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Comprehensive analysis of waste-derived biodegradable plastics: Feedstock valorization, biochemical synthesis pathways, and lifecycle dynamics within a circular economy

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Abstract
The rapid increase in global plastic production has generated severe environmental concerns due to the persistence of petroleum-based polymers in natural ecosystems. Conventional plastics contribute significantly to landfill accumulation, marine pollution, and the formation of microplastics that pose risks to both environmental and human health. In response to these challenges, biodegradable plastics derived from waste biomass have emerged as a sustainable alternative aligned with circular economy principles. This theoretical review presents a comprehensive analysis of waste-derived biodegradable plastics, focusing on feedstock valorization strategies, biochemical synthesis pathways, material performance characteristics, and lifecycle dynamics.
Second-generation feedstocks such as agricultural residues and food-processing waste, along with third-generation sources including algae and chitinous shellfish waste, are examined for their potential to reduce dependence on food-grade raw materials. The microbial synthesis of polyhydroxyalkanoates and the fermentation–polymerization route for polylactic acid production are discussed in detail. In addition, chemical and enzymatic pathways for chitosan production from chitin-rich waste are analyzed. The mechanical, thermal, and degradation properties of these bioplastics are evaluated in comparison with conventional polymers. Life cycle assessment studies indicate that waste-derived bioplastics can significantly lower greenhouse gas emissions and fossil resource consumption, although energy-intensive pretreatment processes remain a limitation. This review highlights current challenges, research gaps, and future directions necessary for the large-scale adoption of biodegradable plastics within a sustainable circular economy framework.

Keywords: Biodegradable plastics, Waste valorization, PHB, PLA, Circular economy, Life cycle assessment

Introduction
Plastics play a vital role in modern society due to their low cost, versatility, and durability. However, the extensive use of petroleum-based plastics has resulted in persistent environmental pollution, as these materials are resistant to natural degradation processes. Large quantities of plastic waste accumulate in landfills and aquatic environments, contributing to ecosystem disruption and microplastic contamination. These challenges have intensified the demand for sustainable polymer alternatives that minimize long-term environmental impact.
Biodegradable plastics have gained increasing attention as potential substitutes for conventional plastics. Unlike traditional polymers, biodegradable plastics can undergo microbial degradation under suitable environmental conditions, leading to reduced persistence after disposal. The sustainability of these materials is further enhanced when they are derived from waste biomass rather than food-based feedstocks. In this context, waste-derived bioplastics represent an important component of circular economy strategies, where waste materials are reintegrated into value-added production cycles.
This paper provides a theoretical review of biodegradable plastics produced from waste resources, emphasizing feedstock utilization, synthesis mechanisms, material properties, and environmental performance.

Classification of Bioplastics
Bioplastics are commonly classified based on their source of origin and biodegradability. Bio-based plastics are produced from renewable biological resources, while biodegradable plastics are defined by their ability to undergo microbial decomposition into carbon dioxide, water, and biomass. These two categories do not always overlap.
Bio-based biodegradable plastics include materials such as polyhydroxyalkanoates and polylactic acid, which are synthesized from renewable resources and exhibit biodegradation under controlled conditions. Bio-based but non-biodegradable plastics, such as bio-polyethylene, possess chemical structures similar to fossil-based plastics and therefore persist in the environment. Fossil-based biodegradable plastics, although less common, can also degrade biologically due to their molecular design. Among these categories, bio-based and biodegradable plastics are considered the most sustainable option for reducing environmental burden.

Waste Feedstock Valorization
Agricultural Residues
Agricultural residues such as rice husk, wheat straw, and maize cob are abundant lignocellulosic resources that remain largely underutilized. These materials consist primarily of cellulose, hemicellulose, and lignin. Pretreatment processes, including alkaline and enzymatic methods, are required to break down the complex structure and release fermentable sugars. These sugars can subsequently serve as carbon sources for microbial bioplastic production, thereby reducing environmental pollution associated with residue burning.

Food and Industrial Waste
Food-processing waste, including potato peels, banana peels, and fruit pulp, is rich in starch and polysaccharides

suitable for bioplastic synthesis. Starch extracted from such waste can be converted into biodegradable films with the aid of plasticizers such as glycerol. Industrial food waste streams, including brewer's spent grain and dairy byproducts like whey, also offer valuable substrates for polymer production. Utilizing these wastes reduces disposal-related environmental impacts while enhancing resource efficiency.

Algal and Chitinous Waste

Algae represent a promising third-generation feedstock due to their rapid growth rate and minimal land requirements. Algal biomass contains polysaccharides such as alginate and carrageenan, which can be processed into biodegradable polymers. In addition, chitin-rich shellfish waste generated by the seafood industry serves as a key source of chitin and chitosan. These materials exhibit favorable film-forming and antimicrobial properties, making them suitable for packaging and biomedical applications.

Biochemical Synthesis Pathways

Microbial Production of PHB and PHAs

Polyhydroxyalkanoates are synthesized intracellularly by microorganisms as storage polymers under nutrient-limited conditions. Polyhydroxybutyrate is the most extensively studied PHA. The biosynthesis pathway involves the conversion of acetyl-CoA into hydroxybutyryl-CoA, followed by polymerization into PHB granules. Waste-derived carbon substrates can be effectively utilized in this process, contributing to circular bioeconomy objectives.

Polylactic Acid Production

Polylactic acid is typically produced through the fermentation of sugars into lactic acid, followed by chemical polymerization. Advanced techniques such as simultaneous saccharification and fermentation improve conversion efficiency when lignocellulosic or starch-based waste is used as feedstock. Ring-opening polymerization of lactide is commonly employed to obtain high-molecular-weight PLA suitable for commercial applications.

Chitin to Chitosan Conversion

Chitosan is obtained from chitin through deacetylation processes that increase solubility and reactivity. Conventional chemical deacetylation involves strong alkaline treatment, while enzymatic methods are being explored as environmentally friendly alternatives. The degree of deacetylation significantly influences the functional properties of chitosan-based materials.

Material Properties and Performance

The practical application of biodegradable plastics is influenced by their mechanical and thermal properties. PLA and PHB exhibit tensile strengths comparable to certain conventional plastics but often suffer from brittleness and low impact resistance. Thermal stability limitations restrict their use in high-temperature applications. To overcome these challenges, blending with other polymers and reinforcement with natural nanofillers such as cellulose nanocrystals are widely investigated. These approaches enhance strength, flexibility, and barrier properties.

Life Cycle Assessment and Environmental Impact

Life cycle assessment studies provide insight into the environmental performance of waste-derived bioplastics. Compared to petroleum-based plastics, these materials generally demonstrate reduced greenhouse gas emissions and fossil energy consumption. However, energy-intensive pretreatment steps and water usage can offset some benefits. End-of-life management plays a critical role in overall sustainability, as improper disposal may lead to methane emissions during anaerobic degradation.

Challenges and Future Prospects

Despite their potential, waste-derived biodegradable plastics face several challenges, including high production costs, limited processing infrastructure, and performance constraints. Standardization of biodegradability testing and improved waste management systems are essential for successful implementation. Future research should focus on cost reduction, metabolic engineering of microbial strains, and the development of efficient composting and recycling infrastructure.

Conclusion

Waste-derived biodegradable plastics offer a viable pathway toward sustainable material development within a circular economy framework. The utilization of agricultural, industrial, and aquatic waste as feedstocks reduces environmental burden while promoting resource efficiency. Although technical and economic challenges persist, continued advancements in synthesis technologies, material engineering, and waste management practices are expected to enhance large-scale adoption. Biodegradable plastics derived from waste resources have the potential to play a significant role in mitigating plastic pollution and supporting environmental sustainability.

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