



Eco-Friendly Biodegradation of Rice Straw Using Efficient Microbial Consortia: A Sustainable Alternative to Stubble Burning

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Abstract: Rice straw burning is a major environmental and agricultural challenge in many rice-growing regions of India, particularly in Punjab, Haryana, Uttar Pradesh, and other parts of the Indo-Gangetic plains. Open-field burning of rice residues releases greenhouse gases, particulate matter, black carbon, and other harmful pollutants, contributing to air pollution, soil degradation, climate change, and public health concerns. Therefore, sustainable and environmentally friendly approaches for rice straw management are urgently needed. This review examines the potential of **lignocellulolytic microorganisms and microbial consortia** for the biological degradation and management of rice straw. Rice straw is primarily composed of cellulose, hemicellulose, and lignin, which make its natural decomposition relatively slow. Microorganisms capable of producing lignocellulose-degrading enzymes, particularly cellulase, xylanase, and lignin-degrading enzymes, can accelerate the breakdown of these complex compounds. Bacteria and fungi, including species belonging to *Bacillus*, *Pseudomonas*, *Trichoderma*, *Aspergillus*, and other lignocellulolytic groups, have demonstrated considerable potential for rice straw decomposition.

The review highlights the mechanisms of microbial degradation, enzyme production, microbial consortia, factors affecting biodegradation, and the conversion of rice straw into nutrient-rich organic matter. Particular attention is given to the synergistic action of microbial consortia, in which different microorganisms collectively degrade cellulose, hemicellulose, and lignin more efficiently than individual strains. The review also discusses the effects of biodegraded rice straw on soil organic matter, nutrient availability, microbial activity, soil fertility, and sustainable crop production.

Microbial biodegradation offers a promising alternative to open-field stubble burning by facilitating agricultural residue recycling while reducing air pollution and greenhouse gas emissions. However, challenges related to degradation rate, microbial compatibility, environmental conditions, large-scale application, and field-level consistency need further investigation. Future research should focus on the development of efficient, stable, cost-effective, and field-adaptable microbial consortia for large-scale rice straw management. Overall, microbial biotechnology represents a promising approach for transforming rice straw from an agricultural waste into a valuable resource for **soil health, sustainable agriculture, and climate-resilient farming**.

Keywords: Rice straw; Lignocellulolytic microorganisms; Microbial consortium; Biodegradation; Cellulase; Xylanase; Lignin degradation; Stubble burning; Crop residue management; Soil fertility; Sustainable agriculture; Agricultural waste recycling.

1. INTRODUCTION

Rice (*Oryza sativa* L.) is a major food crop and an important contributor to food security, particularly in Asia. India produces large quantities of rice straw, and the short interval between rice harvesting and wheat sowing in the Indo-



Gangetic Plains often encourages rapid residue removal. Consequently, open-field burning is widely practiced in states such as Punjab, Haryana and Uttar Pradesh (Singh and Arya, 2021; Abdurakhmonov et al., 2022).

Rice straw burning releases **greenhouse gases, particulate matter, black carbon and other pollutants**, contributing to air pollution, climate change and health problems. It also causes the loss of organic carbon and plant nutrients and may adversely affect soil microbial activity and fertility (Abdurakhmonov et al., 2022; Pradhan et al., 2024; Bhagat et al., 2025). Therefore, environmentally safe methods for rice straw management are urgently needed.

Table 1. Major Components of Rice Straw and Their Biological Degradation

Component	Nature / Role in Rice Straw	Major Degrading Enzymes	Important Microbial Groups	Biological Degradation
Cellulose	Major structural polysaccharide; provides strength to plant cell walls	Cellulase – endoglucanase, exoglucanase and β -glucosidase	<i>Bacillus</i> , <i>Cellulomonas</i> , <i>Trichoderma</i> , <i>Aspergillus</i>	Cellulose is hydrolysed into simpler sugars, mainly glucose, which can be utilized by microorganisms.
Hemicellulose	Complex polysaccharide associated with cellulose and lignin	Xylanase, mannanase, β-xylosidase and other hemicellulases	<i>Bacillus</i> , <i>Pseudomonas</i> , <i>Streptomyces</i> , <i>Aspergillus</i> , <i>Trichoderma</i>	Hemicellulose is broken down into simpler sugars such as xylose and other soluble compounds.
Lignin	Complex aromatic polymer that provides rigidity and protects cellulose and hemicellulose from microbial attack	Laccase, lignin peroxidase (LiP), manganese peroxidase (MnP)	<i>Trametes</i> , <i>Aspergillus</i> , <i>Trichoderma</i> and ligninolytic bacteria	Lignin is oxidatively modified and degraded, exposing cellulose and hemicellulose for further microbial action.
Silica and Mineral Fraction	Contributes to the physical structure and ash content of rice straw	Mainly indirect microbial effects; decomposition of associated organic matter	Soil microorganisms and decomposer communities	Mineral components are gradually released or redistributed during decomposition and residue recycling.
Proteins and Other Organic Compounds	Minor but nutritionally important components of rice straw	Proteases and other microbial enzymes	Bacteria and fungi	Organic compounds are decomposed and contribute to microbial growth and nutrient cycling.

Source: Compiled from published studies on lignocellulolytic microorganisms and rice-straw biodegradation (Wang et al., 2011; Zheng et al., 2020; Xu et al., 2021; Wang et al., 2022).

Rice straw is a valuable **lignocellulosic biomass** consisting mainly of cellulose, hemicellulose and lignin, along with minerals, ash and silica. Its complex structure makes natural decomposition slow. However, lignocellulolytic microorganisms can produce enzymes such as **cellulase, xylanase, laccase, lignin peroxidase and manganese peroxidase**, which break down these structural components and facilitate straw decomposition (Wang et al., 2011; Zheng et al., 2020). (Table-1)

Several bacteria and fungi, including *Bacillus*, *Pseudomonas*, *Cellulomonas*, *Streptomyces*, *Trichoderma*, *Aspergillus* and *Trametes*, have been reported for their lignocellulolytic activities. Their ability to degrade different components of plant biomass makes them useful for biological residue management (Wang et al., 2011; Xu et al., 2021; Wang et al., 2022).



Individual microorganisms may degrade specific components of rice straw, but efficient decomposition generally requires complementary enzymatic activities. **Microbial consortia**, consisting of compatible microorganisms, can therefore provide synergistic degradation of cellulose, hemicellulose and lignin (Wang et al., 2011; Zheng et al., 2020). Zheng et al. (2020) developed a microbial consortium capable of degrading rice straw under low-temperature conditions, while Xu et al. (2021) reported effective lignin degradation by a functional bacterial consortium. Wang et al. (2022) also demonstrated enhanced lignin degradation using a fungal consortium containing *Trametes* species. These studies highlight the potential of selected microbial communities for efficient rice straw decomposition.

Microbial inoculation has also been investigated for compost production and field residue management. A 2022 study reported accelerated rice straw decomposition following application of a novel microbial consortium. Similarly, Zhao et al. (2024) showed that microbial inoculation enhanced straw decomposition by modifying lignocellulose-degrading microbial communities in paddy soils. Sajid et al. (2022) further demonstrated that fungal-consortium pretreatment improved lignocellulose degradation and humification during composting.

Biological degradation of rice straw can also support **nutrient recycling and soil health**. Instead of losing organic matter and nutrients through burning, decomposed straw can be returned to the soil, contributing to organic matter, microbial activity, nutrient cycling and soil fertility (Singh and Arya, 2021; Abdurakhmonov et al., 2022).

Despite its potential, microbial biodegradation is influenced by **temperature, moisture, pH, aeration, nutrient availability, microbial compatibility and incubation period**. High lignin content and the structural complexity of rice straw may also limit decomposition. In addition, inoculum stability, production cost and field performance need to be considered for large-scale application (Zheng et al., 2020; Xu et al., 2021).

Recent advances in microbial biotechnology, molecular identification, metagenomics and synthetic microbial consortia provide opportunities to develop more efficient and stable microbial systems. Such approaches may accelerate rice straw decomposition, reduce stubble burning and promote agricultural residue recycling (Zhao et al., 2024; Anveshitha et al., 2026).

Therefore, this review examines **rice straw composition, lignocellulolytic microorganisms, degrading enzymes, microbial consortia, biodegradation mechanisms, influencing factors, soil-health effects, environmental benefits, limitations and future prospects**. Particular emphasis is given to microbial biodegradation as an eco-friendly strategy for **crop-residue recycling, soil-fertility improvement, pollution reduction and sustainable agriculture**.

2. Review of Literature

Rice straw is a major lignocellulosic agricultural residue composed mainly of **cellulose, hemicellulose and lignin**. Its complex structure makes natural decomposition slow. Therefore, microbial degradation has emerged as an eco-friendly approach for converting rice straw into useful organic matter. Lignocellulolytic microorganisms produce enzymes such as cellulase, xylanase, laccase, lignin peroxidase and manganese peroxidase, which help break down these structural components (Wang et al., 2011; Zheng et al., 2020).

Wang et al. (2011) reported that a microbial consortium containing different lignocellulose-degrading microorganisms efficiently degraded complex plant biomass. Their findings highlighted the importance of cooperation among microorganisms for effective lignocellulose degradation.

Table 2. Important Lignocellulolytic Microorganisms Involved in Rice Straw Degradation

Microorganism / Group	Type	Major Enzymes / Activities	Main Function in Rice Straw Degradation
<i>Bacillus</i> spp.	Bacterium	Cellulase, xylanase	Degrades cellulose and hemicellulose and supports rapid straw decomposition.
<i>Pseudomonas</i> spp.	Bacterium	Cellulase, xylanase, ligninolytic enzymes	Contributes to cellulose, hemicellulose and partial lignin degradation.
<i>Cellulomonas</i> spp.	Bacterium	Cellulase, hemicellulase	Efficiently hydrolyses cellulose and related plant-cell-wall components.
<i>Streptomyces</i> spp.	Bacterium	Cellulase, xylanase and ligninolytic enzymes	Participates in the breakdown of cellulose, hemicellulose and lignin.
<i>Trichoderma</i> spp.	Fungus	Cellulase, xylanase, laccase	Promotes degradation of cellulose and hemicellulose and assists lignin modification.



<i>Aspergillus</i> spp.	Fungus	Cellulase, xylanase, laccase	Produces hydrolytic enzymes and contributes to lignocellulose decomposition.
<i>Trametes</i> spp.	Fungus	Laccase, lignin peroxidase, manganese peroxidase	Particularly effective in lignin degradation and improves access to cellulose and hemicellulose.
Mixed microbial consortia	Bacteria + fungi	Combined cellulolytic, hemicellulolytic and ligninolytic activities	Different microorganisms act synergistically to accelerate overall rice straw decomposition.

Source: Compiled from studies on lignocellulolytic microorganisms and microbial consortia (Wang et al., 2011; Zheng et al., 2020; Xu et al., 2021; Wang et al., 2022).

Zheng et al. (2020) developed a microbial consortium capable of degrading rice straw under low-temperature conditions. The consortium effectively degraded cellulose, hemicellulose and lignin, demonstrating its potential for accelerating straw decomposition under unfavourable conditions.

Xu et al. (2021) investigated a lignin-degrading microbial consortium and identified functional bacteria associated with rice straw degradation. Their study emphasized the importance of microbial diversity and complementary activities in efficient lignin breakdown.

Wang et al. (2022) developed a fungal consortium for rice straw lignin degradation. The consortium showed effective lignin degradation, demonstrating the potential of cooperative fungal systems for biological conversion of rice straw.

Sajid et al. (2022) reported that fungal-consortium pretreatment enhanced lignocellulose degradation and humification during rice straw composting. Their findings indicated that biological pretreatment can improve the accessibility of cellulose and hemicellulose by modifying the lignin structure.

A 2022 study reported that application of a novel microbial consortium accelerated rice straw decomposition and influenced the microbial community during the decomposition process. This approach reduced the time required for effective straw degradation and supported residue recycling.

Zhao et al. (2024) showed that microbial inoculation accelerated rice straw decomposition in paddy fields by modifying lignocellulose-degrading microbial communities. Their findings emphasized the interaction between introduced microorganisms and indigenous soil microorganisms.

Chen et al. (2024) developed a bacterial–fungal consortium for rice straw degradation and optimized conditions for efficient decomposition. The study demonstrated that cooperation between bacteria and fungi can improve the degradation of lignocellulosic components.

Recent studies have increasingly emphasized microbial consortia as an effective approach for rapid rice straw decomposition. Combining cellulolytic, hemicellulolytic and ligninolytic microorganisms can provide complementary activities and improve degradation efficiency (Anveshitha et al., 2026).

Overall, the reviewed studies demonstrate the considerable potential of **lignocellulolytic microorganisms and microbial consortia** for rice straw biodegradation. Further research is needed to improve microbial compatibility, field performance, inoculum stability and cost-effectiveness for large-scale application.

3. Selection of Microorganisms

Published studies have identified a wide range of **bacteria and fungi capable of degrading rice straw**. These microorganisms produce lignocellulolytic enzymes that act on the major structural components of straw, particularly cellulose, hemicellulose and lignin. Microorganisms showing strong degradation ability are considered useful for biological crop-residue management (Wang et al., 2011).

Cellulolytic bacteria such as *Bacillus*, *Cellulomonas* and *Pseudomonas* have been investigated for their ability to produce cellulase and other hydrolytic enzymes. These microorganisms can contribute to the breakdown of cellulose and hemicellulose, thereby increasing the availability of simpler organic compounds during straw decomposition (Wang et al., 2011; Zheng et al., 2020).

Lignin-degrading microorganisms are particularly important because lignin forms a protective barrier around cellulose and hemicellulose. Bacterial and fungal consortia containing effective ligninolytic microorganisms have demonstrated considerable potential for rice straw degradation. Studies by **Xu et al. (2021)** and **Wang et al. (2022)** showed that selected microbial consortia could effectively degrade rice straw lignin and improve overall lignocellulose



decomposition. Thus, the selection of compatible and efficient microorganisms is an important step in developing microbial consortia for rapid and sustainable rice straw biodegradation.

4. Analysis of Enzymatic Degradation

The degradation of rice straw mainly depends on the action of **lignocellulolytic enzymes** produced by microorganisms. **Cellulase** breaks down cellulose into simpler sugars, while **xylanase** acts mainly on hemicellulose. Lignin-degrading enzymes such as **laccase**, **lignin peroxidase** and **manganese peroxidase** help break down the complex lignin structure and increase the accessibility of cellulose and hemicellulose to microbial enzymes (Wang et al., 2011; Zheng et al., 2020).

The combined action of these enzymes is important because cellulose, hemicellulose and lignin are closely associated within the plant cell wall. Effective lignin degradation exposes the carbohydrate components, allowing cellulases and hemicellulases to act more efficiently. Studies on microbial consortia have shown that complementary enzyme activities can enhance the overall degradation of rice straw (Xu et al., 2021; Wang et al., 2022).

Therefore, understanding the production and activity of **cellulase**, **xylanase** and **lignin-degrading enzymes** is essential for improving microbial biodegradation of rice straw. Efficient enzyme-producing microorganisms and compatible microbial consortia may accelerate straw decomposition and support sustainable crop-residue management (Zhao et al., 2024) (Table-3).

Table 3. Important Microbial Consortia Reported for Rice Straw Degradation

Microorganisms / Consortium	Target Component	Major Findings	Reference
Lignocellulose-degrading microbial consortium	Cellulose, hemicellulose and lignin	Efficient degradation of complex lignocellulosic biomass; demonstrated the importance of synergistic microbial activity.	Wang et al. (2011)
LTF-27 microbial consortium	Cellulose, hemicellulose and lignin	Effectively degraded rice straw under low-temperature conditions, showing potential for straw decomposition under unfavourable conditions.	Zheng et al. (2020)
Lignin-degrading bacterial consortium	Mainly lignin	Showed effective rice straw lignin degradation and identified functional bacterial groups involved in the process.	Xu et al. (2021)
<i>Trametes</i>-based fungal consortium	Mainly lignin	Enhanced lignin degradation compared with individual fungal cultures and improved lignocellulose conversion potential.	Wang et al. (2022)
Fungal consortium for rice-straw pretreatment	Lignin, cellulose and hemicellulose	Improved lignocellulose degradation and humification during composting.	Sajid et al. (2022)
Novel lignocellulolytic microbial consortium	Cellulose and hemicellulose	Accelerated rice straw decomposition and influenced microbial community dynamics during decomposition.	2022 study
Microbial inoculation consortium	Cellulose, hemicellulose and lignin	Accelerated rice straw decomposition by reshaping the structure and function of lignocellulose-degrading microbial communities in paddy soil.	Zhao et al. (2024)
Bacterial–fungal consortium	Cellulose, hemicellulose and lignin	Demonstrated improved lignocellulosic degradation through	Chen et al. (2024)



		complementary activities of bacteria and fungi.	
Lignocellulolytic microbial consortia	Cellulose, hemicellulose and lignin	Recent research highlights their potential for rapid rice straw decomposition and sustainable crop-residue management.	Anveshitha et al. (2026)

6. Factors Affecting Biodegradation

The efficiency of rice straw biodegradation depends on several environmental and biological factors. The major factors influencing microbial growth, enzyme production and decomposition efficiency include **temperature, moisture, pH, aeration, nutrient availability, microbial compatibility and incubation period**. Proper conditions help microorganisms remain active and accelerate the breakdown of cellulose, hemicellulose and lignin (Zheng et al., 2020; Xu et al., 2021).

6.1. Temperature: Temperature strongly affects microbial growth and enzyme activity. Each microorganism has an optimum temperature range for effective lignocellulose degradation. Very low or high temperatures may reduce microbial activity and slow decomposition. Therefore, maintaining a suitable temperature is important for efficient rice straw degradation (Zheng et al., 2020).

6.2. Moisture: Adequate moisture is essential for microbial growth, enzyme production and movement of nutrients through the straw. Insufficient moisture restricts microbial activity, whereas excessive moisture can reduce aeration and create unsuitable conditions for some microorganisms. Proper moisture content therefore supports effective decomposition.

6.3. pH: pH influences microbial growth and the activity of lignocellulolytic enzymes. Different bacteria and fungi have different optimum pH ranges. Maintaining a suitable pH helps microorganisms produce cellulase, xylanase and lignin-degrading enzymes efficiently (Xu et al., 2021).

6.4. Aeration: Oxygen availability is particularly important for many aerobic microorganisms involved in lignocellulose degradation. Adequate aeration supports microbial respiration and enzyme production, whereas poor aeration may slow decomposition. Proper aeration is therefore important during aerobic biodegradation and composting.

6.5. Nutrient Availability: Microorganisms require nutrients such as **nitrogen, phosphorus and other minerals** for growth and enzyme production. Rice straw generally has a high carbon content and relatively low nitrogen availability. Additional nutrients may therefore support microbial multiplication and improve the decomposition process.

6.6. Microbial Compatibility: The success of a microbial consortium depends on the compatibility and complementary activities of its members. Compatible microorganisms can work synergistically, with different species contributing to cellulose, hemicellulose or lignin degradation. Incompatible microorganisms may compete with one another and reduce overall degradation efficiency (Wang et al., 2011; Zheng et al., 2020).

6.7. Incubation Period: The duration of incubation influences the extent of rice straw decomposition. Microbial populations and enzyme activities change during decomposition, and longer incubation generally allows greater breakdown of lignocellulosic components. However, the optimum period depends on the microorganisms, environmental conditions and characteristics of the rice straw (Zhao et al., 2024). (Table 4).

7. Effects on Soil Health

The use of **decomposed rice straw** can contribute to maintaining soil health by returning organic matter and plant nutrients to the soil. Published studies have examined its effects on **soil organic matter, nutrient availability, microbial activity and soil fertility**. Biological decomposition converts rice straw into more readily available organic materials, which can support nutrient cycling and improve soil quality (Singh & Arya, 2021; Pradhan et al., 2024).

Table 4. Factors Affecting Microbial Biodegradation of Rice Straw

Factor	Effect on Microbial Biodegradation	Importance
Temperature	Influences microbial growth and enzyme activity. Very low or high temperatures can slow straw decomposition.	Maintains optimum microbial and enzymatic activity.
Moisture	Adequate moisture supports microbial growth and enzyme activity, while excessive moisture may reduce aeration.	Essential for efficient microbial decomposition.



pH	Affects microbial growth and the activity of cellulase, xylanase and lignin-degrading enzymes.	Suitable pH improves enzyme production and degradation.
Aeration	Provides oxygen required by many aerobic decomposing microorganisms. Poor aeration can reduce microbial activity.	Important for aerobic straw decomposition and composting.
Nutrient Availability	Nitrogen, phosphorus and other nutrients support microbial growth and enzyme production.	Promotes microbial multiplication and residue decomposition.
Microbial Compatibility	Compatible microorganisms can work synergistically, while competition may reduce degradation efficiency.	Important for developing effective microbial consortia.
Incubation Period	Decomposition generally increases with time as microbial populations and enzyme activities act on the straw.	Determines the extent and efficiency of straw degradation.

Source: Compiled from published studies on microbial degradation of rice straw (Wang et al., 2011; Zheng et al., 2020; Xu et al., 2021; Zhao et al., 2024).

7.1. Soil Organic Matter: Decomposed rice straw adds organic carbon to the soil and helps maintain soil organic matter. Increased organic matter can improve soil structure, moisture retention and nutrient-holding capacity. Thus, recycling rice straw through biodegradation is preferable to burning, which results in the loss of organic carbon (Singh & Arya, 2021).

7.2. Nitrogen Availability: During decomposition, microorganisms transform organic nitrogen present in rice straw into forms that can participate in soil nutrient cycling. The gradual release of nitrogen from decomposed residues can contribute to plant nutrition and reduce nutrient losses associated with residue burning.

7.3. Phosphorus Availability: Microbial decomposition facilitates the release and cycling of phosphorus present in crop residues. Decomposed rice straw can therefore contribute to maintaining available phosphorus in soil and support nutrient recycling within agricultural systems.

7.4. Potassium Availability: Rice straw contains considerable amounts of potassium. During decomposition, potassium is released from the plant residue and becomes available for soil nutrient cycling. Recycling straw can therefore help return potassium to agricultural fields rather than losing it through burning.

7.5. Soil Microbial Activity: Addition of decomposed rice straw provides organic substrates that support soil microorganisms. Increased microbial activity promotes decomposition, nutrient transformation and organic-matter cycling. Microbial inoculation may further enhance these processes by stimulating lignocellulose-degrading microbial communities (Zhao et al., 2024).

7.6. Soil Fertility: The combined improvement in organic matter, nutrient cycling and microbial activity can contribute to **better soil fertility and long-term soil productivity**. Therefore, microbial decomposition and incorporation of rice straw provide a sustainable approach to crop-residue management while reducing the negative effects associated with open-field burning (Singh & Arya, 2021; Bhagat et al., 2025).

8. Environmental Benefits

Microbial biodegradation of rice straw provides an **eco-friendly alternative to open-field residue burning**. The process converts agricultural residues into useful organic matter and nutrients, thereby reducing pollution and supporting sustainable agricultural practices. The major environmental benefits include the following (Singh & Arya, 2021; Abdurakhmonov et al., 2022).

8.1. Reduction in Stubble Burning: Effective microbial decomposition provides farmers with an alternative method for managing rice straw without burning. This can reduce dependence on open-field burning and promote recycling of crop residues within agricultural systems (Singh & Arya, 2021).

8.2. Reduction in Air Pollution: Rice straw burning releases **particulate matter, carbon monoxide, nitrogen oxides and other pollutants** into the atmosphere. Microbial degradation avoids direct combustion and can therefore help reduce air pollution associated with stubble burning (Abdurakhmonov et al., 2022).



8.3. Reduction in Greenhouse-Gas Emissions: Open burning of crop residues releases greenhouse gases and black carbon. Biological decomposition can reduce the need for burning and supports the recycling of carbon within soil and biomass, contributing to more sustainable residue management (Abdurakhmonov et al., 2022; Singh & Arya, 2021).

8.4. Reduction in Soil Degradation: Unlike burning, microbial decomposition returns **organic matter and nutrients** to the soil. This can help maintain soil organic matter, microbial activity and nutrient cycling, thereby supporting long-term soil health and reducing the negative effects of repeated residue burning (Pradhan et al., 2024; Bhagat et al., 2025).

8.5. Reduction in Agricultural Waste Accumulation: Microbial consortia convert rice straw into **decomposed organic matter** that can be recycled in agricultural fields. This reduces the accumulation of crop residues and promotes the conversion of agricultural waste into a useful resource, supporting the principles of **circular and sustainable agriculture** (Zhao et al., 2024).

8.9. Future Perspectives: Future research should focus on developing **efficient, stable and compatible microbial consortia** with strong cellulolytic, hemicellulolytic and ligninolytic activities for rapid rice straw decomposition. Optimisation of microbial combinations and environmental conditions such as temperature, moisture, pH and inoculum concentration may improve degradation efficiency and consistency (Zhao et al., 2024).

Further studies are needed to develop **low-cost, field-adaptable and farmer-friendly microbial formulations** suitable for different soil and climatic conditions. Large-scale field validation, improved inoculum stability and integration with existing residue-management practices could promote wider adoption, reduce stubble burning and support sustainable agriculture (Anveshitha et al., 2026).

9. Conclusion

The reviewed literature clearly demonstrates that **rice straw biodegradation by lignocellulolytic microorganisms and microbial consortia** is a promising and environmentally sustainable alternative to open-field stubble burning. Microorganisms capable of producing **cellulase, xylanase, laccase and other lignin-degrading enzymes** can effectively break down the complex cellulose, hemicellulose and lignin present in rice straw. The synergistic action of compatible microbial consortia can further accelerate decomposition and improve the efficiency of residue recycling (Wang et al., 2011; Zheng et al., 2020; Xu et al., 2021).

Biological decomposition of rice straw not only helps reduce **air pollution, greenhouse-gas emissions and agricultural waste accumulation**, but also returns organic matter and nutrients to the soil. Decomposed straw can support **soil microbial activity, nutrient cycling, soil fertility and long-term soil health**, making microbial residue management an important component of sustainable agriculture (Singh & Arya, 2021; Zhao et al., 2024).

Overall, microbial biodegradation provides a practical approach for converting rice straw from an agricultural waste into a **valuable soil resource**. However, further research is required to develop **efficient, stable, low-cost and field-adaptable microbial consortia** and to validate their performance under different soil and climatic conditions. Wider adoption of such technologies can reduce dependence on stubble burning and contribute to **cleaner air, healthier soils, sustainable residue management and climate-resilient agriculture** (Anveshitha et al., 2026).

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