

Development and Life Cycle Assessment of Novel Degradable Composite Materials Based on Waste Lignocellulose/Microbial Synthesis

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Abstract: This paper mainly studies the technical approach of constructing new environmentally friendly composites using waste lignocellulose (crop straw, sawdust, etc.) and microbial synthetic polymer materials (polyhydroxyfatty acid esters, PHA or bacterial cellulose, BC). The combination of physical modification and biosynthesis overcomes the brittleness and high cost of a single biomaterial. At the same time, the life cycle assessment (LCA) method was used to compare the differences in carbon footprint and environmental impact between the composite and traditional petroleum-based plastics. The research shows that the composite has broad application prospects in packaging, agricultural film, and other areas, and can significantly reduce greenhouse gas emissions.

Keywords: Waste lignocellulose; Microbial synthesis; Biodegradable composites

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1. Introduction

As global oil resources deplete and environmental pollution becomes more severe, the search for green and environmentally friendly materials that can replace petroleum-based plastics has become an urgent need in both academia and industry. Waste lignocellulose, the largest biomass resource on Earth, is of great strategic significance for achieving carbon neutrality when effectively utilized. At the same time, polymer materials synthesized through microbial fermentation have attracted attention due to their good biocompatibility and complete degradability. Combining waste lignocellulose with microbial synthetic materials can reduce costs, improve the comprehensive mechanical properties of the materials, and create a closed-loop system for the recycling of biological resources. This paper mainly studies the preparation process, performance changes, and life-cycle environmental impact of such composites.

2. Raw material systems and composites preparation

2.1. Sources and composition characteristics of waste lignocellulose

Waste lignocellulose mainly comes from agricultural residues such as corn stalks, wheat straw, and forestry processing waste such as sawdust, bark, etc., all of which can be used to produce waste lignocellulose. Biomass feedstock has a very complex natural barrier against degradation. The core chemical composition is a combination of cellulose, hemicellulose and lignin ^[1]. Cellulose is the framework, hemicellulose is the filler, and lignin wraps the two together like glue, giving the plant the ability to resist biological erosion. The fiber length, crystallinity, and surface hydroxyl distribution density of the composite material all affect the bonding strength between the composite material and the polymer matrix.

2.2. Pretreatment process of waste lignocellulose

Physical and chemical pretreatment is indispensable to improve the dispersion and reactivity of lignocellulose in composites. Mechanical ball milling can break down the crystal structure of cellulose and grind it into the micro-nano scale. Chemical treatments, such as dilute acid hydrolysis or alkali impregnation, can remove some lignin and hemicellulose, expose more active sites of cellulose, and improve the hydrophilicity of the cellulose surface or achieve hydrophobicity through subsequent modification. The steam blast technique relies on the shear force generated by instantaneous pressure relief to achieve cell wall dissociation ^[2]. These treatments not only alter the microscopic morphology of the raw material but also lay the physical foundation for the interfacial compatibility of the subsequent microbial synthesis of materials.

2.3. Microbial synthetic material selection and synthetic pathways

Microbial synthetic materials are mainly polyhydroxyfatty acid esters (PHA) and bacterial cellulose (BC). PHA is an intracellular polyester synthesized by a variety of microorganisms as an energy storage substance under carbon-nitrogen imbalance conditions and has physical properties similar to polypropylene. The synthetic pathway typically involves the gradual polymerization of acetyl-CoA to form macromolecular chains under the catalysis of β -ketothiolase, acetyl-CoA reductase, and PHA synthase. BC is an extracellular polysaccharide secreted by microorganisms such as *Acetobacter* at the gas-liquid interface, with high purity and a nanofiber network structure. The selection of this type of material as a composite matrix ensures complete bioregression of the material at the end treatment stage.

2.4. Preparation and blending techniques of composites

The quality of the preparation process directly affects the final performance of the composites. Melt extrusion is currently the mainstream industrial method, which involves a uniform mixture of lignocellulose powder and microbial polyester particles through high-temperature shearing and continuous production using a twin-screw extruder. In-situ polymerization involves directly adding the modified lignocellulose to the microbial fermentation liquid or monomer polymerization reaction system, allowing the macromolecular chains to grow directly on the fiber surface, resulting in extremely strong interfacial bond forces ^[3]. Solvent casting is generally used to prepare high-transparency and high-barrier film materials, using the evaporation of the co-solvent to rearrange the fibers and matrix at the molecular level to form a dense layered structure.

3. Structural characterization and comprehensive performance evaluation

3.1. Microstructure and interface characterization

Microscopic observations are generally conducted using scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The contact of waste lignocellulose fibers in the cross-section of composite materials with the microbial synthetic matrix (PHA) is the focus of the study. The surface of the untreated fibers is relatively smooth and hydrophilic, and there will be obvious gaps or “disconnections” between them and the hydrophobic polyester matrix. Such interface defects can lead to stress concentration and thereby reduce the mechanical strength of the material. Microscopic

characterization reveals that fibers that have undergone surface coupling or physical modification can be better embedded into the matrix, and the interface layer shows a fuzzy, continuous transition state, indicating a good physical interlocking or chemical bonding between the two.

3.2. Analysis of intermolecular interactions and crystallization behavior

Intermolecular interactions are the microscopic basis that determines the interfacial stability of lignocellulose and microbial polyester. Infrared spectroscopy (FTIR) analysis shows that the hydroxyl groups (-OH) on the surface of modified lignocellulose form hydrogen bond acceptor-donor relationships with carbonyl groups (C=O) on the molecular chains of polyhydroxyalkanoates (PHA) or polylactic acid (PLA), and the intermolecular hydrogen bond network can increase the shear strength at the interface. Lignocellulosic micro-nanofibers have a strong heterogeneous nucleation effect in the polymer matrix. By differential scanning calorimetry (DSC) analysis, it is known that the addition of fibers can act as the site for nucleation growth, allowing the polymer molecular chains to be oriented on the fiber surface, raising the crystallization temperature of the material and refining the grain size. In addition, a transverse crystal structure is formed around the fibers, which can be observed with a polarizing microscope. This particular crystalline form compensates for the slow crystallization rate of the bio-polyester matrix itself, increases the tensile modulus and heat deflection temperature of the composite macroscopically, and enables the material to maintain structural stability in complex mechanical environments.

3.3. Physical properties: Water absorption, barrier properties and durability

The evaluation of physical properties is an important criterion for determining whether a material is practical. Lignocellulose has a natural hygroscopicity, and an increase in lignocellulose content will cause the dimensional stability of the composite material to deteriorate in a humid environment, so a water absorption rate test is needed to determine the equilibrium moisture content. In terms of barrier properties, microbial synthetic materials generally have good oxygen and water vapor barrier properties. The arrangement of fibers in the composite material forms a tortuous path effect, which makes the gas molecule permeation path longer, thereby improving the barrier effect^[5]. Durability tests simulate the actual usage environment and use artificial accelerated aging tests (UV exposure, wet heat cycling, etc.) to evaluate the strength retention rate of the material throughout its life cycle to ensure that the material does not fail prematurely in packaging or agricultural film use.

3.4. Biodegradation performance and mechanism analysis

Biodegradability is the biggest difference between this composite and traditional plastics. Simulated composting experiments were conducted to monitor the weight loss rate and carbon dioxide emissions of the material under certain temperature and humidity conditions. The degradation mechanism is an evolution process from surface to interior: microorganisms in the environment attach to the material surface and secrete extracellular enzymes (lipase, cellulase, etc.) that first attack the amorphous zone and the junction of fibers and matrix. After the matrix degrades, lignocellulose is exposed and further decomposed by cellulose-decomposing bacteria. The synergistic degradation mode makes the degradation rate of the composite material generally faster than that of the single component, and the final degradation products are carbon dioxide, water and biomass, achieving the green cycle of carbon in nature.

4. Life cycle assessment (LCA)

4.1. LCA objectives and scope definition

The first step in life cycle assessment is to determine the purpose of the study, which is to quantitatively evaluate the environmental load of waste lignocellulose-based composites from resource acquisition to final disposal. The scope is defined in a cradle-to-grave manner, including the collection and transportation of agricultural and forestry waste, the

addition of pre-treatment chemicals, the consumption of electricity and steam during microbial fermentation, the molding process of the composites, and the end-of-line composting treatment. The functional unit is the production of one ton of new degradable composites. Once the system boundaries are defined, the material can be compared horizontally with traditional petroleum-based plastics (LDPE, PP) under the same functional conditions to provide scientific data support for the environmental advantages of the material.

4.2. Life cycle inventory analysis

Inventory analysis is a detailed calculation of all input and output flows within the system boundary. On the input side, there are lignocellulose raw materials, nutrient salts for fermentation, process water, and power consumption for production equipment; On the output side are the main product composites, wastewater discharge from the production process, waste gas (CO₂ from fermentation), and solid residues. The calculation of waste lignocellulose generally uses the burden allocation method, that is, because it is a waste, the environmental impact of the front-end planting stage is not included in this system. The data sources are laboratory measurement data plus industrial production database (Ecoinvent). The accuracy of inventory analysis directly affects the reliability of subsequent environmental impact assessments and is the most difficult part of LCA research.

4.3. Impact assessment indicators

Based on the list data, calculate each environmental impact indicator using professional LCA software. Core indicators include global warming potential (GWP), which reflects the size of the carbon footprint; Fossil energy consumption (ADP_{fossil}) reflects the degree of conservation of non-renewable resources; Eutrophication potential (EP) and acidification potential (AP) are mainly used to assess the impact of fermentation wastewater and pre-treatment discharge. The results generally show that although the fermentation process is energy-consuming, the combined GWP is much lower than that of petroleum-based plastics because the raw materials are derived from biomass carbon sinks. In addition, through sensitivity analysis, it can be concluded that improving microbial transformation efficiency and thermal energy recovery utilization rate are two main optimization directions for further reducing the environmental impact score.

5. Application prospects, challenges, and optimization paths

5.1. Application scenarios and market potential

New biodegradable composites based on waste lignocellulose and microbial synthesis have great potential to replace traditional plastics in multiple fields due to their bio-based properties and excellent degradability. In terms of green packaging, it can be made into high-barrier food packaging films, express delivery cushioning packaging, and disposable tableware. Compared with traditional polyethylene materials, it can not only effectively extend the shelf life of food, but also quickly return to nature through industrial composting after being discarded, thus greatly reducing the “white pollution” caused by packaging waste. The most representative application in modern agriculture is biodegradable mulching film. Traditional mulch films are not recyclable and can cause soil compaction, while new composite mulch films can be directly ploughed into the soil after crop harvest and transformed into organic matter through the action of soil microorganisms, saving the cost of manual recycling and protecting the ecological environment of farmland. In addition, due to its good biocompatibility, high-value-added products such as bone repair scaffolds and drug sustained-release carriers can be developed in biomedical engineering. The demand for bio-based composites is growing explosively due to the expanding scope of the global plastic ban and the increasing environmental awareness of consumers. According to industry predictions, biodegradable materials will take up a large share of the plastic market in the next decade, providing a broad stage for the industrialization of lignocellulose composites.

5.2. Key challenges

Despite the promising prospects, the composite faces many serious challenges as it moves from the laboratory to large-scale industrial applications. Cost bottleneck: lignocellulose is cheap and readily available as a raw material, but its pretreatment process is energy-consuming, and the carbon source conversion rate and yield of microbial fermentation (PHA production) have not reached the ideal level, resulting in a much higher finished product price than petroleum-based plastics. Secondly, performance regulation is complex. The hydrophilicity of lignocellulose and the hydrophobicity of bio-polyester result in poor interfacial compatibility, and improper handling can cause the mechanical properties (impact strength, etc.) of the composites to fail to meet the requirements of high-performance applications. The narrow processing window is another technical challenge. Microbial synthetic materials generally have poor thermal stability and are prone to thermal degradation during processing. The addition of lignocellulose increases the melt viscosity, which poses higher requirements for the precise temperature control and shear force of the molding processing equipment. The lag of industry standards has also restricted its marketization. At present, there is no unified standard for evaluating the degradation rate and safety of biodegradable materials in different environments, such as marine, freshwater, and home composting, resulting in uneven product quality in the market and low consumer trust.

5.3. Directions for optimization and research recommendations

In view of the current problems, future research should be advanced in both technological innovation and system integration. From the perspective of material development, the focus should be on solving the problem of “interfacial synergistic enhancement”, developing environmentally friendly new compatibilizers, or using in-situ surface modification techniques to enhance the bonding force between the fiber and the matrix, thereby achieving better mechanical properties than a single component. Use synthetic biology methods to modify microbial strains to reduce costs, optimize fermentation pathways through metabolic engineering to make more efficient use of the mixed sugars (xylose, glucose) produced by the hydrolysis of lignocellulose, increase product concentration, and shorten the fermentation cycle. In terms of processing techniques, explore low-temperature processing techniques or new non-toxic plasticizing systems to broaden the thermal processing window of the material and reduce thermal degradation losses during production. In addition, the comprehensive utilization model of bio-refining should be vigorously promoted. While emphasizing the output of the target composites, by-products such as lignin and hemicellulose derivatives generated during the pretreatment process should also be recovered to offset production costs through high-value multi-product integration. Finally, it is recommended to establish a complete life-cycle dynamic monitoring system, use big data analysis to optimize the allocation of energy consumption in the production chain, and actively promote the standardization construction of performance evaluation and identification of degradable materials at the national and international levels to provide policy guidance and technical support for the healthy development of materials.

6. Conclusion

Therefore, a new type of biodegradable complex based on waste lignocellulose and microbial synthesis can not only achieve high-value utilization of agricultural waste but also provide a highly competitive green solution to plastic pollution. When physical and biological technologies are combined, this type of material offers great flexibility in structural design and performance adjustment. Although there are still objective obstacles, such as cost and processability at present, with the development of synthetic biology and the improvement of the LCA evaluation system, its environmental benefits and economic value will be more obvious. Through interdisciplinary research and industrial chain collaborative improvement, this composite material will play an irreplaceable and important role in the global sustainable development process, helping to achieve the social vision of a zero-carbon cycle.

Disclosure statement

The author declares no conflict of interest.

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