Synthesis of biopolymer materials based on cellulose isolated from lignocellulosic waste

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Abstract: This study focuses on the synthesis of biodegradable biopolymer materials based on cellulose isolated from lignocellulosic waste. Agricultural residues were used as a renewable source for cellulose extraction, which was subsequently incorporated into a starch-based polymer matrix to obtain composite bioplastics. The synthesis process involved cellulose isolation, preparation of starch suspension, plasticization with glycerol, and formation of homogeneous polymer mixtures followed by casting and controlled drying. The influence of component ratios and processing conditions on the formation of bioplastic films was considered during the synthesis stage. The developed approach demonstrates the feasibility of producing biopolymer materials using locally available lignocellulosic resources through a simple and scalable synthesis method. The proposed technology can serve as a basis for environmentally friendly bioplastic production.

Keywords: lignocellulosic waste, cellulose, biopolymer synthesis, bioplastics, starch matrix, glycerol plasticizer

INTRODUCTION

The increasing accumulation of non-degradable plastic waste has become one of the most critical environmental challenges worldwide. Conventional petroleum-based polymers are resistant to natural degradation processes, leading to long-term persistence in soil and aquatic ecosystems. In this context, the development of biodegradable polymer materials derived from renewable resources has attracted significant scientific and industrial interest. Among various alternatives, bioplastics based on natural polymers offer a promising solution due to their environmental compatibility and sustainable origin.

Lignocellulosic waste, generated in large quantities from agricultural activities, represents an abundant and low-cost raw material composed primarily of cellulose, hemicellulose, and lignin. Cellulose, being the most abundant natural polymer, possesses favorable structural characteristics that make it suitable for the synthesis of biopolymer materials. The extraction of cellulose from such waste not only contributes to waste valorization but also provides a renewable feedstock for the production of biodegradable materials.



Figure 1. Schematic representation of bioplastic synthesis based on local lignocellulosic raw materials (straw, cotton stalks) and starch sources (potato, corn)

In bioplastic synthesis, cellulose is often combined with starch to form composite polymer systems. Starch serves as a biodegradable matrix, while cellulose acts as a reinforcing component that enhances the structural integrity of the material. The incorporation of plasticizers, such as glycerol, further facilitates the formation of flexible polymer networks by reducing intermolecular interactions within the matrix. The synthesis process typically involves the preparation of homogeneous mixtures through thermal treatment, followed by casting and controlled drying to obtain bioplastic films.

Despite the simplicity of this approach, the use of locally available lignocellulosic resources for bioplastic synthesis remains insufficiently explored. Therefore, the present study is aimed at developing a synthesis route for biopolymer materials based on cellulose isolated from lignocellulosic waste, emphasizing the use of renewable raw materials and environmentally friendly processing methods.

MATERIAL AND METHODS

Lignocellulosic raw materials, including agricultural residues such as straw and cotton stalks, were collected from local sources, air-dried, and mechanically processed to obtain particles of approximately 1-5 mm in size. Cellulose was isolated from the prepared biomass using an alkaline treatment followed by oxidative bleaching. In the alkaline stage, the ground material was treated with a 6% (w/w) sodium hydroxide solution at 90°C for 2-2.5 hours with a solid-to-liquid ratio of 1:10. The resulting pulp was filtered and repeatedly washed with distilled water until neutral pH was reached. To further remove residual lignin and hemicellulose, the material was subjected to bleaching using a 4% hydrogen peroxide solution at 70°C for 60-90 minutes under mildly alkaline conditions (pH 10-11). The purified cellulose was then washed, dried at 45-50°C, and milled to obtain a fine powder.

Starch used as the polymer matrix was extracted from locally available sources such as potato and corn using a wet extraction method. The raw materials were washed, mechanically disintegrated in water, and filtered to obtain starch suspensions. The suspensions were allowed to settle, and the precipitated starch was separated, washed multiple times with distilled water, and dried at 40-45°C to obtain purified starch powder.

Bioplastic synthesis was carried out by preparing a starch-based polymer system reinforced with the obtained cellulose. A defined amount of starch (10 g) was dispersed in distilled water (100 mL) and stirred to form a homogeneous suspension. The mixture was heated to 70-85°C and maintained for 15-20 minutes to induce gelatinization. Glycerol (2 g) was then added as a plasticizer, and the system was further stirred for 3-5 minutes to ensure uniform distribution. Subsequently, cellulose (0.1-0.5 g) was introduced into the mixture and dispersed under continuous stirring for 5-10 minutes to form a homogeneous composite system.

The resulting viscous polymer mixture was degassed and cast onto a flat glass surface to form films. The films were dried at 40-45°C for 8-12 hours under controlled conditions to obtain bioplastic materials. After drying, the films were carefully removed from the casting surface and stored under ambient conditions prior to further processing.

RESULTS AND DISCUSSION

The applied synthesis route enabled the successful production of biopolymer materials based on cellulose isolated from lignocellulosic waste and starch obtained from local sources. The alkaline treatment followed by oxidative bleaching provided a purified cellulose fraction suitable for further incorporation into the polymer matrix. The selected conditions for cellulose isolation ensured the effective removal of non-cellulosic components, resulting in a material compatible with aqueous polymer systems.



Figure 2. Bioplastic film synthesized from starch and cellulose isolated from lignocellulosic waste

The starch extraction process yielded a homogeneous and stable powder that could be readily dispersed in water. During the thermal treatment stage, the starch suspension underwent gelatinization within the temperature range of 70-85°C, forming a viscous and uniform polymer matrix. This stage was essential for the formation of a continuous phase capable of embedding the cellulose component.

The addition of glycerol as a plasticizer contributed to the formation of a flexible polymer network by reducing intermolecular interactions between starch chains. The incorporation of cellulose into the gelatinized starch matrix resulted in the formation of a composite system, where cellulose particles were distributed throughout the polymer structure. The degree of dispersion was influenced by the mixing conditions and the particle size of the cellulose.

The casting method followed by controlled drying at 40-45°C enabled the formation of continuous bioplastic films. The gradual removal of water under moderate thermal conditions facilitated the stabilization of the polymer network and prevented structural defects associated with rapid drying. The selected synthesis parameters, including component ratios, temperature regime, and processing time, ensured the reproducibility of the bioplastic formation process.

The surface morphology of the synthesized bioplastic films was examined by scanning electron microscopy (SEM) at different magnifications, providing insight into the microstructural organization of the cellulose-starch composite system. At low magnification (Figure 3-a, ×500), the film surface appears relatively continuous and compact, indicating successful formation of a coherent polymer matrix during the casting and drying stages. The absence of large voids or macroscopic defects suggests that the selected processing conditions were suitable for obtaining uniform films.

At higher magnification (Figure 3-b, ×2000), discrete bright domains are observed within the matrix, which can be attributed to cellulose particles embedded in the starch phase. This confirms that cellulose was successfully incorporated into the polymer system. However, the presence of partially aggregated regions indicates that the dispersion of cellulose is not entirely uniform, likely due to the intrinsic tendency of cellulose fibers to form hydrogen-bonded clusters.

The microstructure shown in (Figure 3-c, ×2000) reveals the formation of microcracks distributed across the film surface. These features may be associated with internal stresses generated during solvent evaporation and film shrinkage in the drying process. The appearance of such microcracks suggests that the balance between plasticizer content and matrix cohesion plays a critical role in maintaining structural integrity during film formation.

In contrast, (Figure 3-d, ×2000) demonstrates a more homogeneous distribution of fine cellulose domains within the biopolymer matrix. The relatively uniform dispersion observed in this region indicates improved compatibility between the components, which can be attributed to

effective mixing and appropriate selection of synthesis parameters. The presence of finely distributed cellulose contributes to the formation of a more integrated composite structure.

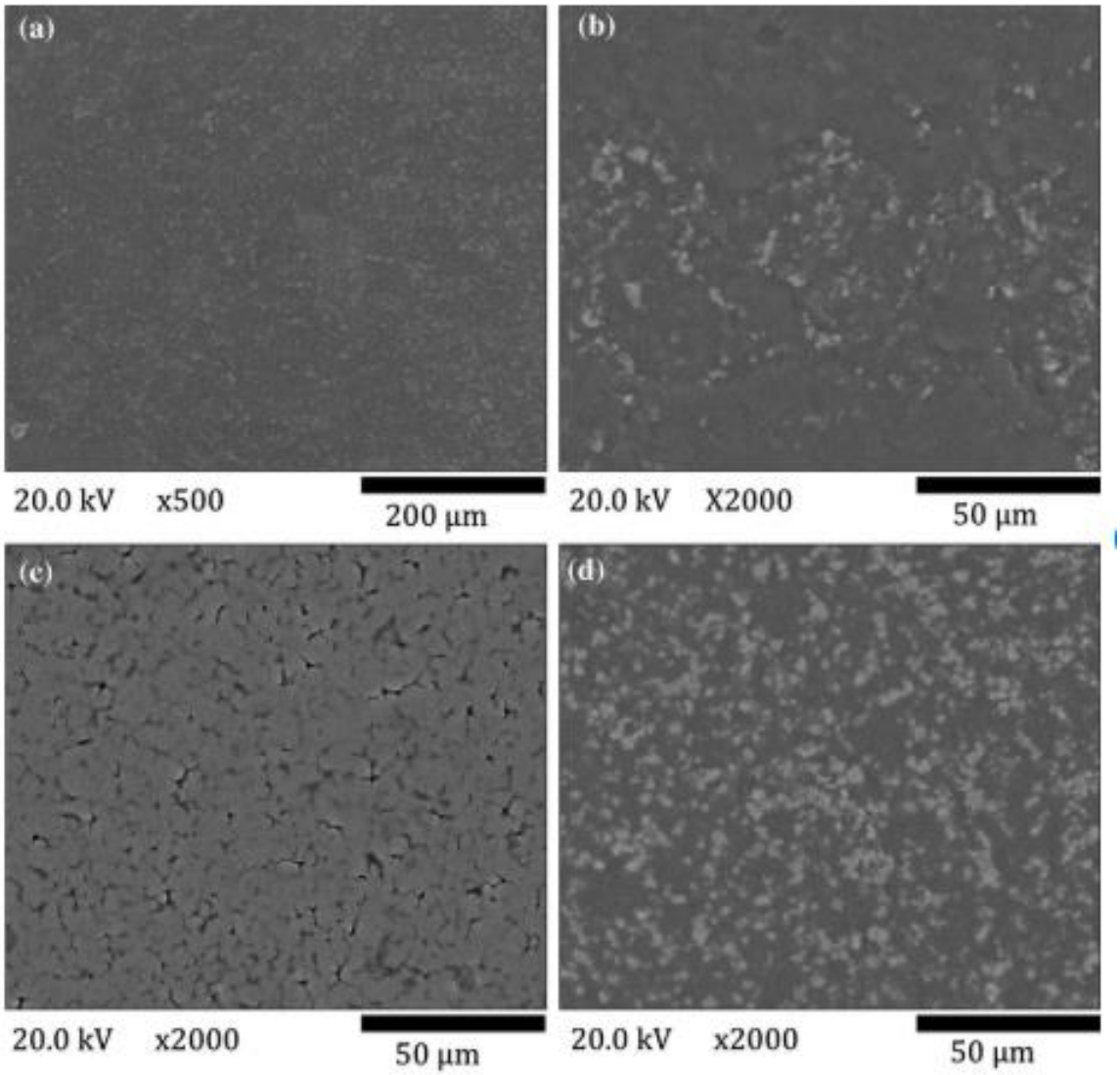

Figure 3. SEM micrographs of bioplastic films based on cellulose isolated from lignocellulosic waste at different magnifications: (a) surface morphology of the bioplastic film at ×500 magnification; (b) distribution of cellulose particles in the polymer matrix at ×2000 magnification; (c) microcrack formation on the film surface at ×2000 magnification; (d) uniform dispersion of fine cellulose domains within the biopolymer matrix at ×2000 magnification

The SEM observations confirm that the applied synthesis method enables the formation of cellulose-reinforced biopolymer films with varying degrees of dispersion and structural uniformity. The microstructural features observed at different magnifications reflect the influence of processing conditions on the organization of the composite system and provide important insights into the formation mechanism of the bioplastic materials.

The results confirm that the combination of locally available starch and cellulose obtained from lignocellulosic waste can be effectively utilized in the synthesis of biopolymer materials. The simplicity of the process and the use of accessible raw materials highlight the practical feasibility of the proposed synthesis approach.

CONCLUSION

In this study, a synthesis route for biodegradable biopolymer materials based on cellulose isolated from lignocellulosic waste was successfully developed. The applied methodology,

including alkaline extraction, oxidative bleaching, and incorporation of cellulose into a starch-based matrix, enabled the formation of homogeneous polymer systems suitable for film production. The selected synthesis parameters, such as component ratios, temperature regime, and processing conditions, ensured the reproducibility and stability of the obtained bioplastic materials. The use of glycerol as a plasticizer facilitated the formation of a continuous polymer network, while the integration of cellulose contributed to the structural integrity of the composite system. The results demonstrate that locally available lignocellulosic resources can be effectively utilized for the synthesis of biodegradable bioplastics through a relatively simple and scalable process, providing a promising basis for the development of environmentally friendly polymer materials.

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