INTRODUCTION

The open border between India and Nepal is an ode to the shared history, sociocultural relationships, and bilateral cooperation between the countries. It evolved due to the centuries of social and economic interactions between communities in the Gangetic plains and the foothills of the Himalayas (Shah, 2017). Thus, with the formation of political borders in the modern world, this social reality promoted the introduction of an open border policy according to which people of both nations could travel freely, engage in economic activities and settle across the border. The policy has seen commendable opportunities on cross border trade, employment, education and family formation that are bound to become a significant resource to hundreds of the people with border communities (Srivastava et al., 2025).

This openness was formalised by the 1950 Treaty of Peace and Friendship between India and Nepal. The open border as a system of trust and interdependence was successfully institutionalised in the treaty and ensured mutual privileges of residence, property, trade and movement (Kushwah & Anand, 2022). The framework has over the decades allowed the Nepali people to access to employment, healthcare and education in India and Indian businesses to have a new market and opportunity throughout Nepal. Contestation of the treaty has not been without its share as some Nepali political players have seen the treaty as unequal, its main provision of being an open border has held and continues to hold the key to bilateral relations (Acharya, 2023).

Meanwhile, the open border creates grave security issues. Loose monitoring has facilitated the movement of drugs, counterfeit currency, small arms and other illegal substances. Efforts by many policy agencies have failed to curb human trafficking particularly the women and child trafficking between Nepal and India as well as internationally (Bhat, 2024).



The crime networks also exploit the vulnerability of the border as stated by the report of the illegal trade, tax evasion and the smuggling of the necessities. In addition, isolated cases of extremist groups and insurgent elements attempting to misuse the border to move or seek refuge have also been seen and this has caused concern about the national security (Pulami, 2023).

The key question that arises by this condition is how intriguing it is to poise the perils of insecurity with the benefits of an open border. In adjunct to hindering the economic and cultural life and impairing the goodwill of both countries, communities whose lives are interrelated across the border would grow indignant if the border were closed or firmly controlled. However, if it is entirely unrestrained, it would lead to a situation that would be favourable to crime, leading to detriment of both states (Pattanaik, 1998). Therefore, the main question is not about the openness of the border but the proper maintenance which would help to curb such cross-border crimes. It is this statement of problem that the current study is about to delve into in order to examine how border governance strikes a balance between security and sustainability.

This fact has a direct bearing on the objectives of the study. The initial objective of it is to assess the nature and extent of security challenges across borders caused by the open border policy. Secondly, it aims at experimenting with sustainable practices which can curtail crime and encourages cooperation without compromising the conventional openness of the frontier. Third, it seeks to propose how Nepal and India can balance between national security and economic integration. These aims are based on the fact that the purely securitised or purely laissez faire policies are insufficient and that a middle ground based on cooperation, communal involvement, and innovation is required.

Despite the narrow scope of the study that is restricted to the Indo-Nepal border, there are general implications of the issues addressed on South Asian regional cooperation. The paper does not attempt to provide any comprehensive economic discussion of bilateral trade or to explore historical territorial conflicts such as Kalapani or Susta except insofar as it has a role to play in the governance of the borders. Instead, the cover is on the political reality of how an open border works and the challenges it poses, and how governance is going to evolve to uphold it. The weakness lies in the use of secondary data since no information regarding the private intelligence and enforcement is disclosed to the public. Moreover, the outcomes may soon be obsolete because of the dynamism of crime trends. The fact that these limitations are identified does not reduce the importance of the study in identifying trends, raising questions, and providing future directions.

The investigation is based upon three key questions. How does the open border between India and Nepal impact on the security issue at the cross-border challenge? How can there be more environmentally friendly approaches to reduce crime and promote collaboration across the border between India and Nepal? How can India and Nepal achieve a balance between security considerations and economic integration in this special border set up? These questions are supposed to put forward the investigation in an forward-looking, problem-focused, and pragmatic manner. They encourage exploration of the possibilities and also the challenges which exist with having an open border. All of the background, historical context, significance, concerns, problem statement, objectives, scope, limitations, and research questions combine to create a logical basis of the analysis of one of the most unique border regimes of the world and provide the solutions to the problems that may be offered to guarantee its long-term safety.

2. LITERATURE REVIEW

There are a number of frameworks that describe the dynamics that affect cross border interactions; this review focuses on consistent ideas within the literature, and uses them specifically in relation to the Indo Nepal open border in balancing security imperatives with sustainable practices.

The book titled Transnational Crime: Law, Theory and Practice at the Crossroads offers an extensive study of the development of cross border criminal law. The book examines the normative foundations and practical problems of controlling the crimes across the national border to assist in closing the gap between the domestic and international criminal law. (Roher et al., 2018)

Nepal-India open borders: Problems and prospects provides a broad-scaled exploration of the Nepal-India open border system, begun with the 1815-16 Sugauli Treaty. The study employs the field research, the opinions of experts and qualitative interviews to provide an informative explanation of the history of its origins, socio-cultural and economic advantages and ever-changing issues such as smuggling, illegal trade, unclarity of boundaries, and security. (Baral & Pyakurel, 2015)



The article, Towards a Regulated Indo-Nepal Border, makes reference to the open border regime as a system that was adopted after the Treaty of Peace and Friendship in 1950. Despite the socio-cultural and economic advantages that it has provided, it has also posed the risks of misuse by weapons traffickers, smugglers, terrorists, extremist organizations, and human traffickers. (Das, 2008)

The article titled A Study on Challenges of Border Management System along the Indo-Nepal Border presents in detail the open border between India and Nepal with its advantages and the serious cases of the security problem. The paper appraises the concerns of the history, law, and practice of operation using the three horizons model as a secondary source. (Bhat, 2024)

In An analysis of AI-driven technologies to increase security along the India-Nepal border, Dhakal et al. (2024) assess the use of artificial intelligence technologies to strengthen security in the area of the India-Nepal border, outlining the potential impact of AI on the functioning of a sustainable border management. The paper sheds light on the AI-based surveillance, predictive analytics, automated border and drone surveillance as some of the best technologies that support operational efficiency in terms of threat detection and responses. (Dhakal et al., 2024)

3. METHODOLOGY

This paper employs a qualitative, analytical, and comparative research design to comprehend the Indo-Nepal open border. The study does not adopt a strictly statistical approach but rather uses descriptions, explanations and shifts in policy discussion. The design integrates doctrinal research with the study of government and international reports. It comprises the descriptive information of present arrangements, analytical reflections on issues, and assessment of possible solutions. In this manner, the research will be able to address the scholars and policymakers.

In the study, different sources of information have been used which gives a complete picture. The important sources are the 1950 Treaty of peace and friendship between India and Nepal, bilateral meetings, reports of bilateral boundary groups, and government documents on the cooperation. Academic writings, reports by think tanks, and media articles are the secondary sources. A combination of these sources helps to make sure that the study does not merely examine legal regulations, but also the reality of border communities as they live.

The analysis of treaties, laws, and policies is used to identify persistent themes of security and openness. The case studies demonstrate how the issues of narcotics smuggling or fake currency are controlled in reality. A comparative analysis of laws in India and Nepal stresses the resemblances and variances in the laws regarding the anti-trafficking or narcotics. With the collective tools, the study will be able to relate events with deeper roots and probable governance modules.

One of the mechanisms of this design is the comparative viewpoint. Knowledge is gathered by the experience of other parts of the world like the Schengen system in the European Union which determines that open borders can be effectual with an operative security response in the form of identity management and sharing of intelligence. However, US-Mexico border is a reminder that unilateral control and tight control are likely to aggravate crime. Such examples are not straight copies but modified to the South Asian conditions. They give concepts of layered security and shared mechanisms which may come in handy in the Indo-Nepal context.

There are also limitations to the methodology. It is majorly dependent on secondary data that can be biased or incomplete. Politics or unrest alter the situation at the border fast and may make the description obsolete. Global comparisons have also the potential of over-generalisation in the event that they are reused without caution. The triangulation of the research, i.e. the cross-checking of facts with different sources, and the preservation of the final conclusions with the social and political facts of Indo-Nepal relations is aimed to overcome these issues.

4. DISCUSSION

4.1 The Strategy of Openness vs. Control of Security.

Lately, the formal coordination between India and Nepal has been resurgent. On July 22, 2025, at the Home Secretary level, discussions took place in New Delhi, during which both states revised and agreed to tighten their cooperation on the border and security (PIB Delhi, 2025). This comprised the development of an amended extradition framework and advancement on a Mutual Legal Assistance agreement (Giri, 2025a). These diplomatic anchors are useful in avoiding



the occurrence of sudden disruptions to lawful crossers by supporting a pragmatic model, where enforcement and facilitation are co-designed, as opposed to being introduced as opposites.

The technical maintenance of the border itself is also very important, as it reduces the conflict and limits the chances of illegal entry. After a six-year break, the Boundary Working Group convened again in July 2025 and resolved to finish boundary work by 2027, omitting legacy areas such as Kalapani and Susta, but including the repair of pillars and encroachments (Giri, 2025b). This commitment is significant since the proper demarcation improves patrolling geometry, reduces controversial accounts on the ground, and elevates the admissibility of evidence in cases where the facts of cross-border aspects are involved. To ensure daily livelihood mobility in predictable ways, border district coordination meetings at integrated check points, such as those reported at Nepalgunj, are an add-on to national level deliberations by transforming commitments into local protocols to time-deliver joint patrol, night feeder track and standard operating procedure of the handover of suspects and confiscation of property (TRN, 2025).

The final balancing technique is that of considering technology as a delicate instrument instead of a crude obstacle. The shift towards intelligent surveillance enabling surveillance of the entire border without over policing the entire border is manifested in the recent order to install drones and anti-drone systems on high-risk points such as Sunauli and Raxaul and vulnerable points in Uttar Pradesh (TNN, 2025c). To uphold the uninterrupted flow of legitimate travels as interdiction concentrates on dubious trends, the design thinking integrates facial recognition in checkpoints, analytics and aerial surveillance with open data protection and supervision. To make sure that people living in border towns comprehend the reasons why certain corridors check more often and how to find a way to recover time wasted or false positive, these measures should be included in the works of collaboration and backed by the open dialogue. The aim is not to close the border but to reduce the area of operation of crime networks (TNN, 2025c).

4.2 Human Rights Concerns of Borderland Communities.

Acknowledging the fact that a large number of the crossers are daily wage earners, family vacationers and small traders, whose dignity and livelihood is pegged on mere movement is the initial move towards human rights protection in the governance of the borders (Kumar, 2013). Any increase in security should be accompanied by procedural protection such as gender sensitive search methodology, multilingual signs, open screening, and redressing grievances (Deane, 2010). The Supreme Court of India has said in previous cases concerning trafficking and vulnerable women, that the state had positive responsibilities. In such instances, the Court has led concerted efforts in combat against child prostitution and trafficking, enhanced child protection and rescue, as well as demanded dignity, criminalisation of consent among adults in sex work, and the rehabilitation models. These decisions affect the practice of the border by obligating respect to individual rights in the process of interdiction and rescue (Trivedi & Chamar, 2025).

Family pressure, bondage through debt, as well as, fraudulent recruitment, all contribute to cross-border vulnerabilities and do not necessarily show up at the checkpoints. The 2024 country assessment of Nepal on Trafficking in Persons (Office to Monitor and Combat Trafficking in Persons, 2024) indicates how sham employment and grooming online are exploited by traffickers to take advantage of the open border and the UNODC Global Report on Trafficking in Persons indicates the continued under-identification in South Asia and suggests survivor centred screening in identifying subtle coercion (UNODC, 2025). Under the human rights implications, both police and security staff need safe areas of confidential reporting, trauma-informed interview, and credible referral options to shelters on one side, as well as legal assistance on the other (K.C., 2019). Another element of rights protection in the community is predictability of regulations. The sudden, enigmatic restrictions or shutdowns may leave residents without their income, bitter and compelled to go to middlemen who impose rent-seeking charges or link residents to illegal handlers.

4.3 Crime Reduction Sustainable Practices.

Sustainable border security does not seek to simply switch routes; but to establish an environment in which the incentives behind crime would eventually be reduced. The first pillar is economic inclusion where earning through smuggling and trafficking become less attractive. The transaction costs of the formal economy are minimized and the premium that smugglers depend on is squeezed through bilateral actions to decongest freight by extending cargo rail access beyond Birgunj to Biratnagar, and perhaps Noutanwa (Prasain, 2025). By linking livelihood programs to rural municipalities, border gramme panchayats, vendor credit lines associated with clean compliance records, skills qualifications of transport workers, households can be removed out of criminal networks which benefit financially out of financial hardships and seasonal changes (Choudhary & Ghosh, 2015).



The second pillar is community-centred prevention. Local knowledge in feeder road interdictions is converted into early warning using the methods of witness protection, small rewards, and confidential hotlines. Border schools and market committees can also organise regular awareness campaigns on the right to safe migration, indications of coercion, and how to enter shelters without any fear (Plan International, 2025).

The third pillar is ecological cooperation which regards forests and corridors as shared resources and not as contentious buffer zones. Wildlife conflicts and agricultural distress on border belts can be utilized by the criminal actors to intimidate the communities or capture lands near forest boundaries (D&B Bureau, 2022). This requirement of the demand minimization and cross-border financial oversight of the shadow hawala and front companies to launder proceeds is further underscored by the wider regional increase in synthetic drug imports in the adjacent areas like the Golden Triangle (Peck, 2025). In cases where there is a healthy supply chain, the interdiction dominated approach cannot work; thus sustainable reduction requires cooperation among financial intelligence, livelihoods, and social health.

4.4 Bilateral and Institutional Cooperation mechanisms.

Institutional design must connect high levels of commitment to the performance at the district level with the minimum translation loss. The instruments that had long been pending, like the conclusion of a Mutual Legal Assistance agreement and the negotiations on the amendment of the Extradition Treaty, received a boost through the July 2025 Home Secretary level discussions that had not been resumed since 1996 (PIB Delhi, 2025). Such tools are not merely diplomatic awards, and they enable collaborative investigative teams to trace money trails across jurisdictions as well as to minimize the gap between the moment of detecting the money and transferring evidence. The April 2025 level talks on the Director General level of the customs and frequent Sashastra Seema Bal and Armed Police Force coordination meetings form a lattice of sectoral cooperation on the seizures, valuation fraud and profiling of high risk consignors (Indian Mandarins, 2025). The area in which policing occurs is further stabilised by the technical undertakings made by the Boundary Working Group on pillar maintenance by ensuring that the bases of the patrols and prosecutions are founded on an agreed demarcation (Giri, 2025b).

In order to operationalise these structures, each of the sides may assign Border Crime Coordination Cells where police, customs, border guarding and prosecution officers will be located at particular integrated check posts and rail heads (TRN, 2025). A bilateral standard operating procedure should include and not append the civil society shelters as partners to create the timelines of handover of the victim, medical examination, taking of statements and repatriation (Bhat, 2024). In instances where controlled deliveries are required, field officers can quickly verify and proceed with controlled deliveries by maintaining shared watchlists and samples libraries on drugs and counterfeit currency at land ports (Sinha, 2021). Success metrics should be in terms of conversion rates of interdiction to conviction whilst saving the life of the victims of trafficking instead of measuring success by the number of seizures.

The same consideration should be given to local cooperation mechanisms. Coordination meetings of district officials at ICPs that are captured so as to be visible at Nepalgunj and other nodes can be put on a steady basis and trimestral schedules made known with minutes of such meetings recording actual activities, including setting feeder road cuts to lessen deviations, fitting lighting on precise stretches, and synchronizing the use of the festival season (TRN, 2025). Piloting of joint training modules in which SSB and APF squads are trained together about body worn camera protocols, interviewing techniques and evidence handling increases interoperability (Puri & Verma, 2024). These little measures render high-level assurances at ground level.

4.5 Technology and Innovation of Border Management.

Technology does not work everywhere but when targeted at the areas that the criminal logistics are weak, it works best. To track movement in the night and detect drops within the air, drones and anti-drone systems are also being implemented on the sensitive sections of the Indo-Nepal border, specifically, in Uttar Pradesh and high volume nodes such as Sunauli and Raxaul (TNN, 2025c). The corresponding innovation is algorithmic triage at the border points, when secondary checks are only initiated in case of the risk scoring worth using it in terms of license plates, driving history, and consignment information. These tools reduce the work of regular crossers and manpower savings on more in-depth inspections into flagged flows.

In addition to electronic seals, GPS-based tracking of the transit sites and time-limited customs will allow broader access to cargo rail, which will help reduce the congestion in the single nodes, decrease turnaround time, and discourage smuggling compared to legitimate routes (Banerjee & Sanganerla, 2023). India has expanded the number and capacity



of land ports through its Land Ports Authority and the official dashboards show passenger and trade data which makes it easier to map risks and conduct performance audits. In this case, the innovation does not only lie in the hardware but also in the data: agencies will have an opportunity to share anonymised risk patterns without breaching privacy (LPAI, 2022).

Finally, human systems should be subjected to innovation. Along with the reduction of the wrongful detention, there are mobile legal assistance and interpreter services at the crossings that also contribute to the quality of the statements. Body camera analytics can be applied in policing to determine the pattern of repeated complaints at specific gates and may cause a supervisory check-up (Das, 2008).

5. FINDINGS

5.1 Effect of the Open Border on the Cross-Border Security Problems.

The free movement of people and goods through the open border between India and Nepal that was created by the 1950 Treaty of Peace and Friendship has strengthened centuries-old social and economic relationships across the Terai and foothills of the Himalayas. Illegal flows of drugs, illegal alcohol, wildlife, counterfeit money and others are often documented by the police on relatively unpoliced routes. The size and flexibility of trafficking systems that rely on night-time traffic and rural roads to escape notice is evidenced by new arrests in the area of Jaynagar in July 2025. The Sashastra Seema Bal captured more than 300 kg of ganja within a mere distance of the boundary pillar and this demonstrates that they were using organised feeder routes that cut across the legitimate trade routes as well as daily commuters (TNN, 2025b).

The gender-based violence factsheet of the Nepal Police published in 2023 (Nepal Police, 2024) and the Global Report on Trafficking in Persons of United Nations Office on Drugs and Crime (UNODC) published in 2024 (UNODC, 2025) indicate that women and girls still constitute a significant trafficking victim count in the South Asia, which underlines the gravity of such a practice. Much the same is observed in the US Trafficking in Persons reports on India and Nepal (Office to Monitor and Combat Trafficking in Persons, 2024). These gaps may be further aggravated in the border areas where there is inconsistency in victim referral systems and jurisdictional coordination. The day-to-day burden of operation is left to the local stations, border outposts and district administrations that need to balance between facilitating legal movement and preventing crime.

5.2 Character of Illicit activities and Crimes.

The border economy supports small-scale trade, kinship travel and agricultural labour mobility, but promotes the development of a variety of criminal portfolios as well. Towards the end of the year 2024, there were reports of increased interception of cocaine in Nepal and it is recorded by the Indian law enforcement agencies that large amounts of heroin and cannabis were intercepted. Smuggling of narcotics has dynamic trends (TNN, 2025b). These are not in-country flows only to the western borders of India. They are also along the central and eastern corridors that run to Nepal as it has been demonstrated by the arrests that have been related to the supply chains of illegal goods obtained at the border and to inland cities (TNN, 2025d). Price arbitrage and regulatory arbitrage, at the same time, promotes smuggling, as seen with the smuggling of alcohol into prohibition areas in Bihar and other states. Such smuggling networks can deal with various commodities.

The Indo-Nepal passage is strongly associated with the transnational issue of forced labour and sexual exploitation human trafficking (Republica, 2024). Judicial interventions such as *Bachpan Bachao Andolan v. Union of India*, (2011) 5 SCC 1, in which the Court prohibited the employment of children in circuses and rescued and rehabilitated them; *Vishal Jeet v. Union of India*, AIR 1990 SC 1412, in which guidelines were given to fight child prostitution and trafficking; and the constant guidelines in the case of *Budhadev Karmaskar v. State of West Bengal* that underlined dignity, equal protection under the law, and rehabilitation systems of sex workers besides trafficking; which also reinforce the need to have operational safe houses, prosecution support, and anti-human trafficking units capable of operating collaboratively across state lines and in conjunction with Nepali equivalents by creating the normative basis of the administrative action in the border districts.

5.3 Border Communities and Socio Economic Interdependence.

Borderland livelihoods rely on period markets, minor trade as well as seasonal mobility. To sustain the household resilience and price stability in the local economies, the open border makes the daily wage workers of districts such as



Pashupatinagar, Biratnagar, Birgunj, Bhairahawa and Nepalgunj to cross along with their Indian counterparts in Sukhia Pokhari, Jogbani, Raxaul, Nautanwa and Jaynagar with ease (LPAI, 2022). The government-to-government investments in integrated checkpoints and rail connectivity as recorded in official bilateral briefs and land ports publications of India have shown that the government is taking a calculated decision to focus large masses of cargo at modernised nodes and allow relatively unrestricted movement of human beings elsewhere (MEA, GoI, 2024). It has been seen from local experience that a short-term increase in border regulations will lessen the income of loaders, transport workers, and small traders, which makes these actors depend on the services of unofficial handlers who may be engaged by criminal syndicates (MEA, GoI, 2024). A refined balance must be established between ensuring predictable facilitation in formal gates and increased patrols, light and surveillance to stretch of risks, to deter illegal flows, but at the same time day labour and kinship travel must not be harmed.

The problem of security and livelihoods is also affected by conservation issues. The Naxalbari-Jhapa elephant corridor illustrates the need to have transboundary ecological governance. Human-wild life conflict may be cross-border as seen by the cases of the elephant deaths reported on the Nepal side of the border, which was attributed to electrocution. Fencing or deterrence activities should be synchronized in order to avoid collateral damage to migratory species (TNN, 2025e). Increasing collaboration in conservation practices between forest departments, local governments and security agencies can help reduce the conflict, stabilize communities that depend on agriculture and eradicate another channel that criminal actors may exploit in forest edge settlements by grabbing land or intimidating them (Upreti, 2022).

5.4 Indian and Nepalese Institutional Frameworks.

Although further practice has then yielded several bilateral means of security coordination, the Treaty of 1950 acts as the major guidelines of friendship and mutual privileges (Kandel, 2024). The agreements to mitigate inter-border crime, enhance pillars along the boundary and enhance the infrastructure have been reaffirmed at the Home Secretary level (PIB Delhi, 2025), during the coordination meetings between the SSB and the Nepal Armed Police Force (MEA, GoI, 2025), and in the project monitoring committees of police capacity building. The primary focus of Indian national policy instruments is the development of the border regions, administration of land ports, and control of drugs by the Narcotics Control Bureau and State Special Task Forces. Attempts are in progress to improve investigation, survivor management, and prosecution via the anti-human trafficking bureau and national action plans in Nepal (Das, 2008). The preventive role of transboundary crimes in addition to enabling lawful movement are the operative roles of the Sashastra Seema Bal, which require investment in forensics, human resource, and information sharing.

5.5 Comparative Analysis to other Open Borders.

By including identity management, watchlist interoperability and situational awareness between jurisdictions in the design, open borders such as the Schengen region of the European Union demonstrate that there is no conflict between security and convenience (Ceccorulli, 2020). Although the history and socioeconomics of the Indo-Nepal vary, there are certain lessons which can be applied in other things. To begin with, risk differentiation should be introduced in the infrastructure. To allocate the enforcement resources to the high-risk consignments instead of the low-risk flows, the integrated check posts may combine electronic cargo tracking, trusted trader schemes as well as layered inspection (LPAI, 2022). Second, joint training and patrol guidelines accelerate the response time and reduce redundancy (Das, 2008). Third, lack of social fear of retaliation in a community where traffickers have social networks to integrate, such as via parts of the US-Mexico border, demonstrates that increasing the hardening of unilaterally without an added legal way to move and livelihoods to support them is more likely to push off routes and not decrease crime. This points out the significance of bilateral and localised solutions where economic alternatives are put into consideration (Gerber, 2020). The prerequisite of differentiated controls is both countries already investing in modern rail links and freight gateways, as stipulated in the Indo-Nepal bilateral brief and land port material (MEA, GoI, 2024). Most recent changes to these systems, like single window platforms and sharing data on high-risk drivers or consignors would be in line with the best practices observed in other integration zones.

Considering the South Asian trends identified by UNODC, it can be observed that women and girls remain disproportionately affected, and that a careful resolution can often be determined through the frontline officers observing certain dynamics of coercion instead of the obvious entrapment (UNODC, 2025). As practice shows, to transform detections into successful prosecutions, it is necessary to screen the victims first in a node at the border, offer multilingual information, and cooperate with the civil society shelters (Tamang, 2017). It can be possible to bring these elements to



the Indo Nepal context by bilateral standard operating procedures and joint funding of survivor services near busy crossings such as Raxaul Birgunj and Jogbani Biratnagar.

5.6 Community involvement in Border Governance.

The border communities are well familiar with the terrain, social networks and tracks. This information done through an organised engagement may maintain social legitimacy within law enforcement and create early warning of wildlife, drug, and trafficking offences (Bhat, 2024). Some of the practical tools are the community liaison meetings related to village panchayats/rural municipalities, the confidential tip lines operated concurrently by both the border forces and district police, and the awareness campaigns on human trafficking conducted by youths within the marketplaces and schools that explain the indicators of human trafficking and the right to safe migration. Women can be trained into collectives and self-help groups to act as first responders who can report on any suspicious recruitment, document labour contracts and liaise with anti-human trafficking groups to make safe referrals (Bhat, 2024). Quick community alerts frequently lead to detention of illegal spirits in Madhubani and the other neighbouring districts which underlays the institutionalisation of reward schemes and witness protection to help protect informants against retaliation (TNN, 2025a).

6. CONCLUSION AND RECOMMENDATIONS

An analysis of the Indo-Nepal open border reveals a crucial contradiction, while the border continues to serve as a historical basis for cultural similarities and economic subsistence, it also poses modern security risks that put pressure on both the two countries' ability to govern and their bilateral ties. In many ways, the 1950 Treaty of Peace and Friendship has been successful in fostering interdependence and trust. The daily flow of people, products, and even familial ties benefits border communities in maintaining a standard of living and fostering interpersonal relationships. However, the same transparency can also be used by criminals to engage in drug trafficking, smuggling, wildlife crime, counterfeiting, and trafficking. The main takeaway is that the Indo-Nepal border cannot be viewed solely from the standpoints of openness or security; rather, it should be addressed using a multi-layered strategy that incorporates security, development, and sustainability.

The findings demonstrate the globalisation of security risk issues, which calls for the development of institutional and legal remedies. Human trafficking remains a severe problem, particularly when it comes to women and children, and both India and Nepal are being criticised internationally for their poor victim identification and lack of support. Drug trafficking and contraband smuggling persist because of differences in regulatory frameworks and penetrable terrain. It results in the conclusion that, besides the law enforcement, the structural incentives to crime should be reduced using inclusive economic policies and formalised bilateral cooperation to ensure sustainable security.

There are certain recommendations that come about as a result of these revelations.

Bilateral institutional structures should be reinforced, making it operationalised at the district level through coordinated victim referral systems, cross-border sharing of evidence and also through joint investigation teams. The Boundary Working Group needs to keep on scheduling regular meetings to ensure that the pillars are upheld and to clarify any form of ambiguity to ensure that law enforcement is operating in a straight line. The collaboration between the Indian Sashastra Seema Bal and the Nepalese Armed Police Force needs to be reinforced through joint training and communication along with night patrols and deployments.

Second, being one of the pillars of governance, community participation must be formalised where in the case of suspicions of night activity, or recruitment for illicit activities, the locals are the first to point out. Their knowledge may be utilized via mini-reward initiatives, security plans and personal hotlines. The youth groups and women self-help groups can come together in an effort to encourage prevention through raising the awareness of labour rights, safe migration, and anti-trafficking laws.

Third, technology innovation should be applied with caution. Drone surveillance, anti-drone weapons, and analytics using AI may be deployed in popular checkpoints and areas of concern to detect unlawful flows without disrupting the routine. The tools that can be used to enforce it include GPS-enabled electronic cargo seals, automated risk profiling, and biometric-enabled facilitation lanes with suspected shipments and high-risk offenders.



Fourth, sustainable strategies of crime reduction cannot be achieved without policing. Reliance on smuggling will be lessened with the support of livelihood programs for borderland workers, microcredit for small traders, and ongoing assistance for agricultural exports.

Lastly, future collaborations should encourage comparative learning. Despite the US-Mexico border's caution against unilateral securitisation, the Schengen regime's experiences demonstrate the benefits of interoperable watchlists and layered controls. India and Nepal should change the concept of risk differentiation and community involvement to make more deliberate decisions that protect the unique historical culture of a shared border.

In conclusion, the open border between India and Nepal will always remain one of the distinguishing features of the relationship between the two countries. It cannot afford to abandon its weaknesses without risking the security of the region and the entire country but it cannot afford to shut down without betraying the millions of people who use it. The solution is to develop an inclusive, collaborative, and sustainable model of governance of borders with the empowerment of communities, the promotion of human rights, and the application of smart security.

References:

1. Acharya, M. (2023). *The 1950 Indo-Nepal Treaty of Peace and Friendship: Road to Review*. <https://doi.org/10.31219/osf.io/kdxzf>
2. Banerjee, P., & Sangneria, A. (2023). Strengthening Regional Integration in South Asia: Towards Highly Facilitated Trade Corridors. *Journal Of Land Ports And Border Economy*, 2, 1–22.
3. Baral, L. R., & Pyakurel, U. P. (2015). *Nepal-India open borders: Problems and prospects*. Vij Books India Pvt Ltd.
4. Bhat, A. S. (2024). A Study on Challenges of Border Management System along the Indo-Nepal Border. *The Journal of Nuwakot Adarsha Multiple Campus*, 5(1), 84–99. <https://doi.org/10.3126/jnamc.v5i1.76702>
5. Ceccorulli, M. (2020). Back to Schengen: The collective securitisation of the EU free-border area. In *Collective Securitisation and Security Governance in the European Union*. Routledge.
6. Choudhary, N., & Ghosh, A. (2015). Indo-Nepal economic cooperation: A subregional perspective. *Asia-Pacific Development Journal*, 21(2), 23–52.
7. Das, P. (2008). Towards a Regulated Indo-Nepal Border. *Strategic Analysis*, 32(5), 879–900. <https://doi.org/10.1080/09700160802309233>
8. D&B Bureau. (2022, September 10). India-Nepal: MoU on Biodiversity Conservation. *Diplomacy & Beyond Plus*. <https://diplomacybeyond.com/india-nepal-mou-on-biodiversity-conservation/>
9. Deane, T. (2010). Cross-Border Trafficking in Nepal and India—Violating Women's Rights. *Human Rights Review*, 11(4), 491–513. <https://doi.org/10.1007/s12142-010-0162-y>
10. Dhakal, S., Parvez, A., Das, P., Saxena, S., & Memoria, M. (2024). An Analysis of AI-Driven Technologies for Enhancing Security along the India-Nepal Border. *2024 International Conference on Computing, Sciences and Communications (ICCSC)*, 1–6.
11. Gerber, J. (2020). Governed and ungoverned integration in the Mexico–US border region. *Regions and Cohesion*, 10(2), 21–40. <https://doi.org/10.3167/reco.2020.100203>
12. Giri, A. (2025a, July 24). Nepal, India agree on mutual legal assistance deal. *The Kathmandu Post*. <https://kathmandupost.com/national/2025/07/24/nepal-india-agree-on-mutual-legal-assistance-deal?>
13. Giri, A. (2025b, July 30). Nepal, India to finish boundary work in three years, barring Kalapani and Susta. *The Kathmandu Post*. <https://kathmandupost.com/national/2025/07/30/nepal-india-to-finish-boundary-work-in-three-years-barring-kalapani-and-susta?>
14. Indian Mandarins. (2025, April 15). *India And Nepal Hold 21st Dg Level Talks On Customs Cooperation*. Indian Mandarins. <https://www.indianmandarins.com/news/india-and-nepal-hold-21st-dg-level-talks-on-customs-cooperation/30604?>
15. Kandel, I. P. (2024). Indo-Nepal Treaty of 1950: A Realist Perspective. *Journey for Sustainable Development and Peace Journal*, 2(2), 28–38. <https://doi.org/10.3126/jsdpj.v2i2.69561>



16. K.C., D. K. (2019). Cross-Border Crime and Its Security Concerns in Nepal. *Journal of APF Command and Staff College*, 2(1), 21–31. <https://doi.org/10.3126/japfsc.v2i1.26729>
17. Kumar, R. (2013). India–Nepal Open Border: Springboard for Opportunities. *International Studies*, 50(1–2), 165–183. <https://doi.org/10.1177/0020881716654406>
18. Kushwah, K., & Anand, A. (2022). The Indo-Nepal Treaty of Peace and Friendship, 1950: Revisiting the Tale of Two Nations. *Prayagraj L. Rev.*, 1, 1–14.
19. LPAI. (2022). *Land Port: Gateway to India* (No. Apr' 21 – Mar'22; 10 Years Celebration of LPAI, p. 63). LPAI. https://lpai.gov.in/sites/default/files/2022-09/Gateway_to_India_MagazineV2_0.pdf
20. MEA, GoI. (2024, June 20). *India–Nepal Bilateral Brief*. <https://www.mea.gov.in/Portal/ForeignRelation/Open-bilateral-brief-20-June-2024.pdf>
21. MEA, GoI. (2025). *Ministry Of External Affairs Annual Report 2024*. Policy Planning and Research Division, MEA.
22. Nepal Police. (2024). *Annual Factsheet on Gender-Based Violence 2023-24*. Police Headquarters Crime, Investigation Department. https://www.nepalpolice.gov.np/media/filer_public/57/33/5733d531-91bb-4450-8fb2-d2dd21d9022e/fy_2080-81_annual_infographics_-_en.pdf
23. Office to Monitor and Combat Trafficking in Persons. (2024). *2024 Trafficking in Persons Report: Nepal*. U.S. Department of State. <https://www.state.gov/reports/2024-trafficking-in-persons-report/nepal/>
24. Pattanaik, S. S. (1998). Indo-Nepal open border: Implications for bilateral relations and security. *Strategic Analysis*, 22(3), 461–478. <https://doi.org/10.1080/09700169808458825>
25. Peck, G. (2025, May 28). Southeast Asia's illicit methamphetamine trade is at a record high, the UN says. *AP News*. <https://apnews.com/article/asia-golden-triangle-methamphetamine-trafficking-myanmar-crime-3bd96335d313204dd22633f949b6d00f>
26. PIB Delhi. (2025, July 23). *India and Nepal holds Home Secretary Level Talks in New Delhi*. <https://www.pib.gov.in/www.pib.gov.in/Pressreleaseshare.aspx?PRID=2147422>
27. Plan International. (2025). *The Power Of Communities: Plan International Nepal's Anti-Trafficking Campaign* (p. 14) [Case Study]. Plan International. <https://plan-international.org/uploads/sites/79/2025/01/The-Power-of-Communities.pdf>
28. Prasain, K. (2025, August 1). Rail cargo access reaches Biratnagar and Bhairahawa. *The Kathmandu Post*. <https://kathmandupost.com/money/2025/08/01/nepal-india-expand-rail-cargo-access-to-biratnagar-and-bhairahawa>
29. Pulami, M. J. (2023). Introducing the Idea of Border Governance for Nepal-India Open Border. *Journal of Political Science*, 23(1), 77–97.
30. Puri, S., & Verma, K. (2024). Indo-Tibetan and Indo-Nepal Border Security: Roles, Challenges, and Policy Implications of ITBP and SSB. *Intelligence*, 20(1), 395–401.
31. Republica. (2024, August 8). The Crisis of Cocaine Trafficking thru Nepal. *Republica*. <https://myrepublica.nagariknetwork.com/news/the-crisis-of-cocaine-trafficking-thru-nepal-676f44f6be13c.html>
32. Roher, J., Dalla Guarda, N., & Khalid, M. (2018). *Transnational Crime: Law, Theory and Practice at the Crossroads*. Routledge.
33. Shah, S. H. (2017). Indo-Nepal relations: A bilateral paradox. *IUP Journal of International Relations*, 11(4), 28–48.
34. Sinha, R. (2021). *Linking Land Borders: India's Integrated Check Posts*. Centre for Social and Economic Progress. https://csep.org/wp-content/uploads/2021/06/WP_Linking-land-borders-ICP-1.pdf
35. Srivastava, S., Chaurasiya, S., & Ghimire, S. R. (2025). Socio-Economic and Governance Impacts of Cross-Border Policies on Indo-Nepal Border Communities. *Journal of Development Review*, 10(2), 219–237. <https://doi.org/10.3126/jdr.v10i2.84075>
36. Tamang, K. K. (2017). *Practice of good governance and corruption control along Nepal-India border administration* [PhD Thesis]. <http://archive.nnl.gov.np/handle/123456789/47>



37. TNN. (2025a, June 21). Liquor seized by SSB in Madhubani. *The Times of India*. <https://timesofindia.indiatimes.com/city/patna/liquor-seized-by-ssb-in-madhubani/articleshow/121995334.cms?>
38. TNN. (2025b, July 8). SSB seizes ganja near India-Nepal border. *Times of India*. <https://timesofindia.indiatimes.com/city/patna/ssb-seizes-ganja-near-india-nepal-border/articleshow/122322057.cms>
39. TNN. (2025c, August 30). Drone, anti-drone tech to boost security on Indo-Nepal border. *The Times of India*. <https://timesofindia.indiatimes.com/city/lucknow/drone-anti-drone-tech-to-boost-security-on-indo-nepal-border/articleshow/123591908.cms?>
40. TNN. (2025d, September 18). Indore police arrest interstate drug trafficker supplying smack from Nepal border. *The Times of India*. <https://timesofindia.indiatimes.com/city/indore/indore-police-arrest-interstate-drug-trafficker-supplying-smack-from-nepal-border/articleshow/123972929.cms>
41. TNN. (2025e, September 21). Elephant crosses over to Nepal, electrocuted. *The Times of India*. <https://timesofindia.indiatimes.com/city/kolkata/elephant-crosses-over-to-nepal-electrocuted/articleshow/124020925.cms>
42. Trivedi, H., & Chamar, P. (2025). Human Trafficking In India: Legal Frameworks, Challenges, And Policy Recommendations. *VIDYA - A JOURNAL OF GUJARAT UNIVERSITY*, 4(2), 261–277. <https://doi.org/10.47413/hqk3we21>
43. TRN. (2025, June 30). Coordination meeting of security officials of Nepal, India held. *The Rising Nepal*. <https://risingnepaldaily.com/news/64325>
44. UNODC. (2025). *GLOBAL REPORT ON TRAFFICKING IN PERSONS 2024*. UNITED NATIONS. https://www.unodc.org/documents/data-and-analysis/glotip/2024/GLOTIP2024_BOOK.pdf
45. Upreti, Y. (2022). A study of inter-agencies cooperation in border governance of Nepal. *Journal of APF Command and Staff College*, 5(1), 109–130.



DOIs:10.2015/IJIRMF/ICICSF-2025-P43

--:--

Research Paper / Article / Review

International Conference On “Innovative Convergence for Sustainable Future”

Date : 12 - 13 December, 2025

(ICICSF-2025)



Impact of HR Practices on Employee Involvement – A Systematic Literature Review

¹ Vivek Kumar, ² Dr. Anusha Priya¹Research scholar, Jharkhand Rai University, Ranchi, Jharkhand, India²Associate Professor, Jharkhand Rai University, Ranchi, Jharkhand, Indiavk Singh8387@gmail.com,

Abstract: This literature review aims to synthesize empirical studies demonstrating the role of Human practices on employee involvement. The purpose of the study is to examine available literatures and observe their findings related to the impact that Human Resource practices have on employee engagement, involvement and performance levels. The result of the study is compiled after a systematic review and the subsequent thematic content analysis of different literatures which were published in form of reports and research papers. The literature was thoroughly examined, and the documents closely matching with the inclusion criteria were chosen to reach out to a conclusion. The study is purely original and is based on study of secondary data available through different journals. Proper detailed study of literatures has been done in order to find the conclusion. The result of the study highlights the need of having efficient Human resource practices in organizations to get the best out of their employees. Majority of literatures have established that there is a positive and a direct relationship between human resource practices and employee involvement/engagement level which results in increased performance.

Keywords: Human resource practices, employee involvement, employee engagement, systematic review, employee performance

1.INTRODUCTION

Human resource practices refer to the strategies and policies that are designed to manage and develop an organization's workforce. These practices influence operational efficiency and impact the employee's psychological attachment to the organization, their job satisfaction levels and job commitment (Khan et al., 2020). Human Resource Management acts as the backbone for all the organizations and service sector organizations in particular. Effective human resource practices are essential for increasing productivity and profitability of the organization. They also ensure that organizations have a competitive advantage compared to their competitors. Effective human resource practices create a sense of job security and help to retain employees for a longer period of time. The sense of job security gives a competitive edge to the organizations (Foruzandeh, 2022).

2.Literature Review

There are several literatures that describe the role of Human Resource practices on employee involvement. Human Resource factors (motivation, promotions, rewards, recognitions, training, development programs and fringe benefits) boost employee's loyalty and help them to perform better (Triansyah et al., 2023). Employee involvement is defined as the degree to which the employees are engaged, motivated, and empowered to contribute in organizational decision-making and overall performance (Boxall & Purcell, 2016). Employee involvement is far more than just employee engagement or satisfaction rather it includes employee's participation in problem solving, discretionary effort, and voice behaviors that help organizations to adapt and innovate (Benson, 2013). HRM practices like training and development, performance appraisal etc. significantly influence employee performance and engagement in academic settings (Yadav et al., 2025).



HR practices should be designed insuch a way that employee behavior and organizational goals are aligned. Effective HR practices can lead to enhanced motivation, commitment, and organizational performance (Saks, 2022). Employee engagement activities (such as flexible work arrangements, participative decision making etc.) increase the sense of psychological ownership and commitment among employees (Bakker &Demerouti, 2017).Employee involvement is a driver of tangible performance benefits. Involved employees generally demonstrate higher level of job satisfaction (Ariani, 2013), stronger organizational commitment (Meyer & Allen, 2004), increased innovation (Jiang, Lepak, Hu, & Baer, 2012), and lower employee turnover (Ismail &Warrak, 2020).

A. Aims and Objectives

The Literature review aims to answer the following questions:

- What is the role of HRM in organizations?
- How do Human Resource practices impact the performance of employees?
- What are the different HRM factors that influence the performance of employees?

B. Research Framework

Figure1. showcases the research model used for this Systematic Literature Review. This review aims to identify the relationship between Human Resource practices like (recruitment/selection, compensation, training and performance appraisal) and performance of employees.

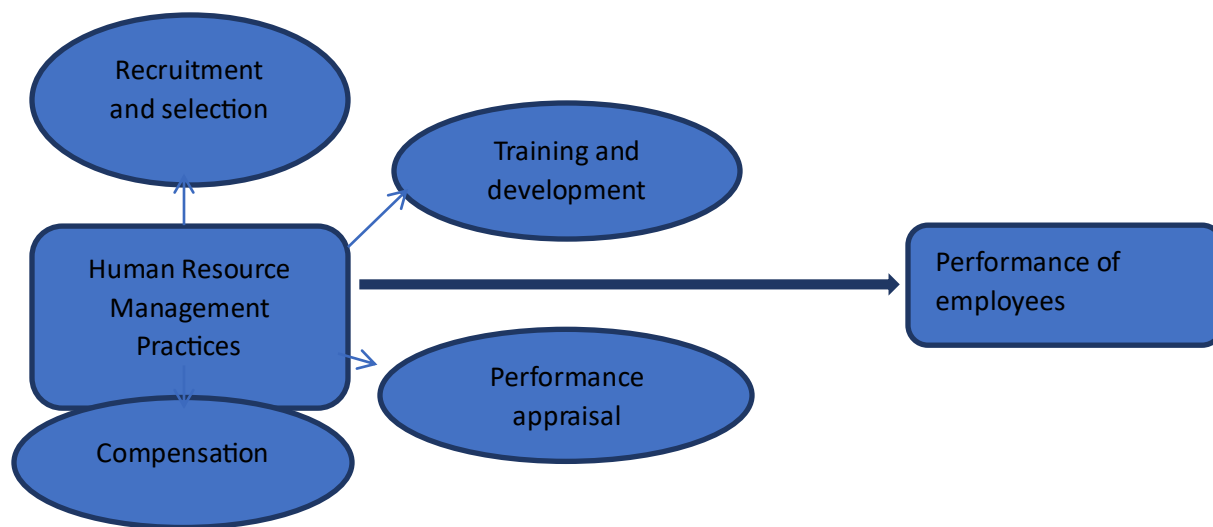


Fig1. Research Model

3.Methodology

a. Research strategy and Data collection

In this systematic literature review extensive literature from relevant domain were identified and studied. This study uses secondary data. Literature search was done among papers that tend to establish relationship between Human Resource practices and employee's performance. The papers were selected from different databases like Science Direct, Google scholar, Research Gate, Google and several journals in this domain

Sl. No.	Name of Journal
1	The International journal of human resources management
2	European Journal of Innovation Management
3	European Journal of Business and Management Research



4	European Journal of Management and Business Economics.
5	International Journal of Economics, Commerce and Management
6	South African Journal of Human Resource Management
7	OPUS: HR Journal
8	Personnel Review
9	Frontiers in Psychology
10	International Journal of Business Administration
11	Journal of Occupational Health Psychology

Table: List of Journals from where the literature was selected.

b. Keywords and subwords were used to search the database. These were :

Keywords	Impact of Human Resource practices on employee's Involvement and engagement level
Sub words	Employee performance, Organization performance, Employee motivation, HR policies, Human Resources practices, recruitment and selection, training and development, appraisal and compensation policy.

c. Inclusion and exclusion criteria

Inclusion criteria:

The literature selected for this systematic review met the following criterion:

- Empirical papers related to domain of HRM
- Language used was English.
- Publication year was 2015 to 2024.
- Studies HRM practices and which tries to establish its impact on employee performance to some extent.

Exclusion criteria:

- Literature that failed to establish relationship between Human Resource variables and employee's performance.
- Literature with no significant discussion on the topic.
- Grey literature has been excluded.
- Conceptual papers have been excluded

C. Results

The significant results analyzed after studying different literatures are summarized in the table below.

Most of the literatures show that there is a direct relationship between Human Resource practices and employee's performance. Most of the literature suggests that when employees are provided with a safe and productive work environment and are treated well, their productivity increases. It also increases the commitment, loyalty and competence of the employees.

Author/Year	Sample's content	Result
Rana, S. (2015)	High Involvement HR practices and employee involvement	There has been a positive correlation between high involvement work practices and employee's involvement and engagement
Saira Hassan (2016)	HRM practices and employee performance	HRM practices like Compensation, Performance Appraisal and Training have appositve impact on employee involvement and performance.
Jiang et al. (2017)	Ability Motivation Opportunity framework and HR practices	Studied HR Practices in the light of AMO framework and established that HR



		practices have an impact on employee involvement and innovation.
Chahar&Hatwal (2018)	HRM, Employee engagement and Employee performance	Good HR practices increase employee engagement and their performance
Fletcher et al. (2018)	Perception about training and development , Employee engagement	Positive training and development perceptions will lead to high employee engagement and satisfaction.
Al-dalahmeh et al. (2018)	Employee, engagement, employee performance and satisfaction	HR practices improves satisfaction level of employees which in turn results in better performance from them.
Bos-Nehles&Veenendaal (2019)	Human Resource practices and innovative work behavior	Study was conducted in context of Dutch manufacturing firms and a positive relationship between HR practices and innovative work behavior of employees was established.
Bayazit&Bayazit (2019)	Flexible HR practices and employee wellbeing	Study was conducted in Turkish firms and a it was observed that there is a positive relationship between flexible HR practices and employee wellbeing
Oliveira Keating et al. (2020)	Green HRM and Employee engagement	Green and Sustainable HR practices have a positive impact on employee engagement
Sinaga,S.P.H.,etal(2020)	HRM and Employee performance	Knowledge management and HRM have a positive and direct impact on employee performance.
Putra,M.R.,& Gupron,G. (2020)	Employee performance	Human resources management effect positively and indirectly on employee performance. They act as motivational force.
Ohud.A.Altalhi(2021)	HRM and employee Performance	Human resource Management practices have a direct impact on employee's performance.
Taslim et al. (2021)	AI driven HR system and Employee involvement	In AI driven systems employee involvement plays an important role in ensuring ethics and performance.
Rabiul et al. (2021)	HR practices and employee's psychological states	Study was conducted in Malaysian context and it was observed that good HR practices can enhance the feeling of safety and availability and increase employee engagement.
Kraus et al. (2021)	Strategic HRM practices and employee innovation	Strategic human resource practices lead to employee innovation.
Ngozi et al. (2022)	Employee engagement and talent retention	Good HR practice leads to employee retention.
Adula,M.,Kant,S.,&Birbirs ,Z.A.(2022)	HRM	Human resource Management has a positive influence and indirectly impacts employee performance through organizational performance.
Papalexandris&Panayotopoulou, 2022	Strategic HRM	Strategic HRM can increase employee involvement by using participation mechanisms.
Abuhantash,A.(2023).	HR Practices andperformance of employees	There is a positive correlation between human resource spracticeson performance



		of employees. Employee's performance can be increased if they are monitored.
Triansyah, F.A., Hejin, W., & Stefania, S. (2023)	Employee performance and HR practices	HRM practices have a positive influence on employee engagement and performance
Silalahi et al., 2024	HR practices and Employee resilience	In dynamic organizational settings, good HR practices can positively impact employee's resilience.
Al-Taie and Khattak (2024)	Impact of Organizational support on work behavior	When organizational support is bundled with good HR practices it leads to innovative work behavior

Table: Results of included articles and papers (compiled by author)

4. Results and discussion

The extensive study of literature demonstrates a direct and positive relationship between HR practices and employee involvement. Effective and efficient HR practices lead to high employee involvement and engagement levels. Organizations should strive hard in order to improve their HR practices so as to achieve high employee involvement levels. Dissatisfaction among employees is a resultant of toxic work culture. This dissatisfaction leads to low employee involvement and performance levels. Employee's productivity decreases and lead to problems like performance issues, high absenteeism, high employee turnover etc. Although some studies have shown that there is no direct relationship but this may be due to some other factors as well. Organizations should aim to have a work culture that is free of toxicity and should adopt good HR practices so as to keep the employees motivated and performing.

5. Conclusion:

At the end of the systematic literature review, it can be concluded that there is a positive and direct relationship between Human Resource practices and employee involvement/engagement levels. This increases their commitment and performance levels. Human resource is the most important resource of the organization. It is the most complex as well. Thus, Human resource management plays a vital role in providing employees with the best working conditions and keep them satisfied so as to bring out their best performance. Although, some studies have shown that there is insignificant relationship between the variables to some extent but this does not mean that they are negatively related. This may be a result of several other factors such as planning, size of organization, type of management etc. In general there is a positive relationship between human resource practices and employee performance. Out of 64 identified articles, 22 articles were selected for study and almost all of them have established a direct relationship between human resource practices and employee motivation and performance. Toxicity of workplace results in dissatisfaction among employees which leads to decreased productivity and performances. Good human resource practices leads to high engagement and involvement levels of employees which leads to increased productivity.

References

1. Abuhantash, A. (2023). The Impact of Human Resource Information Systems on Organizational Performance: A Systematic Literature Review. *European Journal of Business and Management Research*, 8(3), 239-245.
2. Al-Taie, A. A. M., & Khattak, M. N. (2024). High-commitment human resource practices and innovative work behavior in higher education institutions in the UAE: The moderating role of gender. *Frontiers in Psychology*, 15, 1401916. <https://doi.org/10.3389/fpsyg.2024.1401916>.
3. Ariani, D. W. (2013). The relationship between employee engagement, organizational citizenship behavior, and counterproductive work behavior. *International Journal of Business Administration*, 4(2), 46–56.
4. Bakker, A. B., & Demerouti, E. (2017). Job demands–resources theory: Taking stock and looking forward. *Journal of Occupational Health Psychology*, 22(3), 273–285.
5. Bayazit, Ö., & Bayazit, M. (2019). The impact of flexible work arrangements on work–family conflict, health, and family-supportive culture. *International Journal of Human Resource Management*.
6. Benson, G. S. (2013). *Employee Involvement: Research Foundations*. Center for Effective Organizations.
7. Bos-Nehles, A., & Veenendaal, A. (2019). Employee perceived HR practices and innovative work behavior: The role of innovative climate. *International Journal of Human Resource Management*.



8. Boxall, P., & Purcell, J. (2016). *Strategy and Human Resource Management* (4th ed.). Palgrave Macmillan.
9. Chahar, B., & Hatwal, V. (2018). Human Resource Management practices and its impact on employees' engagement and performance. *OPUS: HR Journal*, 9(1), 16–35.
10. Fletcher, L., Gkorezis, P., & Theodorou, M. (2018). Employee perceptions of training and development and its relationship with engagement, job satisfaction, anxiety, and retention. *International Journal of Human Resource Management*.
11. Ismail, T., & Warrak, E. (2020). Employee involvement and retention: Evidence from Lebanese organizations. *International Journal of Human Resource Management*, 31(8), 1–20.
12. Jiang, Y., Wang, C., & Lepak, D. P. (2017). High-performance work systems and organizational effectiveness: The mediating role of social capital. *Personnel Review*, 46(5), 828–845. <https://doi.org/10.1108/PR-09-2016-0257>
13. Khan, M. A., Nawaz, A., & Ali, A. (2020). *Impact of HR practices on employee involvement: Evidence from emerging economies*. *International Journal of Human Resource Studies*, 10(2), 45–61.
14. Kraus, S., Denyer, D., Tranfield, D., et al. (2021). Innovation and human resource management: A systematic literature review. *European Journal of Innovation Management*.
15. Meyer, J. P., & Allen, N. J. (2004). TCM employee commitment survey academic users guide 2004. *London, Ontario: University of Western Ontario*.
16. Oliveira, K., Keating, L., & Silva, M. (2020). An innovative strategic human resource management in uncertain world: A systematic literature review. *Social and Political Issues on Sustainable Development in the Post Covid-19 Crisis* (pp.235-246).
17. Papalexandris, N., & Panayotopoulou, L. (2022). Employee involvement and participation in multinational companies: The role of HR. *Administrative Sciences*, 12(1), 41. <https://doi.org/10.3390/admsci12010041>.
18. Rabiul, M. K., Mohamed, A. E., Patwary, A. K., Yean, T. F., & Osman, S. Z. (2021). Linking human resources practices to employee engagement in the hospitality industry: the mediating influences of psychological safety, availability and meaningfulness. *European Journal of Management and Business Economics*.
19. Rana, S. (2015). High-involvement work practices and employee engagement. *Human Resource Development International*, 18(3), 308–316.
20. Saks, A. M. (2022). Caring human resources management and employee engagement. *Human Resource Management Review*, 32(3), 100-110.
21. Silalahi, S. A., Hutagalung, R., & Nasution, D. (2024). The role of high-involvement HRM practices in building employee resilience. *Administrative Sciences*, 14(11), 292. <https://doi.org/10.3390/admsci14110292>
22. Taslim, H., et al. (2021). Employee involvement in AI-driven HR decision-making: A systematic review. *South African Journal of Human Resource Management*.
23. Yadav, M., Bhakar, S., & Upadhyay, Y. (2025). Impact of HRM practices on employee engagement and employee performance with special reference to academicians and work professionals. *Research Gate*.



DOIs:10.2015/IJIRMF/ICICSF-2025-P44

--:--

Research Paper / Article / Review

International Conference On “Innovative Convergence for Sustainable Future”

Date : 12 - 13 December, 2025

(ICICSF-2025)



Understanding The Role Of Fintech In Transforming Financial Services

¹**Dr. Neha Chandra**, Associate Professor of Department of Management, Jharkhand Rai University

²**Soni Kachhap**, Student, (BBA), Jharkhand Rai University

Jharkhand Rai University, Ranchi

Email – kachhapsoni26@gmail.com

Abstract: The rapid growth of Financial Technology (Fintech) has significantly transformed the traditional financial services landscape in India. The integration of digital tools such as mobile banking, UPI payments, online lending platforms, and automated financial systems has reshaped how individuals and businesses access and manage financial services. This research aims to examine the role of fintech in modernizing financial services, with a specific focus on its impact on banking, lending, and payments. The study also evaluates user awareness, adoption patterns, satisfaction levels, and key challenges associated with fintech usage.

A descriptive research design was adopted, and primary data was collected through a structured questionnaire distributed to respondents across various age groups, genders, and occupations. The findings reveal that young adults, particularly those aged 18–25, are the highest adopters of fintech services due to their familiarity with technology and frequent digital interactions. The study also shows almost equal participation across genders, indicating widespread acceptance of fintech platforms. Students formed the largest user category, suggesting that fintech has become an integral part of everyday transactions among the youth.

Overall, the study concludes that fintech is playing a transformative role in India's financial ecosystem by making services faster, more accessible, and more customer-centric. However, for sustainable growth, greater regulatory oversight, improved cybersecurity measures, and enhanced digital awareness are essential. The research highlights strong future potential for fintech in driving financial inclusion and shaping the future of digital finance in India.

Key words: Fintech, Cyber Security, Digital Finance, UPI payments, Financial Technology.

1. INTRODUCTION

Financial Technology, commonly known as *Fintech*, refers to the use of digital tools and technology to provide financial services in a faster, easier, and more convenient way. Today, people no longer depend only on bank branches for tasks like sending money, checking balances, paying bills, or applying for loans. Fintech applications such as UPI apps, digital wallets, mobile banking, and online lending platforms have made these activities simple and instant.

Fintech has changed the way we handle money. Instead of standing in long queues or filling out paperwork, customers can make transactions with just a smartphone. Services like UPI, internet banking, QR code payments, and digital loan apps have made financial services more accessible to everyone. This shift has not only improved convenience but has also encouraged more people to use banking and financial services.

In India, fintech has grown very quickly because of cheaper internet, widespread smartphone usage, and government initiatives that support digital payments. Fintech also helps people who previously did not have access to banking, especially in rural or remote areas. It gives them the ability to send money, save safely, and access small loans.



Although fintech offers many benefits, it also brings challenges such as cyber fraud, data privacy issues, and the need for digital literacy. Many people still hesitate to use digital platforms because they fear online risks or do not fully understand how fintech works.

Therefore, this study focuses on understanding how fintech is transforming financial services, what changes it brings to banking and lending, how users perceive these changes, and what challenges need to be solved in the future. The study aims to provide a simple and clear explanation of how fintech is shaping the financial world and what role it will play in the coming years.

2.LITERATURE REVIEW

Pandey, Gupta Yadav (2025)

This review presents a hybrid methodological approach to mapping fintech's transformative role in financial services, with particular emphasis on the Indian context. Pandey et al. explore advancements in digital payments, loan origination, and investment platforms. They note the accelerating adoption of mobile wallets, e-KYC processes, and peer-to-peer lending. While fintech enhances financial inclusion and access, the authors discuss obstacles in data security and regulatory harmonization. Their synthesis underscores the importance of ongoing innovation and adaptive regulation to support the sector's growth.

Madhuri, A. (2024)

This literature review explores the key areas of innovation brought about by fintech, including payment systems, lending practices, investment management, and regulatory challenges. The integration of technology into finance has not only enhanced operational efficiencies but has also led to the creation of new business

models that challenge traditional banking practices, highlighting the need for a comprehensive understanding of fintech's role in the modern financial landscape.

Bhatt (2022)

Bhatt's hybrid review uses bibliometrics and thematic analysis to decode the interconnectedness of fintech, digitalization, and financial services. The author elaborates on the convergence of artificial intelligence, blockchain, and cloud computing, which collectively

transform financial institutions. Bhatt finds increased innovation, improved service efficiency, and expanded access are outcomes of this digitalization. The review suggests researchers examine regulatory adaptation and consumer protection as essential factors for fintech-driven transformation, spotlighting the rapid pace of technological change in global finance.

Jha (2024)

Jha offers a systematic review of fintech's influence on financial inclusion. The study examines digital wallets, micro-lending, and mobile banking, concluding these innovations have democratized financial access for marginalized populations, especially in developing countries. Jha highlights how regulation and technological literacy play pivotal roles in fintech's adoption and effectiveness. Barriers such as consumer mistrust and digital illiteracy persist, indicating areas for policy intervention and financial education. Overall, fintech is recognized for bridging gaps in the accessibility of banking and financial products.

Milian, Spinola & de Carvalho (2019)

This literature review explores the diverse landscape of fintech innovations, mapping how technologies such as blockchain, crowdfunding, and neo-banking challenge financial system incumbents. Milian et al. stress that fintech's disruptive power arises from rapid digital adoption and changes in consumer behavior. Their analysis underscores the need for institutions to pursue open innovation, strategic partnerships, and regulatory compliance. The review identifies research gaps in customer trust and operational risks, emphasizing the ongoing interplay between technology and policy.

Giglio (2022)

Giglio surveys a broad spectrum of fintech research, categorizing trends by technology, innovation, and market evolution. The author notes fintech's contribution to reducing entry barriers and facilitating new business models, particularly in insurance, lending, and payments. According to Giglio, risk management through RegTech,



consumer-centric solutions, and the competitive potential of digital platforms are reshaping how financial services operate. The review calls for future research in cybersecurity, sustainability, and regulatory challenges, positioning fintech as a major driver of industry change.

3. Objective of the study:

- To analyze the role of FinTech in transforming traditional financial services.
- To examine the impact of FinTech on banking, identify the challenges and future prospects of fintech in India.

4. RESEARCH METHODOLOGY

Statement of the Problem: While India's FinTech sector is driving unprecedented transformation in financial services, the industry still faces fundamental obstacles. Regulatory uncertainty, frequent changes in compliance norms, and inconsistent governance frameworks challenge sustainable expansion. The digital divide, especially in rural and semi-urban areas, restricts the reach and impact of FinTech innovations, risking a widening gap in financial inclusion. Persistent concerns regarding data privacy, cybersecurity, and consumer protection hinder user trust. Additionally, intense market competition makes long-term growth and customer loyalty difficult for emerging FinTech ventures. This project aims to investigate solutions for overcoming these barriers and maximizing the sector's national benefits.

The data gathered for research is primary and descriptive approach is used for the study. Both qualitative and quantitative methods are used. Convenience Sampling was used to collect data from 80-90 respondents. The primary data is collected through structured questionnaires and google forms. Google forms and questionnaires were distributed to college students, young professionals, regular users of digital banking etc.

Research Design

The study adopts a **descriptive and analytical research design**, aimed at examining the impact of fintech on financial services and understanding user perceptions.

Research Approach

A **mixed-method approach** (both quantitative and qualitative) is used:

- **Quantitative:** To measure usage patterns, satisfaction levels, and trends.
- **Qualitative:** To understand user perceptions, concerns, and experiences.

Data Sources

- **Primary Data:** Collected through structured questionnaires.
- **Secondary Data:** Collected from journals, research papers, and reports.

Sampling Design

- **Population:** Students, young professionals, business owners, and digital banking users.
- **Sampling Technique:** Convenience sampling (due to accessibility of respondents).
- **Sample Size:** Approximately 80–90 respondents.

Data Collection Methods

- Structured questionnaire using **Google Forms**
- Survey responses from fintech users
- Limited informal discussions for qualitative insights

Measurement Tools

- Likert Scale (for satisfaction and perception)
- Multiple-choice questions (for usage patterns)

Data Analysis Techniques

- **Descriptive Statistics** (percentage analysis, frequency distribution)
- **Graphical Representation** (charts and tables)



• Thematic Analysis (for qualitative responses)

Data Collection Method

Primary Data:

- Small group discussions with target segments (such as MSME owners or digital wallet users) help in understanding collective perceptions and attitudes toward fintech solutions.
- Structured surveys (using Google Forms) are distributed to fintech users, bank customers, or professionals to gather quantitative data on usage patterns, satisfaction, adoption barriers, and demographic profiles.
- Interviews: Semi-structured or structured interviews with fintech executives, bankers, regulators, and subject matter experts allow deeper qualitative insights into challenges, strategies, and emerging trends.

Options	Below 18	18-25	26-35	36-45	46-55	Above 55
Responses	13	38	11	11	10	3
Percentage	15.1%	44.2%	12.8%	12.8%	11.6%	3.5%

Interpretation: The data shows that the 18–25 age group dominates the survey with 44.2%, indicating that young adults are the primary users of fintech services. Moderate participation is seen among the 26–45 age groups, reflecting steady adoption among working professionals. Very low responses from the 46+ groups suggest limited fintech usage among older individuals due to lower digital familiarity.

Options	Male	Female	Prefer not to say	Other
Responses	38	37	8	3
Percentage	44.2%	9.3%	9.3%	2.5%

Interpretation: The gender distribution shows a near-balanced participation, with males (44.2%) and females (43%) representing almost equal shares. This indicates that fintech usage is widespread across both genders. A smaller segment (9.3%) preferred not to disclose gender, while only a very small percentage identified as other, showing limited representation from non-binary groups.

Options	Student	Working Professional	Business Owner	Other
Responses	51	11	20	4
Percentage	59.3%	12.8%	23.3%	3.4%

Interpretation: The data shows that students form the majority (59.3%), indicating that younger and tech-savvy individuals are the primary users of fintech services. Business owners (23.3%) also represent a significant portion, suggesting active use of digital payments for transactions. Working professionals (12.8%) form a smaller segment, while very few respondents fall under the 'Other' category.

Other	UPI Payments	Mobile Wallets	Online Banking	Digital Lending	Investment	Insurance	None
Responses	60	16	15	7	16	8	7

Interpretation: The chart clearly shows that UPI-based payments are the most widely used fintech service, with the highest number of responses. Moderate usage is seen for mobile wallets, online banking, and investment apps, indicating diverse fintech adoption. Digital lending and insurance services show relatively lower usage, reflecting limited reliance on these services among respondents.

Other	Multiples time a day	Once a day	Few times a week	Rarely	Never
Responses	65	3	11	2	5
Percentage	75.6%	3.5%	12.8%	2.3%	5.8%

Interpretation: The data shows that 75.6% of respondents use UPI multiple times a day, highlighting the deep integration of digital payments into daily routines. A smaller portion uses UPI once a day (around 3–4%) or a few times a week (12.8%), indicating occasional usage. Very few respondents use UPI rarely or never, showing that digital payments have become almost universal.

Options	Google Pay	PhonePe	Paytm	Banking Pay	Other
Responses	23	37	13	5	8
Percentage	26.7%	43%	15.1%	5.8%	9.3%

Interpretation: The chart shows that PhonePe is the most widely used fintech app (43%), making it the preferred



choice among respondents. Google Pay follows with 26.7%, indicating strong usage due to its simplicity and reliability. Paytm (15.1%) has moderate adoption, while banking apps and other platforms are used by a smaller percentage of users.

Options	Very Easy	Easy	Neutral	Difficult	Very Difficult
Responses	37	25	23	1	0
Percentage	43%	29.1%	26.7%	1.2%	0%

Interpretation: The results show that most respondents find online banking easier than traditional banking, with 43% rating it “Very easy” and 29.1% rating it “Easy.” A quarter of respondents (26.7%) feel neutral, indicating neither major benefits nor difficulties. Only a very small percentage finds online banking difficult or very difficult, showing strong acceptance of digital banking services.

Options	Yes	No	Not Sure
Responses	61	8	17
Percentage	70.9%	9.3%	19.8%

Interpretation: A large majority (70.9%) of respondents believe that fintech apps significantly reduce the need to visit a physical bank branch, showing strong reliance on digital services. Only 9.3% feel fintech does not reduce branch visits, while 19.8% are unsure. This indicates that fintech has remarkably improved convenience and accessibility in banking.

Options	Very Satisfied	Satisfied	Neutral	Unsatisfied	Very Unsatisfied
Responses	17	30	31	3	5
Percentage	19.8%	34.9%	36%	3.5%	5.8%

Interpretation: The majority of respondents expressed positive satisfaction with fintech-based banking services, with 34.9% “Satisfied” and 19.8% “Very Satisfied.” About 36% remain neutral, indicating neither strong satisfaction nor dissatisfaction. Very few respondents reported dissatisfaction, showing that fintech banking is widely accepted and meets user expectations.

Options	Yes	No
Responses	40	46
Percentage	46.5%	53.5%

Interpretation: The results show that 53.5% of respondents have not used online lending or BNPL services, while 46.5% have used them. This indicates a nearly balanced usage pattern, with digital lending gaining popularity but still facing hesitation among some users due to trust, interest rates, or awareness issues.

Options	1	2	3	4	5
Responses	7	6	29	13	10
Percentage	10.8%	9.2%	44.6%	20%	15.4%

Interpretation: Among users of digital lending services, most respondents rated their satisfaction as average (44.6%), suggesting that the experience is functional but not exceptional. Around 20% were satisfied and 15.4% very satisfied, indicating a positive overall trend. A smaller share—10.8% very unsatisfied and 9.2% unsatisfied—shows that some users faced issues such as high interest rates, processing delays, or hidden charges.

Options	Yes	No	Maybe
Responses	57	7	22
Percentage	66.3%	8.1%	25.6%

Interpretation: A large majority of respondents (66.3%) believe that digital lending is faster than traditional bank loans, reflecting strong confidence in fintech loan platforms. Meanwhile, 25.6% responded “Maybe,” showing that some users are uncertain about speed differences. Only 8.1% stated “No,” indicating very few people feel traditional loans are faster.

Options	Very Secure	Moderately Secure	Neutral	Slightly Insecure	Very Insecure
Responses	15	31	29	11	0
Percentage	17.4%	36%	33.7%	12.8%	0%

Interpretation: Most respondents feel safe while making online payments, with 36% feeling moderately secure and 17.4% feeling very secure. A significant portion (33.7%) is neutral, indicating mixed or uncertain perceptions of security. Only 12.8% feel slightly insecure, and almost none feel very insecure, showing overall strong trust in



digital payment systems.

Options	Data Privacy	Cyber Fraud	Technical Issues/ Glitches	Lack of Trust	Hidden Charges	No Concerns
Responses	28	34	34	21	10	9

Interpretation: The data shows that the major concerns users have about fintech apps are cyber fraud and technical issues, both selected by the highest number of respondents. Data privacy is also a significant worry, reflecting users' sensitivity toward personal and financial information. Concerns like lack of trust, hidden charges, and no concerns have lower responses, indicating that issues differ based on individual experiences.

Options	Yes	No	Partially
Responses	42	31	13
Percentage	48.8%	36%	15.1%

Interpretation: The data reveals that 48.8% of respondents have faced fraud or payment failure, indicating a significant level of risk experienced while using fintech services. 36% have not faced any issues, showing that many users still have smooth digital payment experiences. Meanwhile, 15.1% experienced issues partially, meaning occasional or minor problems.

Options	Yes	No	Maybe
Responses	32	18	36
Percentage	37.2%	20.9%	41.9%

Interpretation: The responses show mixed views on whether fintech will fully replace traditional banking. While 37.2% believe it will, the majority are uncertain, with 41.9% choosing "Maybe." A smaller segment (20.9%) does not believe fintech can completely replace traditional banks, indicating trust in the continued relevance of conventional banking systems.

Rate the overall impact of fintech on the financial system.

Options	1(Very Low)	2	3	4	5(Very High)
Responses	1	7	29	33	16
Percentage	1.2%	8.1%	33.7%	38.4%	18.6 %

Interpretation: The majority of respondents rated the impact of fintech on the financial system as high, with 38.4% choosing 4 and 18.6% choosing 5 (Very High). A considerable portion (33.7%) rated it as moderate, reflecting balanced awareness of both benefits and limitations. Only a small percentage (8.1%) rated the impact low, showing strong overall belief in fintech's positive influence.

5.Findings:

- Young individuals (18–25) are the dominant users of fintech services, representing the largest age segment.
- Gender participation is balanced, with almost equal responses from males and females.
- Students make up the majority of users, showing that fintech adoption is highest among younger, digitally active groups.
- Business owners use fintech moderately, mostly for transactions.
- UPI dominates fintech usage.
- Digital payments are habitual and widely accepted.
- Strong user comfort with digital banking and very few face difficulties.
- Digital services significantly reduce physical banking. Only a small portion still prefers branch visits.
- High satisfaction indicates strong trust in fintech banking. Neutral users show potential for improvement.
- Digital lending adoption is growing. Some users still hesitate due to trust or cost.
- Digital lending offers convenience but needs better transparency. Positive satisfaction trends are emerging.



- Speed is the major advantage of fintech lending.
- High trust in digital payment safety.
- Security and reliability are major user worries.
- Security issues affect nearly half of users. Though many users have smooth experiences
- Users see strong growth in fintech but are uncertain about full replacement. Traditional banks remain relevant to some users.
- Fintech is viewed as highly beneficial.

6.RECOMMENDATIONS

For the better functioning of Financial Services, everyone including users, Fintech companies, Financial Institutions, Banks, Government should work together. Fintech Companies should improve cybersecurity measures, strengthen authentication, reduce technical glitches, improve customer support. This will help in building trust among the users. Banks and Financial Institutions should focus on strengthening partnerships with fintech companies to deliver faster and more innovative financial products. They should try to adopt AI and automation to speed up services like loan approvals and fraud detection. Users should avoid sharing OTP, or personal data with anyone. They should immediately report any kind of fraud or failed payments to banks. Strict policies should be made by governments for digital lending apps to prevent the misuse and ensure consumer protection. More digital awareness programs should be adopted. Digital literacy campaigns should be held on regular basis to educate the users.

7.CONCLUSION

The study concludes that fintech has brought significant transformation to India's financial services ecosystem. UPI, mobile banking, online payments, and digital lending have become an integral part of daily life, especially among younger users. Fintech has improved financial services by improving speed, convenience, accessibility, transparency and efficiency, reducing the reliance on traditional bank branches.

Traditional banking processes, which often involve paperwork, long waiting times, and branch dependency, are increasingly being replaced by digital platforms that provide instant services, seamless transactions, and 24×7 availability. This shift highlights a broader transition toward a digital-first financial system where technology plays a central role in service delivery.

Although satisfaction levels are high, digital lending still shows mixed experiences due to concerns around interest rates, transparency, and customer support. Security remains a major challenge, with many users reporting fraud attempts and payment failures.

Despite these challenges, the overall perception of fintech's impact is highly positive. Users believe fintech will continue to grow, but may not fully replace traditional banks soon mainly because many still value trust, security, and physical presence associated with traditional banking.

The role of regulation is also important. A balanced regulatory framework is required to support innovation while ensuring user protection and responsible business practices. As fintech grows, regulatory institutions must continuously adapt to new technologies and evolving digital models.

Overall, the study concludes that fintech is reshaping financial services by promoting digital innovation, enhancing customer experience, and encouraging more inclusive financial ecosystems. While challenges remain, the potential for growth and improvement is tremendous. With ongoing technological advancements and continued focus on security and user awareness, fintech is expected to play an increasingly significant role in shaping the future of financial services.

REFERENCES

1. Madhuri, A. "The role of fintech in transforming financial services." unified visions (2024): 252.
2. Pandey, D.K., Gupta, S., & Yadav, R.K. (2025). FinTech literature reviews: A hybrid approach. Journal of Innovation & Knowledge.
3. Jha, S. (2024). Fintech services and financial inclusion: a systematic literature review. Journal of



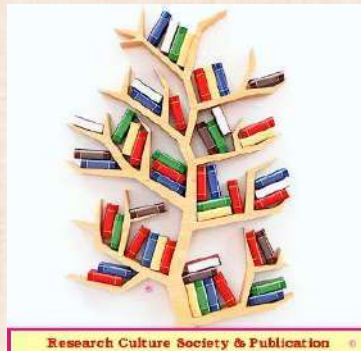
Science and Technology Policy Management, 16(7), 1167–1184.

4. Bhatt, A. (2022). Decoding the trinity of Fintech, digitalization and financial services: A hybrid bibliometric and thematic review. *Cogent Economics & Finance*, 10(1), 2114160.
5. Giglio, F. (2022). Fintech: A Literature Review. *International Business Research*, 15(1), 80–91.
6. Milian, E.Z., Spinola, M. de M., & de Carvalho, M.M. (2019). Fintech: A literature review and research agenda. *Journal of Innovation & Knowledge*, 4(2), 116–129.

Benefits to publish in IJIRMF:

- ❖ IJIRMF is an Open-Access, Scientific, Peer-reviewed, Refereed, Indexed, International Journal with wide scope of publication.
- ❖ Author Research Guidelines & Support.
- ❖ Platform to researchers and scholars of different study field and subject.
- ❖ Reliable and Rapidly growing Publication with nominal APC/PPC.
- ❖ Prestigious Editorials from different Institutes of the world.
- ❖ Communication of authors to get the manuscript status time to time.
- ❖ Full text of all published papers/ articles in the form of PDF format and Digital Object Identification System (DOIs).
- ❖ Individual copy of "Certificate of Publication" to all Authors of Paper.
- ❖ Indexing of journal in databases like Google Scholar, Academia, Scribd, Mendeley, Internet Archive and others.
- ❖ Open Access Journal Database for High visibility and promotion of your paper with keyword and abstract.
- ❖ Conference, Seminar Special Issue and Proceedings Publication.

Published By



RESEARCH CULTURE SOCIETY & PUBLICATION

Email: rcsjournals@gmail.com

Web Email: editor@ijirmf.com

WWW.IJIRMF.COM