STARCH AND CELLULOSE PLASTIC COMPOSITES – A REVIEW

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Abstract
Bio-plastics are environmentally friendly polymers derived from renewable plant sources such as sweet potatoes, corn starch, sugarcane, soybean oil, and hemp oil. Unlike petroleum-based plastics, they are biodegradable through microbial action, reducing long-term pollution and dependence on fossil fuels. Among the various types of bio-plastics, those derived from starch and cellulose stand out due to their abundance, renewability, low cost, and biodegradability. Starch, a polysaccharide obtained from crops, and cellulose, the primary structural component of plant cell walls, can be combined to form green plastic composites with improved properties. Blending starch with cellulose fibers enhances mechanical strength, thermal stability, and moisture resistance compared to using starch or cellulose alone. These composites can be processed using conventional plastic-forming techniques and are suitable for applications in packaging, agriculture, and disposable products. Modification techniques such as plasticization, cross-linking, and esterification are used to address challenges like water sensitivity and brittleness. The integration of starch and cellulose into composite plastics supports global efforts toward sustainability and waste reduction. However, limitations related to processing, durability, and scalability remain. This review presents an overview of the composition, preparation methods, properties, and applications of starch and cellulose plastic composites, highlighting their potential and the need for further development.

Keywords: Starch, Cellulose, Bioplastics, Biodegradable, Composites

Introduction

Starch is a naturally occurring polymer made up of glucose units linked by α-1,4-glycosidic bonds, commonly found in crops like yams, cassava, corn, and potatoes.[1] It is the second most abundant natural polymer after cellulose and is widely used due to its low cost, biodegradability, and ease of extraction. While starch is used for energy storage in plants, cellulose, composed of glucose units linked by β-1,4-glycosidic bonds, is the primary structural component of plant cell walls. Though both have industrial applications, starch's high sensitivity to moisture limits its usability. However, combining starch with cellulose or synthetic polymers enhances its performance, yielding biodegradable composites with improved mechanical and thermal properties.[2] These blends can be used in the production of items like packaging materials, flowerpots, and disposable goods.

In contrast, synthetic plastics such as polyethylene, PVC, and polystyrene are non-biodegradable materials used extensively in everyday items. Due to their molecular stability, plastics persist in the environment, contributing significantly to pollution and landfill accumulation.[3] Although efforts have been made to recycle or convert waste plastics into fuels, results remain inconsistent. As such, there is growing interest in biodegradable alternatives derived from renewable resources. Bioplastics made from starch and cellulose, often in composite form, present a promising solution. These materials decompose naturally, and when reinforced with natural fibers, offer environmentally friendly substitutes for conventional plastics. This review centers on such starch/cellulose composites and their potential in sustainable plastic production.

Problems with Petroleum-Based Plastics

- Health Hazards: Petroleum-derived plastics often contain toxic chemicals like Bisphenol A (BPA) and styrene, which are linked to endocrine disruption, developmental disorders, and cancer. These chemicals can leach into food and beverages when plastic containers are heated, washed, or stressed.[4]

- Environmental Pollution from Improper Disposal: Large volumes of discarded plastics end up in landfills, oceans, and other ecosystems, causing long-term pollution. Plastics degrade slowly, fragmenting into microplastics that pollute waterways, kill marine life, and enter the food chain.[5]
- Overuse of Petroleum Resources: The production of plastics consumes approximately 4% of the world's crude oil, with monomers like ethylene, propylene, and styrene derived directly from fossil fuels. This accelerates the depletion of non-renewable resources and increases global oil dependency.[5]
- Emission of Greenhouse Gases: Plastic manufacturing processes release CO_2, CH_4, and heat, significantly contributing to global warming. Increased plastic production is correlated with rising emissions and the impacts of climate change.[6]
- Marine Ecosystem Threats: Plastics that reach oceans often form floating debris zones and are ingested by marine animals, causing injuries, starvation, or death. Toxic microplastics disrupt marine food webs and affect human seafood safety.[7]
- Limited Degradability and Accumulation: Most synthetic plastics are non-biodegradable and can persist in the environment for hundreds of years. Their durability makes recycling inefficient and waste management costly, leading to continuous accumulation.[5-7]

Why starch/cellulose plastics?

Starch and cellulose plastics, often grouped under the term bioplastics, are environmentally friendly alternatives to conventional petroleum-based plastics. Bioplastics are derived from renewable biomass sources such as plants, trees, agricultural residues, and other organic matter.[8] These materials offer several significant advantages over traditional plastics:

- Reduced Carbon Footprint: The use of plant-based feedstocks reduces greenhouse gas emissions compared to fossil fuel-derived plastics, contributing to climate change mitigation.[9]
- Lower Energy Consumption in Production: The manufacturing of starch and cellulose plastics typically requires less energy than petroleum-based plastics, making the process more sustainable.[9]
- Use of Renewable Resources: Starch and cellulose are sourced from biomass, a renewable and abundant resource that includes crops, grasses, wood, and even biodegradable animal by-products, ensuring long-term sustainability.[10]
- Minimized Environmental Pollution: These bioplastics are biodegradable and decompose naturally over time, helping reduce the accumulation of non-biodegradable waste in landfills, waterways, and ecosystems.[11]
- Free from Harmful Additives: Unlike conventional plastics, starch/cellulose plastics do not contain toxic additives such as phthalates or bisphenol-A (BPA), which are known to cause health problems.[12]
- Safe for Food Packaging: These bioplastics are non-reactive and do not alter the taste or smell of food stored in them, making them ideal for safe food contact applications.[13]

Comparing Starch and Cellulose

Cellulose is a natural polymer that does not dissolve in water, primarily due to its high crystallinity, which leads to a high melt enthalpy, a large amount of energy is required to disrupt its ordered structure.[14] This high degree of crystallinity also contributes to cellulose's excellent mechanical strength. Cellulose is tasteless and odourless, and while some forms, such as the outer shell of corn, are safe for human consumption, most humans cannot digest cellulose. Only a few animals, including termites and ruminants like cows, buffalo, and deer, can break it down, thanks to the presence of specialised enzymes and microorganisms in their digestive systems.[14]

In contrast, starch is water-responsive and digestible by humans because the human body produces enzymes like amylase, which break starch down into glucose.[15] Starch becomes soluble in water when heated, undergoing a transformation known as gelatinization. During this process, the semi-crystalline starch granules swell, burst, and release amylose molecules, which then interact to form a viscous, gel-like network. This property of starch is essential for many food and industrial applications, especially where thickening or binding is required.

The stark difference in water solubility and digestibility between starch and cellulose stems from their molecular arrangement and degree of crystallinity. While cellulose's rigid, crystalline structure makes it insoluble and indigestible for most organisms, starch's more amorphous structure allows it to interact with water and enzymes, making it suitable for both food applications and biodegradable plastic formulations.[16] Understanding these structural differences is crucial in designing starch/cellulose composites that balance strength and processability.

STARCH AND CELLULOSE COMPOSITE PLASTICS

The incorporation of cellulose fibres into thermoplastic starch (TPS) significantly enhances its mechanical properties, gas barrier performance, and resistance to water. This improvement is attributed to the lower hydrophilicity of cellulose compared to starch. When cellulose is blended with TPS, the composite structure restricts water absorption by mobilizing sites previously available for water binding. However, one of the major limitations in producing starch/cellulose composites is the difficulty in achieving uniform dispersion of the cellulose fibres within the starch matrix.[17]

A composite typically involves the combination of two or more polymers or the reinforcement of a polymer matrix with natural or synthetic fibres. The goal is to merge the advantageous properties of both components, producing a material with superior strength and functionality. Recent advances have demonstrated the reinforcement of natural matrices such as wheat gluten and soy protein with fibres like hemp, jute, and bamboo to yield biocomposites with significantly improved mechanical performance.[18] Composites composed entirely of biopolymers, including potato starch, plant proteins, polyhydroxybutyrate (PHB), and plant fibres, are of particular interest for creating materials with unique functional characteristics and environmental sustainability.

Cellulose fibres are especially promising as reinforcement materials in thermoplastic matrices due to their ability to enhance both thermal stability and mechanical strength. Commercial cellulose improves the performance of starch-based plastics.[19] Typically, the preparation of starch–cellulose composites involve solvent systems like sodium hydroxide/polyethylene glycol or sodium hydroxide/urea acting as plasticizers to aid in blending. The inclusion of cellulose not only addresses starch's limitations, such as moisture sensitivity and brittleness, but also maintains biodegradability and cost-efficiency, making such blends highly suitable for sustainable material development.

Cellulose can be extracted from various sources, such as paper waste or plant materials. In one method, paper waste is soaked in de-ionized water for 24 hours, followed by treatment with sodium hydroxide at 80°C for 36 hours to swell and isolate the cellulose fibres (Keshk *et al.,* 2013).[20] For plant-derived cellulose, Fischer *et al.* (2008)[21] described a four-step process: sample preparation (grinding), removal of extractives, lignin removal to yield holocellulose, and hemicellulose removal to obtain α-cellulose. Modern procedures often use toluene-ethanol in place of benzene-methanol to minimize the health hazards associated with older solvent systems.

Starch extraction can be carried out by dispersing corn powder in de-ionized water and stirring it for 24 hours at room temperature. To prepare the starch–cellulose blend composite, the extracted cellulose and the wet starch slurry are mixed in hot de-ionized water, stirred continuously for 24 hours at 70°C, and then centrifuged. The mixture is washed thoroughly until neutral and dried under reduced pressure. The process can be varied by adjusting the starch-to-cellulose ratio and operating temperatures to achieve specific mechanical or physical properties (Keshk *et al.,* 2013).[20] Previous studies illustrating such composite formulations are presented in Table 1.

Table 1: Previous studies of composites prepared from starch reinforced with cellulose fibres.

Study	Starch Type	Plasticizer Ratio Used	Source of Cellulose	Key Findings / Notes
Liu *et al.* (2015) [22]	Pea starch	2.4% glycerol	Tonkin cane bamboo	Improved tensile strength and biodegradability
Bodirlau *et al.* (2014) [23]	Corn starch	2.8% glycerol	*Populus alba* seed hairs	Enhanced moisture resistance and flexibility
Keshk *et al.* (2013) [20]	Corn starch	2.2% glycerol	Paper waste (recycled cellulose)	Notable increase in thermal stability and structural integrity
Osorio *et al.* (2014) [24]	Potato starch	2.0% glycerol	Bacterial cellulose (*Gluconacetobacter medellinensis*)	High reinforcement efficiency and biodegradability
Raabe *et al.* (2015) [25]	Cassava starch	2.6% glycerol	Eucalyptus pulp cellulose fibres	Good mechanical performance and reduced water sensitivity

Properties of starch/cellulose blend composites

Starch/cellulose blend composites exhibit enhanced physicochemical and mechanical properties compared to pure thermoplastic starch (TPS). One notable characteristic is the stronger C–O bond stretching band observed in the blends, which may result from molecular interactions between the amorphous regions of starch and cellulose. These interactions contribute to improved structural integrity and performance of the composite material.

- Thermal Stability: Starch/cellulose composites, especially in a 2:1 starch-to-cellulose ratio, demonstrate improved thermal stability and lower thermal expansion compared to starch-only plastics.[26] This enhancement is attributed to the thermal robustness of cellulose fibres, which reinforces the composite structure under heat.
- Tensile Strength: The incorporation of cellulose fibres significantly increases mechanical properties such as ultimate tensile strength (UTS) and elastic modulus.[27] The strong interfacial adhesion between the starch matrix and cellulose fibres results in improved load-bearing capacity. However, the percent elongation at break decreases compared to pure TPS, likely due to the high crystallinity and stiffness introduced by the cellulose fibres.
- Resistance to Moisture: Starch/cellulose composites have higher resistance to moisture than pure TPS or cellulose plastics. Cellulose fibres, being less hydrophilic than starch, reduce water absorption and partially absorb glycerol, leading to a decrease in the overall hydrophilic behavior of the blend.[28]
- Biodegradability: These composites remain biodegradable, although the rate of degradation tends to slow as cellulose content increases. The reduced weight loss during degradation and the higher onset temperature of thermal breakdown suggest that increasing fibre content enhances the composite's thermal and structural stability. This improvement is due to the inherently greater thermal stability of cellulose and its compatibility with starch as a polysaccharide-based material.[28]

Applications of Starch/Cellulose Blend Composites

Starch/cellulose blend composites have found diverse applications due to their favorable mechanical strength, biocompatibility, biodegradability, and low toxicity.

- In the medical field, these composites are used in the fabrication of maxillofacial bone plates, tissue scaffolds, and controlled drug delivery systems, where safe interaction with biological tissues is essential.[29] Their ability to naturally degrade and support tissue regeneration makes them suitable for temporary biomedical implants.
- In packaging, starch/cellulose composites are valued for their enhanced oxygen and moisture barrier properties, offering an eco-friendly alternative to conventional plastic films. Their use helps reduce environmental pollution from single-use packaging materials. Additionally, in agriculture, these composites are used to produce biodegradable plant pots and seedling trays. After use, such items can decompose in the soil, enriching it while eliminating plastic waste. Overall, the versatility and sustainability of starch/cellulose composites make them excellent candidates for a wide range of industrial and environmental applications.

Conclusion

Starch and cellulose-based plastic composites present a promising and sustainable alternative to conventional petroleum-based plastics. These biocomposites combine the renewable, biodegradable nature of starch with the mechanical strength and moisture resistance of cellulose fibres, resulting in materials that are not only environmentally friendly but also functionally effective. The synergy between these two natural polymers enhances the thermal stability, tensile strength, and water resistance of the final product, making them suitable for applications in packaging, agriculture, and biomedical fields. The preparation processes are relatively straightforward, and the raw materials are abundant and inexpensive. Despite these advantages, challenges such as fibre dispersion, moisture sensitivity, and scalability still need to be addressed for broader commercial adoption.

Recommendation

To fully harness the potential of starch/cellulose composites, further research and development should focus on improving fibre–matrix compatibility, optimizing composite formulations, and scaling up production methods. The use of eco-friendly plasticizers and cross-linking agents can enhance mechanical and barrier properties without compromising biodegradability. In addition, government policies and industrial incentives should support the transition toward bio-based materials by promoting sustainable packaging solutions and discouraging single-use plastics. Academic and industrial collaborations are recommended to develop standardized processing techniques and to explore new applications in biomedical devices, electronics, and automotive components. With continued innovation and investment, starch/cellulose composites could play a key role in the future of green materials and circular economies.

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