



# Physics and Physical Principles Involved in Carbon Sequestration and Relative Scientific Practices: A Review

<sup>1</sup>Sreedevi Nimishakavi, <sup>2</sup>A. K. Singh, <sup>3</sup>Naga Aishwarya Tallapragada, <sup>4</sup>Ashok Gellu

<sup>1</sup>Assistant Professor, Department of Physics, Avanthi Institute of Engineering & Technology, Gunthapalli, Abdullapurmet, Telangana, India – 501512.

<sup>2</sup>Retired Scientist (DMRL), and Professor, Mahatma Gandhi Institute of Science and Technology, Gandipet, R. R. District, Telangana, India – 500075.

<sup>3</sup>Department of Dental Sciences, Dentist, Spelmansgatan17b, Kristinehamn, Sweden 68131

<sup>4</sup>Assistant Professor (P), Department of Environmental Science, Dr. B. R. Ambedkar Open University, Hyderabad. Email - <sup>1</sup>nsdrn2013@gmail.com <sup>2</sup>aksingh235@gmail.com <sup>3</sup>tnaishwarya1995@gmail.com <sup>4</sup>ashokgellu@gmail.com

**Abstract:** *Physics provides the fundamental understanding and tools that are necessary to develop, optimize, and monitor sustainable materials and processes for effective carbon sequestration. An attempt has been made in present work to throw some light on leveraging physics principles to capture CO<sub>2</sub> from concentrated sources, utilizing waste energy, and optimizing processes with computational modelling. Incidentally, it offers the most promising pathways for cost efficient carbon sequestration*

**Key Words:** : Carbon Sequestration, Modelling, Sustainable Materials, Physics Principles, Cost – Efficient.

## 1. INTRODUCTION:

The process of capturing and storing atmospheric CO<sub>2</sub> to reduce its concentration in the atmosphere and mitigate climate change is called carbon sequestration. Its occurrence is through natural biological process like photosynthesis in plants and trees or through geological and technological methods such as storing CO<sub>2</sub> in underground reservoirs [1].

In natural and biological sequestration plants, trees and other vegetation absorb CO<sub>2</sub> from the atmospheres, storing it as organic matter in leaves, trunks and roots. Carbon can also be stored in soils through the decomposition of organic materials [2-5]. Oceans absorb a significant amount of carbon from the atmosphere. Geological and technological carbon capture and storage (CCS) is a technology that captures CO<sub>2</sub> from industrial sources, like power plants, and injects it into deep underground formations for a long – term storage [6].

Underground storage is similar to CCS. This this encompasses storing captured carbon in geological formations like salt caverns. Enhanced natural processes focus on enhancing natural sequestration processes, for example, through land management and forestry practices. They convert it into biofuels and then capture and store the carbon released during combustion. Inject captured CO<sub>2</sub> deep underground into formations like saline aquifers or depleted oil and gas reservoirs for long term storage [7]. To prevent leaks, it requires careful engineering monitoring and adherence to safety protocols.

Mineralization is a process that uses natural chemical reactions to turn CO<sub>2</sub> into stable solid carbonates, often with minerals like basalt or olivine. Establishment of carbon markets and providing incentives to encourage investment and participation in carbon sequestration projects. Implementing robust systems, including AI-powered satellite technology, to monitor the effectiveness of different methods and guide future decisions. Research, incubating new technologies and providing training to develop the workforce needed for carbon sequestration projects is very important. International collaboration is required to share the knowledge with the other nations to implement and improve sequestration problem strategies as environmental remediation is a circular global issue [8-11].

## 2. DISCUSSION:

Bio-based materials like bio char, engineered wood and bamboo which lock carbon in their structure and novel materials such as carbon-negative cements, bio-plastics, and mycelium-based composites are the sustainable materials for carbon sequestration. Some industrial materials like fly ash and ionic liquids can also be useful for carbon capture and storage.



Physics is very useful in carbon sequestration for modelling, monitoring, and assessing potential storage sites through the application of principles like fluid dynamics, wave physics, and geophysics. It provides the tools to understand and predict how carbon dioxide (CO<sub>2</sub>) behaves underground by ensuring the processes' safety and efficiency by using methods such as seismic surveys and advanced numerical simulations [12].

Location assessment and modelling geophysics techniques like 2D (2-dimensional) and 3D (3-dimensional) seismic surveys are used to characterize potential storage sites, evaluate the integrity of the 'seal' rock, and to identify potential hazards like faults. Physics based numerical and analytical methods are used to simulate the behaviour of CO<sub>2</sub> in deep saline aquifers, predicting how it will be trapped through processes like dissolution, mineralization, and residual gas trapping [13-16].

Principles of rock physics are used to understand how rock properties, such as porosity and permeability affect the storage capacity and behaviour of CO<sub>2</sub> [17]. Monitoring and verification wave physics seismic methods which rely on the principles of wave physics, are used to monitor the movement and growth of injected CO<sub>2</sub> plumes over the time [18]. The time lapse monitoring technique uses multiple seismic surveys at different times to calculate changes in the subsurface, helping to track the CO<sub>2</sub> plume's progress [19].

Advanced techniques physics – informed machine learning is developed by researchers by developing machine learning models that incorporate physical equations into their architecture or loss function. This hybrid approach leverages the power of Artificial Intelligence for faster simulations while ensuring the physically consistent results with governing laws like Darcy's law and conservation of mass [20]. Joint inversion technique combines multiple geophysical data sets to create a more accurate and higher – resolution picture of the subsurface, helping to predict movement in a better way and fate of the sequestered CO<sub>2</sub>.

There is much to know about the use of AI in sustainable materials, as its application is growing across different areas of research, development and manufacturing. AI is used to accelerate the discovery of new sustainable materials, to decrease wastes up to 30% reduction. AI also optimizes production processes by improving energy efficiency and enable circular economy initiatives like recycling.

Physics based sustainable materials play a significant role in carbon sequestration, primarily through mechanisms like physical adsorption and mineral carbonation, often in engineered systems [21]. Principles from physics are also used in modelling and monitoring the long-term behaviour of sequestered CO<sub>2</sub> in geological formations. Physics – based materials utilize physical principles, such as surface area, porosity and molecular interactions to capture and store CO<sub>2</sub>. Physisorption captures CO<sub>2</sub> through pores. That is, physical adsorption. Zeolites are microforms aluminosilicate materials which have large surface areas and can effectively absorb CO<sub>2</sub>, especially at low pressures and temperatures. This capture process is driven by the physical structure and electrostatic interactions with cations in their pores [22-23].

Activated carbon, carbon nanotubes and graphene-based materials are excellent physio sorbents due to their high surface area and tuneable pore structures, allowing for efficient gas flow and CO<sub>2</sub> uptake [24]. Biochar, a stable form of carbon produced from biomass pyrolysis, is a sustainable example with high surface area that is effective for carbon capture in soil [25].

Researchers have developed hybrid foams made of gelatine and nano cellulose infused with a high concentration of zeolites (~ 90% by weight). The material's porous, open structure allows for high gas flows and selective CO<sub>2</sub> capture. Mineral carbonation method involves the chemical reaction of CO<sub>2</sub> with naturally occurring minerals like CaCO<sub>3</sub>. While the reaction is chemical the underlying processes of fluid flow and diffusion are governed by the physics principles.

The natural calcium silicate mineral wollastonite is highly efficient at carbon sequestration, reacting with CO<sub>2</sub> in cement-based materials to form calcium carbonate. Its incorporation can also enhance the mechanical properties and durability of sustainable concrete. In enhanced weathering projects, crushed basalt rock dust is spread on land to react with atmospheric CO<sub>2</sub>. The process leverages the large surface area of the crushed rock to accelerate natural chemical reactions [26].

The role of physics in development and monitoring physics principles also provide the foundation for the broader application of carbon sequestration technologies include modelling – simulation and geophysical monitoring. Computational physics, including molecular dynamics simulations and physics-based mechanistic models, helps in designing new materials, predicting their performance, and optimizing carbon capture and storage (CCS) processes in engineered reactors or geological formations. [27-28]

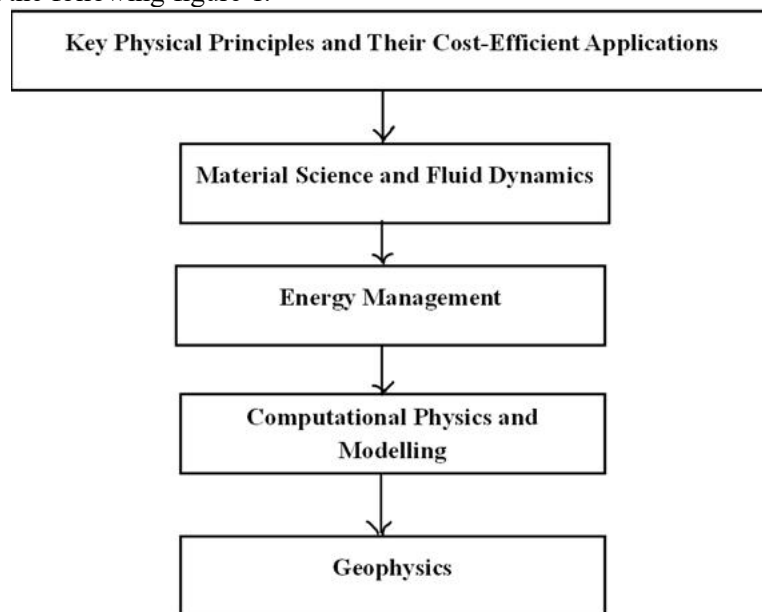
Physics is central to geological sequestration, governing how CO<sub>2</sub> is compressed, injected, and trapped underground. Key physical principles include the dynamics of multiphase flow in porous rock, which determines how the CO<sub>2</sub> moves and then displaces fluids [29]. Additionally, hydrodynamics trapping relies on the physical properties of the rock formation, where a caprock formation with low permeability traps the dense, supercritical CO<sub>2</sub> beneath it.



Techniques like time-lapse seismic surveys and ground surface deformation measurements (InSAR) are used to track the movement and long-term stability of injected CO<sub>2</sub> plumes within deep saline aquifers or depleted reservoirs [30]. These methods rely on understanding the physics of wave propagation and fluid dynamics in porous media. Physics is also vital for monitoring storage integrity through rock physics modelling that interprets seismic data to track changes in the reservoirs.

#### Cost – efficient management:

Key physical principles in carbon sequestration and their cost – efficient applications are discussed in this section [31] as shown in the following figure 1.



**Figure 1: Core Physical Principles of Carbon Sequestration.**

An ultimate physics principle is the separation of a dilute substance (CO<sub>2</sub>) from a mixture (air) inherently requires a large amount of energy to overcome entropy. A cost-efficient application approach in capturing CO<sub>2</sub> from concentrated industrial sources like power plants (where CO<sub>2</sub> can be ~ 10 – 15 % of the exhaust) is significantly more cost – effective than capturing it from the atmosphere (with only ~ 0.04% CO<sub>2</sub>). The energy penalty and associated costs are substantially lower at the source.

Physics-driven design in materials engineering helps in creating highly efficient capture mediums. The use of advanced materials like Metal-Organic Frameworks (MOFs) are specialized physic-sorbents allows for selective CO<sub>2</sub> adsorption with lower energy input for release (desorption). Specially tailored pore structures of these materials with the high surface area are specific designs using physical simulations, for improving performance and longevity, for effective operational costs.

In mineral carbonation, cost-effective, naturally abundant minerals like wollastonite are used to react with CO<sub>2</sub> to form stable carbonates, by offering a highly-efficient sequestration method when processed into a fine powder [32]. Applying the laws of energy conservation and transfer can significantly cut operational costs in energy management. Re-using ‘cold energy’ from the processing of Liquified Natural Gas (LNG) to chill air for direct capture (DAC) allows physi-sorbents to work more efficiently by removing water vapour, thus avoiding expensive water-removal steps and leveraging otherwise wasted energy.

Physics-informed machine learning models and simulations can predict outcomes faster and more cheaply than the traditional methods. Using advanced computational techniques, like physics-informed neural networks (PINNs), which helps in cost-effectively identified and asses, that are suitable underground geological storage sites for safe, long-term sequestration [33]. These models optimize site selection, injection rates, and monitoring programs, by reducing the need for extensive and expensive field characterization.

Thorough understanding of the physics behind the fluid flow through porous media is essential for secure geological storage. The physical properties of the site (high permeability, porosity) in deep saline formations can increase CO<sub>2</sub> injection rates and storage potential that in turn reduces overall costs [34]. To ensure containment geophysical methods like time-lapse seismic surveys are used for cost-effective, accurate monitoring of underground CO<sub>2</sub> plumes.



### 3. CONCLUSION:

The most cost-efficient uses of physics in carbon sequestration leverage gets along the fundamental physical principles like thermodynamics and material science to optimize and reduce energy consumption, by focussing primarily on point-source capture, utilizing the by-products or baggage or waste energy, and by employing advanced computational modelling. In summary, these techniques offer the most optimising pathways for cost-efficient carbon sequestration.

### 4. CONFLICT OF INTEREST:

The authors declare that they have no competing financial interest or personal gain in this paper. This work has been done with a sheer interest on environmental remediation and conditioned physical principles involved in it. There is no other conflict of interest.

### REFERENCES:

1. Srinu Nagireddi et al. (2023): Carbon Dioxide Capture, Utilization, and Sequestration: Current Status, Challenges, and Future Prospects for Global Decarbonization. ACS publications, 4 (1).
2. K. Biswas et al. (2023): Carbon and cellulose-based nanofiller reinforcement to strengthen carbon fiber-epoxy composites: Processing, characterizations, and applications. *Front Mater.*, 9, 10.3389.
3. Xiao et al. (2021): Review of recent developments in cement composites reinforced with fibers and nanomaterials. *Front. Struct. Civ. Eng.*, 15.
4. Ajab Shir and R. Gupta (2024): Effects of pretreatment methods and physical properties of cellulose fibers on compatibility of fiber-cement composites: a review. *Smart & Sustainable Infrastructure: Building a Greener Tomorrow*, Springer Nature, pp. 253-264.
5. Prabhugouda Patil and Dr. A. Kiran Kumar 2017: Biological carbon sequestration through fruit crops (perennial crops—natural “sponges” for absorbing carbon dioxide from the atmosphere). *Plant Archives* 17 (2), pp. 1041-1046.
6. Enobong Hanson et al. (2025): Carbon capture, utilization, and storage (CCUS) technologies: Evaluating the effectiveness of advanced CCUS solutions for reducing CO<sub>2</sub> emissions. *Journal of Results in Surfaces and Interfaces*. 18, 100381.
7. Rohit Shaw and Soumyajit Mukherjee (2022): The development of carbon capture and storage (CCS) in India: A critical review. *Carbon Capture Science & Technology*. 2, 100036.
8. Jaime S. King et al., In This Together: International Collaborations for Environmental and Human Health. PMID: PMC10881263 PMID: 37655569.
9. Bressler, R. Daniel (2021): “The Mortality Cost of Carbon.” *Nature Communications* 12 (1).
10. Gardiner S (2004): “The Global Warming Tragedy and the Dangerous Illusion of the Kyoto Protocol.” *Ethics and Intergenerational Affairs*, 18, 23–39.
11. Paris Agreement, article 9, supra note 4. As part of the Paris Agreement, developed countries were urged to scale up their level of support with a concrete roadmap to achieve the goal of mobilizing US\$100 billion per year by 2020 for climate action in developing countries.
12. Kailun Chen et al. (2024): Carbon sequestration, performance optimization, and environmental impact assessment of functional materials in cementitious composites. *Journal of CO<sub>2</sub> Utilization*. 90, 102986.
13. Kumar, A., et al. (2004): Reservoir Simulation of CO<sub>2</sub> Storage in Deep Saline Aquifers. In *Proceedings of the DOE 14th Symposium on Improved Oil Recovery*, Tulsa, OK, USA, 17–21.
14. Doranehgard, M.H., and Dehghanpour, H. (2020). Quantification of convective and diffusive transport during CO<sub>2</sub> dissolution in oil: A numerical and analytical study. *Phys. Fluids*, 32, 085110.
15. Taha Rabea El-Qalamosh et al. (2023): A multi-disciplinary approach for trap identification in the Southern Meleiha Area, North Western Desert, Egypt: integrating seismic, well log, and fault seal analysis. *Geomech. Geophys. Geo-energ., Geo-resour.*, 9
16. Sreedevi N et al. (2024): A review on the impact of sustainable materials for environmental remediation. *Proceedings of the National Seminar on Science without Borders: A Multidisciplinary Vision for the Future*. Book chapter, 94-104, ISBN: 978-93-49022-03-4.
17. Yang, H.S., and Kim, N.S. (1996): Determination of rock properties by accelerated neural network. In *Proceedings of the 2nd North American Rock Mechanics Symposium*, Montréal, QC, Canada, 19–21, 1567–1572.
18. Rami Eid et al. (2015): Seismic monitoring of CO<sub>2</sub> plume growth, evolution, and migration in a heterogeneous reservoir: Role, impact, and importance of patchy saturation. *International Journal of Greenhouse Gas Control*, 43, 70-81.



19. Doughty, C. (2010): Investigation of CO<sub>2</sub> Plume Behavior for a Large-Scale Pilot Test of Geologic Carbon Storage in a Saline Formation. *Transp. Porous Media*, 82, 49–76.
20. <https://www.sciopen.com/article/10.46690/ager.2025.03.07>
21. Kailun Chen et al. (2024): Carbon sequestration, performance optimization, and environmental impact assessment of functional materials in cementitious composites. *Journal of CO<sub>2</sub> Utilization*. 90
22. Davarpanah et al. (2020): CO<sub>2</sub> capture on natural zeolite clinoptilolite: effect of temperature and role of the adsorption sites. *J. Environ. Manag.*, 275, 111229.
23. Susana Valencia (2021): *Molecules. Zeolitic Microporous Materials and Their Applications*. 26 (3) 730.
24. Xingyuan Gao et al. (2022): Carbonaceous materials as adsorbents for CO<sub>2</sub> capture: synthesis and modification. *Carbon Capture Science & Technology*. 3, 100039.
25. S. González et al. (2013): Sustainable biomass-based carbon adsorbents for post-combustion CO<sub>2</sub> capture. *Chem. Eng. J.*
26. Huang et al. (2011): Carbonation curing for wollastonite-Portland cementitious materials: CO<sub>2</sub> sequestration potential and feasibility assessment. *J. Clean. Prod.*, 211, pp. 830-841.
27. Muhammad Tawalbeh et al. (2025): Artificial intelligence and material design in carbon capture and utilization: A review of emerging synergies. *Carbon Capture Science & Technology*. 16
28. Kazim et al. (2023): Artificial intelligence application in membrane processes and prediction of fouling for better resource recovery. *J. Resour. Recover*, 1
29. Ali Saeedi (2012): *Experimental Study of Multiphase Flow in Porous Media during CO<sub>2</sub> Geo-Sequestration Processes*, 40-48, ISBN: 978-3-642-25040-8.
30. <https://doi.org/10.1002/2015WR017609>
31. Quentin Grafton et al. (2021): A global analysis of the cost-efficiency of forest carbon sequestration. 185. DOI:10.1787/e4d45973-en
32. Muhammad Imran Rashid et al. (2023): Developments in mineral carbonation for carbon sequestration. *Heliyon*, 9 (11), e21796.
33. De Gruyter (2025): Applications of physics-informed neural networks in geosciences: From basic seismology to comprehensive environmental studies. *Open Geosciences*, 202517(1), DOI:10.1515/geo-2025-0853.
34. Maryana Emad Helmi et al. (2025): Unlocking the potential of CO<sub>2</sub> storage in saline aquifers: Challenges, knowledge gaps, and future directions for large-scale storage. *Carbon Capture Science & Technology*, 16