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Resource Utilization of Xylan Residue: Application of Composting Techniques and Microbial Inoculants

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Abstract **Review Article**

Xylan residue is a solid waste generated from the production of xylose using raw materials such as corn cobs, and it is rich in lignocellulose, showcasing significant potential for reutilization. However, the accumulation of xylan residue poses considerable economic and environmental burdens due to the lack of effective processing technologies. This study aims to investigate the impact of lignocellulose-degrading microorganisms on the aerobic composting process of xylan residue, focusing on its physicochemical properties, maturity, and microbial diversity. The analysis also examines the influencing factors during the composting process, including temperature, pH, moisture content, oxygen concentration, and carbon-to-nitrogen ratio, highlighting the role of microbial communities at different stages. By introducing lignocellulose-degrading microbial strains, the study seeks to accelerate the conversion of organic matter in xylan residue, enhance the quality and stability of compost, and ultimately provide scientific evidence and technical support for the resource utilization and sustainable development of waste. This research not only contributes to optimizing composting processes but also plays a role in promoting the development of a circular economy.

Keywords: Xylan residue, Composting, Microbial inoculants.

0 INTRODUCTION

Xylan residue, a solid waste produced during the extraction of xylose from plant materials such as corn cobs, is rich in lignocellulose. Its main components include cellulose (48.5%), lignin (28.0%), and hemicellulose (23.5%). As a high-quality reusable resource, xylan residue has gained considerable attention. Currently, its utilization is concentrated in various fields, including energy production, environmental pollution control, and agriculture and animal husbandry.

In the energy sector, xylan residue is regarded as a primary raw material for bioethanol due to its excellent cleanliness and renewability. For instance, studies have shown that under sodium hydroxide pre-treatment conditions, lignin in xylan residue can be effectively removed, resulting in a high yield of ethanol under suitable temperature and enzymatic conditions [1]. Additionally, many researchers are exploring the anaerobic fermentation potential of xylan residue to convert it into combustible gas and fuel, thereby opening new pathways for sustainable energy utilization [2]. In terms of environmental remediation, xylan residue is also being utilized as a high-quality raw material for the production of activated carbon. Research indicates that through chemical activation methods (such as phosphoric acid and zinc chloride), xylan residue can be transformed into efficient activated carbon that effectively adsorbs environmental pollutants, reduces production costs, and protects the ecological environment [3]. Moreover, due to its good permeability and water retention capacity, xylan residue is used as a substrate for mushroom cultivation, demonstrating significant economic benefits in large-scale production [4].

To protect the environmental ecosystem, the Chinese government issued the "Opinions on Accelerating the Establishment of a Waste Recycling System" in February 2024, emphasizing the importance of meticulous management, effective recycling, resource utilization, and circular use of waste [5]. In this context, finding efficient and eco-friendly methods for the resource treatment of xylan residue is particularly urgent. Composting is widely recognized as a key approach for the resource utilization of agricultural waste. The composting process transforms organic matter in waste into nutrient-rich humus through aerobic fermentation, ultimately producing high-quality organic fertilizers [6]. Xylan residue, as a typical organic solid waste, can similarly achieve environmental treatment and resource utilization through composting.

1. Aerobic Composting of Xylan Residue

Aerobic composting is the process by which aerobic microorganisms absorb, oxidize, and decompose waste in an oxygen-rich environment. During this process, aerobic microorganisms effectively penetrate and absorb organic matter, promoting its degradation. Aerobic composting offers advantages such as high fermentation efficiency, short stabilization time, and the ability to eliminate pathogens and insect eggs, thus becoming an important technological means for the harmless treatment of organic solid waste. Several factors during the composting process directly influence microbial activity and composting effectiveness. The main influencing factors include:

1.1 Temperature

Temperature has a critical impact on microbial growth and metabolism. Both excessively low and high temperatures can inhibit microbial activity, thereby affecting the composting process. Microbial activity causes fluctuations in temperature at different stages of composting. Typically, composting can be divided into four phases: the heating phase, high-temperature phase, cooling phase, and maturation phase [7]. During the high-temperature phase, thermophilic microorganisms are active and can effectively decompose resistant lignocellulose while eliminating pathogens and weed seeds.

1.2 pH

The pH value during composting is crucial for microbial activity. During the decomposition of organic matter, microorganisms generate organic acids, leading to a decrease in pH. However, as organic nitrogen compounds are produced, the pH of the compost may rise to alkaline levels. Generally, the pH at the completion of composting is maintained between 5.5 and 8.5 [8].

1.3 Moisture Content

Moisture content is an important factor affecting microbial growth and metabolic activities. Research indicates that the optimal moisture content lies between 50% and 60%, effectively promoting the microbial decomposition of organic matter. Excessively low moisture content may inhibit microbial activity, while overly high moisture content can lead to oxygen deficiency, delaying the composting process [9].

1.4 Oxygen Concentration

The composting process requires sufficient oxygen to maintain microbial metabolic activity. Adequate oxygen accelerates the decomposition of organic matter, raises the temperature of the compost, and shortens the composting cycle. Conversely, low oxygen levels reduce the activity of aerobic microorganisms, thereby impacting decomposition efficiency [10].

1.5 C/N Ratio

Carbon and nitrogen are essential elements for microbial growth and metabolism. Studies suggest that the C/N ratio of compost materials should be maintained between 25 and 35 to ensure effective microbial metabolism and fermentation [11]. Both excessively low and high C/N ratios can negatively impact composting efficiency and fertilizer effectiveness.

These factors interact to collectively determine the effectiveness of the composting process. Therefore, in-depth research on these factors and their mechanisms is crucial for optimizing the composting treatment of xylan residue.

2. Mechanisms of Microbial Inoculants in Xylan Residue Composting

2.1 Diversity of Microorganisms during Aerobic Composting

The diversity of microbial communities during the composting process plays a critical role in the efficiency and quality of compost. Research shows that the composition of microbial communities varies at different phases of composting, directly influencing the maturity and harmlessness of the compost [12]. Studies by Wang *et al*., [13] have found that bacteria are the most abundant microorganisms and have the strongest capacity to decompose lignocellulose during the composting process. In the early to mid-stages of composting, bacterial diversity and abundance are significantly higher than in the later stages, while bacteria play a key role in degrading resistant materials during the high-temperature phase. Although fungal abundance is lower during this period, fungi still serve important functions in the later stages of composting. Additionally, the number of actinomycetes varies with temperature changes during composting. Overall, the abundance of bacteria, fungi, and actinomycetes exhibits a trend of high-low-high variation during the composting process. These microorganisms participate in the degradation of organic matter in compost through community succession, with different microorganisms displaying varying tolerance to temperature, thus having different roles at different stages of composting.

2.2 Functions and Roles of Microorganisms in Xylan Residue Composting

During the composting of xylan residue, the majority of microorganisms engage in nitrogen cycling and the degradation of lignocellulose, both of which are critical for composting efficiency and quality. Additionally, a small number of microorganisms possess growth-promoting properties that can induce plants to develop disease resistance.

2.2.1 Participation in Nitrogen Cycling

In the composting process, nitrogen primarily exists in the form of organic nitrogen, including proteins, peptides, nucleic acids, amino acids, and chitin. The composting process often accompanies the mineralization of organic nitrogen (e.g., volatilization of NH_3), nitrification, and denitrification (releasing N_2O). Simultaneously, the biological fixation of inorganic nitrogen occurs. Microorganisms play a core role in nitrogen cycling, including nitrogen-fixing bacteria, ammonifying bacteria, nitrifying bacteria, and denitrifying bacteria [14]. Adding nitrogen-transforming and nitrogen-fixing microorganisms to compost can enhance nitrogen fertilizer efficiency and its long-term utilization. For instance, nitrogen-fixing microorganisms such as Azotobacter and Rhizobium can fix atmospheric N_2 into ammonium nitrogen; nitrifying bacteria like Nitrosomonas and Nitrobacter convert nitrite into plant-available nitrogen fertilizer. Furthermore, ammonia released during the degradation of organic matter serves as an effective means of enhancing nitrogen fertilizer efficiency [15].

2.2.2 Participation in Lignocellulose Degradation

Xylan residue, a solid waste left after extracting xylose from agricultural waste like corn cobs and sugarcane bagasse, mainly comprises cellulose, lignin, and hemicellulose. Lignin-degrading enzymes are extracellular enzymes secreted by lignin-degrading microorganisms responsible for lignin degradation. As lignin is a cross-linked phenolic polymer known for its high rigidity and decay resistance, its degradation primarily relies on lignin-degrading enzymes. Additionally, microorganisms secrete cellulases and xylanases to break down cellulose and hemicellulose. Research indicates that the degradation of lignocellulose relies on the synergistic action of a multi-enzyme system, and enhancements in specific enzyme activities are critically significant for the biodegradation of crop residues [16, 17].

2.2.3 Participation in Other Biological Activities

Apart from nitrogen cycling and lignocellulose degradation, microorganisms in compost also perform other essential functions. Some plant growth-promoting bacteria can enhance nutrient uptake in plants and regulate plant growth [18]. Furthermore, many microorganisms engage in mutualistic relationships with plants, inducing plants to develop disease resistance, thereby warding off pathogen attacks. For example, iron-oxidizing bacteria can produce siderophores to absorb iron from the soil, forming iron-siderophore complexes that inhibit the growth of pathogenic microorganisms. When inoculated into the soil, plant growth-promoting bacteria can colonize the root zone and compete with pathogens for growth space, further enhancing the plants' disease resistance [19].

Microbial inoculants in xylan residue composting not only promote the degradation of organic matter and nitrogen cycling but also enhance soil fertility and plant resilience through their diverse functions, providing significant support for sustainable agricultural development.

3. Application Prospects of Lignocellulose-Degrading Microbial Strains in Xylan Residue Composting

As agricultural waste treatment technologies continue to advance, the application prospects of lignocellulose-degrading microbial strains in xylan residue composting are increasingly gaining attention. Xylan residue, being an organic solid waste rich in lignocellulose, poses certain challenges for its composting treatment due to its high cellulose and lignin content. Therefore, developing specific microbial strains with lignocellulose degradation capabilities will provide crucial support for its resource utilization.

Lignocellulose-degrading microbial strains obtained through domestication can significantly accelerate the conversion of organic matter in xylan residue, promoting the maturation and stability of compost. For example, studies have shown that specific lignocellulose-degrading microorganisms (such as certain white-rot fungi and actinomycetes) can effectively decompose lignin and cellulose, thereby speeding up the degradation of organic matter during composting [20]. Such microbial strains not only enhance the decomposition rate of compost but also increase the final stability of the compost, providing a more reliable source of biofertilizer for subsequent applications.

The impact of lignocellulose-degrading microbial strains on nutrient release in xylan residue composting is also particularly important. Through the introduction of these microbial strains, studies have found that they can promote effective release of nitrogen, phosphorus, and potassium, thereby providing abundant nutrient support for plant growth [21]. Relevant research indicates that compost treated with lignocellulose-degrading microorganisms exhibits a significant increase in nitrogen mineralization rate, with an average nitrogen release rate exceeding 30%. This result demonstrates that the introduction of these microbial strains can effectively enhance the fertilizer efficiency of compost.

The regulatory effect of lignocellulose-degrading microbial strains on the structure and microbial community of xylan residue compost is also an important area of research. The introduction of these strains affects the diversity and community composition of microorganisms within the compost, thereby optimizing microbial activity and organic matter decomposition processes. Some studies have explored the impact of these microbial strains on compost microbial communities and found that specific strains can promote the proliferation of aerobic microorganisms, improve compost aeration and water retention capacity, and thus enhance the overall quality and stability of the compost [22, 23]. This construction of microbial communities not only accelerates compost maturation but also increases compost's adaptability to environmental changes.

The application of lignocellulose-degrading microbial strains in xylan residue composting not only aids in improving decomposition efficiency and nutrient release but also optimizes microbial community structure, offering new ideas and methods for the efficient resource utilization of agricultural waste. Future research will further investigate the combinatorial use of different microbial strains and their effects on compost performance, promoting the sustainable utilization of lignocellulosic waste.

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