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Role of decomposer microorganisms in agricultural and horticultural waste management and nutrient recycling: A comprehensive review

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Abstract

Agricultural and plantation residues constitute a major fraction of global biomass, posing significant challenges in terms of disposal, environmental sustainability, and nutrient management. These residues are predominantly composed of lignocellulosic materials, including cellulose, hemicellulose, and lignin, which confer structural rigidity and resistance to natural degradation. Conventional practices such as open-field burning lead to severe environmental consequences, including greenhouse gas emissions and nutrient loss. Microbial decomposition has emerged as an effective and sustainable strategy for converting these residues into valuable organic inputs. This review critically examines the role of decomposer microorganisms, particularly cellulolytic and ligninolytic fungi and bacteria, in accelerating the breakdown of agricultural residues. Key microbial taxa such as *Trichoderma* spp., *Aspergillus* spp., *Penicillium* spp., *Pleurotus* spp., and *Phanerochaete chrysosporium* are discussed in relation to their enzymatic potential and decomposition efficiency. The importance of microbial consortia, nitrogen supplementation, and integration with vermicomposting systems is also highlighted. Furthermore, recent advancements in straw-decomposing inoculants (SDIs) and their synergistic interaction with nitrogen fertilizers are explored. The review concludes that microbial-mediated decomposition offers a viable pathway for sustainable residue management, improved soil fertility, and the promotion of circular bioeconomy in agriculture.

Keywords: Lignocellulosic biomass, decomposer microorganisms, composting, microbial consortia, straw decomposition, nutrient recycling, *Trichoderma*

Introduction

Agricultural waste management is a significant global challenge due to the massive generation of lignocellulosic residues and their limited utilization. Around the world, large quantities of crop residues, including rice straw, wheat straw, sugarcane bagasse, maize stover, and coconut coir pith, are produced, often exceeding the capacity for effective recycling (FAO, 2021) ^[4]. In India alone, agricultural residue generation is estimated at approximately 600–700 million metric tonnes annually, with nearly 25–30% remaining surplus and under-utilized (MNRE, 2022) ^[13]. Among these residues, rice straw is particularly significant, contributing nearly 140 million tonnes annually, a large portion of which is disposed of through open-field burning (Gadde *et al.*, 2009) ^[5].

The practice of burning these residues leads to severe environmental consequences, including emissions of greenhouse gases such as carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O), as well as particulate matter that contributes to air pollution (Sidhu *et al.*, 2007) ^[18]. In addition to environmental degradation, burning results in the loss of valuable nutrients such as nitrogen, phosphorus, and potassium, thereby reducing soil fertility.

Plantation crops also generate significant biomass. For instance, areca nut plantations produce approximately 4–6 tonnes of dry biomass per hectare annually in the form of fronds, husk, and leaf sheaths (Bhat and Sujatha, 2019) ^[11]. Similarly, coir pith, a by-product of coconut processing, is produced in quantities exceeding 7–8 million tonnes annually and is characterized by its high lignin content and resistance to degradation (Nair and Francis, 2017) ^[15].

The recalcitrant nature of these residues is primarily due to their lignocellulosic composition, which includes cellulose (35–50%), hemicellulose (20–35%), and lignin (15–30%) (Kumar *et*

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al., 2022) ^[11]. These structural polymers limit microbial accessibility and slow down natural decomposition processes, necessitating efficient strategies to accelerate the breakdown of these materials and facilitate nutrient recycling.

Microbial decomposition has emerged as a sustainable solution, in which microorganisms utilize enzymatic systems to degrade complex organic compounds into simpler forms. This review focuses on the role of decomposer microorganisms, their mechanisms of action, and their application in agricultural waste management.

Lignocellulosic biomass represents a complex matrix of polysaccharides and phenolic compounds that provide structural integrity to plant cell walls. Cellulose is a linear polymer of β -1,4-linked glucose units, while hemicellulose is a branched heteropolymer composed of various sugars such as xylose, mannose, and arabinose. Lignin, on the other hand, is an aromatic polymer that forms a protective barrier around cellulose and hemicellulose, making them less accessible to enzymatic degradation (Kirk and Farrell, 1987) ^[10].

The high carbon-to-nitrogen (C:N) ratio of agricultural residues complicates decomposition further. Microorganisms require nitrogen for growth and metabolic activity; therefore, they immobilise available soil nitrogen during decomposition, leading to competition with crops (Singh *et al.*, 2018) ^[19]. This often results in a temporary nitrogen deficiency in the soil, adversely affecting plant growth. While many people rely on chemical nitrogen fertilisers, using organic sources such as seeds, deoiled cakes from neem, pongamia, and castor can offer useful alternatives. Multiplex Annapurna, the purest form of organic manure produced in India for the past three decades, exemplifies this approach.

Conventional composting methods, which depend on natural microbial populations, are often slow, particularly for high-lignin materials such as coir pith and sugarcane trash (Bernal *et al.*, 2009) ^[2]. Thus, the use of specialised decomposer microorganisms has become important for enhancing decomposition efficiency.

Role of Decomposer Microorganisms in Residue Degradation

Cellulolytic and Ligninolytic Fungi

Fungi are the main decomposers of lignocellulosic biomass due to their ability to produce extracellular enzymes that can break down complex polymers. Cellulolytic fungi generate enzymes such as cellulases and hemicellulases, which hydrolyze cellulose and hemicellulose into simple sugars. Meanwhile, ligninolytic fungi produce oxidative enzymes, including lignin peroxidase, manganese peroxidase, and laccase, which are responsible for degrading lignin (Sánchez, 2009) ^[17].

Research has shown that fungal species such as *Trichoderma harzianum*, *Aspergillus niger*, and *Penicillium* spp. display high enzymatic activity and are effective in decomposing residues (Kim *et al.*, 2011) ^[9]. These fungi colonise plant residues and initiate the decomposition process by secreting enzymes that disrupt the lignocellulosic structure.

Trichoderma spp.

Trichoderma species are among the most widely used decomposer fungi due to their rapid growth and high cellulolytic activity.

Trichoderma harzianum

Trichoderma harzianum is one of the most extensively studied fungal decomposers due to its rapid growth and high cellulolytic

activity. This fungus produces enzymes such as cellulases and hemicellulases, which help break down the components of plant cell walls. Research has shown that inoculating compost with *T. harzianum* significantly reduces the carbon-to-nitrogen (C:N) ratio and accelerates the decomposition process (Singh *et al.*, 2018) ^[19]. Additionally, it enhances microbial activity and improves nutrient availability.

Trichoderma reesei

Trichoderma reesei is recognised for its remarkable ability to produce cellulase. This fungus plays a crucial role in breaking down cellulose into fermentable sugars. During the decomposition process, it decreases the cellulose content and increases the porosity of the substrate, thereby improving microbial accessibility (Phutela and Sahni, 2013) ^[16].

Trichoderma koningii

Trichoderma koningii contributes to lignocellulose degradation through the production of cellulolytic and ligninolytic enzymes. It reduces total carbon content and improves nitrogen concentration, leading to enhanced compost maturity (Mukhlis *et al.*, 2013) ^[14].

Trichoderma harzianum produces a wide range of enzymes, including endoglucanases, exoglucanases, and β -glucosidases, which collectively degrade cellulose (Singh *et al.*, 2018) ^[19].

In composting systems, inoculation with *Trichoderma* significantly reduces organic carbon content and C:N ratio while increasing nitrogen availability. For instance, Dhapate *et al.* (2013) ^[3] reported that inoculation of sugarcane trash with fungal cultures, including *Trichoderma*, resulted in a reduction in C:N ratio to 16.3 and an increase in nitrogen content to 1.07%.

Aspergillus spp.

Aspergillus species play a crucial role in decomposition through the production of hydrolytic enzymes such as cellulases, xylanases, and pectinases. *Aspergillus niger* has been widely studied for its ability to degrade agricultural residues and improve compost quality (Sánchez, 2009) ^[17].

Penicillium spp.

Penicillium expansum has been shown to enhance composting efficiency by accelerating lignocellulose degradation and improving microbial activity. Wang *et al.* (2011) ^[21] reported that inoculation with *P. expansum* increased decomposition rate by up to 57.5% compared to the control.

White-Rot Fungi: *Pleurotus* spp. and *Phanerochaete chrysosporium*

White-rot fungi are distinct for their ability to break down lignin. One example is *Pleurotus ostreatus*, which produces enzymes such as laccase and manganese peroxidase that facilitate efficient lignin degradation (Sánchez, 2009) ^[17]. Similarly, *Phanerochaete chrysosporium* is recognised for its enzyme system that degrades lignin, thereby increasing the accessibility of cellulose for further breakdown (Tien and Kirk, 1983) ^[20].

Bacterial Decomposers

Although fungi dominate lignocellulosic decomposition, bacteria also play an important role, particularly in later stages. *Acetobacter aceti* contributes to decomposition by oxidising ethanol into acetic acid, facilitating nutrient cycling (Kadere *et al.*, 2008) ^[7].

Microbial Consortia and Synergistic Interactions

The use of microbial consortia has been shown to significantly enhance decomposition efficiency compared to individual strains. Synergistic interactions among fungi and bacteria result in improved enzymatic activity and faster degradation of complex substrates.

Kausar *et al.* (2010) ^[8] reported that a consortium of *Aspergillus niger* and *Trichoderma viride* reduced the C: N ratio from 29.3 to 19.5 within three weeks, demonstrating rapid compost stabilisation. Similarly, Dhapate *et al.* (2013) ^[3] observed that a mixture of fungal isolates resulted in the highest decomposition efficiency, including 38% weight loss and a significant reduction in organic carbon.

Co-application of Decomposers and Nitrogen Fertiliser

The high carbon-to-nitrogen (C: N) ratio of crop residues requires nitrogen supplementation for efficient decomposition. Microorganisms need nitrogen for protein synthesis and metabolic activity; thus, a lack of nitrogen can limit decomposition and lead to competition for nutrients with crops.

In a study by Liu *et al.* (2023) ^[12], the co-application of straw-decomposing inoculants (SDIs) with ammonium nitrogen fertiliser significantly increased the decomposition rate, crop growth, and yield. The optimal treatment (IA3) resulted in a 16% increase in the decomposition rate and a 13% increase in rice yield compared to the control group.

However, excessive nitrogen application can result in nutrient loss and environmental pollution. Therefore, it is crucial to apply nitrogen in a balanced manner for optimal results.

Microbial Dynamics during Composting

Composting involves different microbial phases:

- Mesophilic phase: Initial microbial activity
- Thermophilic phase: High temperature (up to 70–80°C) with rapid decomposition
- Maturation phase: Stabilization and humification

Bacterial and fungal populations increase during the initial stages (up to 60 days) the temperature can rise up to 80 degrees during this period and which is an indicator of microbial involvement in decomposition (Dhapate *et al.*, 2013) ^[3]. During the thermophilic phase, temperature increases due to microbial activity, leading to the dominance of thermophilic organisms.

In later stages, actinomycetes become dominant and contribute to the breakdown of resistant compounds, resulting in compost stabilisation.

Integration of Microbial Decomposition with Vermicomposting

The integration of microbial inoculants with vermicomposting has emerged as an effective strategy for enhancing decomposition efficiency. Microbial pre-treatment breaks down complex polymers, making the substrate suitable for earthworm activity.

Earthworms such as *Eisenia fetida* further enhance decomposition by fragmenting organic matter and stimulating microbial activity (Joshi *et al.*, 2015) ^[6]. This synergistic interaction results in faster composting, reduced C:N ratio, and improved nutrient availability.

Environmental and Agricultural Significance

Microbial decomposition offers several environmental and agricultural benefits, including:

- Reduction in residue burning and air pollution

- Improvement in soil fertility and structure
- Enhanced nutrient recycling
- Increased crop productivity

It supports sustainable agriculture by promoting efficient resource utilization and reducing dependency on chemical fertilizers.

Conclusion

Decomposer microorganisms play a vital role in the sustainable management of lignocellulosic agricultural residues. Fungi such as *Trichoderma*, *Aspergillus*, and *Pleurotus* are highly efficient in degrading complex organic matter through enzymatic mechanisms. The use of microbial consortia further enhances decomposition efficiency through synergistic interactions.

The integration of decomposer microorganisms with nitrogen fertilization and vermicomposting represents a holistic approach to residue management. These strategies not only accelerate decomposition but also improve soil health and crop productivity.

Future research should focus on optimizing microbial formulations, improving field-level application techniques, and integrating decomposer technologies into sustainable agricultural practices.

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