Supplementary Material

Cellulose-Based Biopolymers from Banana Pseudostem Waste: Innovations for Sustainable Bioplastics

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A comprehensive summary of recent studies on bioplastics, including key findings, research gaps, and recommendations, is provided in Supplementary Material, Table S1.
The literature highlights:

- Strong interest in bio-based plastics from agricultural and food wastes, supporting circular economy principles and environmental sustainability.
- Challenges in production, such as high cost, limited thermal stability, water resistance, and mechanical performance, which require further research and optimization.
- Opportunities for enhanced functionality, industrial scalability, and application-specific improvements through novel extraction methods, polymer blending, and process optimization.
- The underutilization of lignocellulosic fibers, including banana pseudostem, as raw materials for biodegradable packaging.

This summary provides context for the development of cellulose-based bioplastics and informs subsequent experimental design and material characterization.

Table S1. Summary of key literature on bioplastics: Findings and research gaps

Reference	Work done	Findings/ Key results	Gaps /Recommendations
[25]	Literature review on bio-based plastics from biological and agricultural wastes	• Strong interest in bio-based plastics from agricultural and food waste; improves waste management. • Complex production reduces economic feasibility. • Bio-based plastics are environmentally friendly and support effective organic waste management.	• Chemical and enzymatic extraction of biopolymers from food waste. • Blend bioplastics with additives to improve thermal stability, water resistance, brittleness, and melt strength. • Solvent-based polymer extraction for production.

		• Further research and novel approaches can enhance sustainability and human life expectancy.	• Enhancement in mechanical properties: heat resistance, shock resistance, processability.
[39]	Overview of developments in methods for designing bioplastics from valorized food waste over the past decade	• Bioplastics from fruit and vegetable waste support a circular economy and zero waste. • They foster industry–agro-food sector synergies and reduce environmental pollution.	• Improvement in manufacturing technologies, expand applications, set standards, reduce production costs. • Development of cheaper feedstocks, efficient processes, and effective blends/composites.
[40]	Review of wood- and fermentation-based materials with barrier properties and packaging potential	Presented various packaging materials legislations.	• Revision of bioplastic legislation.
[41]	Review of bioplastics' biodegradability (biotic and abiotic) and related standards/certifications for compostability and degradation	Stricter regulations, fostering eco-friendly attitudes, and sustainability education can better use resources and reduce economic losses from plastic waste.	Expand Life Cycle Assessment (LCA) and End-of-Life (EOL) analyses to evaluate plastic sustainability.
[42]	Compile primary research from academic and industrial studies on bioplastics' environmental impact.	• Some bioplastics are non-recyclable, but their impacts are less severe than conventional plastics. • LCA is the most important key for evaluating environmental impact.	Undertaking LCA and Land Use Change (LUC) analyses in order to confirm the eco-friendliness of new bioplastics.
[33]	Review of bioplastics' production, market trends, environmental and socio-economic benefits, and their chemical, mechanical properties and applications.	• Biodegradation may require controlled conditions for some bioplastics. • Bioplastics with synthetic fractions need EOL remediation. • Biotechnology advances enable new versatile bioplastics and engineered biopolymers.	• Proper waste management and effective EOL remediation strategies • Consumer awareness creation
[8]	Review of bioplastics production from starch and lignocellulosic fibers, including pros, cons, and methods for extracting natural polymers from plant biomass.	• Lignocellulosic fibers enhance bioplastics' properties and offer a biomass reuse alternative. • Injection molding is a widely used polymer processing technology.	• Development of viable industrial processes. • Improvement of functionality of bioplastic materials • Optimisation of thermal properties, water vapour barriers, brittleness and low melt point.

[12]	Analyses of the role of several studies to find effective strategies to decrease the production cost and to ease the availability of bio-plastics.	• Bioplastics offer unique qualities and flexibility versus traditional plastics. • Their biodegradability, renewability, recyclability, reusability,. and compostability enable diverse applications. • High cost is a major drawback needing further research.	Developing strategies to reduce cost of production of bioplastics.
[43]	Overview on the bioplastic materials, classification and modification in packaging applications.	• Polylactic acids (PLAs) are biodegradable, bio-based plastics with growing renewable demand. • Polyhydroxyalkanoates (PHAs) are scalable from various biomass sources with expanding production potential. • Starch and cellulose matrices are the most used for bioplastic manufacturing.	• Enhancing the functionality of bioplastics. • Conducting storage studies on packaging equipment to validate the industrial use of biobased packaging films
[27]	Convertion of carboxyl methyl cellulose (CMC) from sugarcane bagasse waste into a biodegradable polymer for packaging.	• The developed biodegradable plastic was hydrophilic, flexible, transparent, robust, and degraded faster than existing options. • Soil-burial tests confirmed its environmental compatibility and commercial potential.	Development of economical extraction methods for the recovery of CMC.
[6]	Review of environmental issues in plastic production/disposal and circular economy principles. Advances in bioplastic feedstocks and manufacturing technologies.	• Emerging chemical and biological methods can upcycle heterogeneous plastic and bioplastic waste into higher-quality materials. • Circularity-focused policies push companies to assess product life cycles and guide consumers toward sustainable plastics. • Clear regulations and financial incentives are crucial to scale bioplastics from niche to large-scale sustainable markets.	• Investigate various wastes for bioplastic production. • Use second-generation feedstocks to ensure sustainable, available raw materials. • Standardize and harmonize assessments, including LCA.
[44]	Biodegradable protective bags were developed using banana fiber from plant waste, promoting a	• Viability of banana pseudostem for bioplastic	• Increased research on utilization of banana pseudostem in production of bioplastics for packaging

	circular economy and environmentally friendly processes, with production carried out via compounding extrusion and film blowing		• Greening of the bioplastic manufacturing process
[29]	General overview of the various applications of cellulose in the packaging industry	There is low application of lignocellulosic fibres in bioplastics, specifically underutilization of banana pseudostem for production of bioplastics.	
[45]	Cellulose film was synthesized from delignified banana stem fibers using the ionic liquid 1-Allyl-3-methylimidazolium chloride (AMIm)[Cl] and evaluated for mango packaging.	• Cellulose film packaging decreased the disease and color indexes of mangos. • Prolonged the storage and shelf life of marketable fruits. • The cellulose film indicated an excellent biodegradability as compared to the PE plastic film.	
[46]	Extraction of cellulose from agricultural residues and plants resource and characterisation.	• Microcrystalline cellulose is widely used for its plasticity, cohesiveness when wet, and tableting/binding properties. • Bacterial cellulose is tasteless, odorless, highly dispersible, and has numerous industrial applications. • Cellulose biosynthesis is not yet fully understood. • Research on cellulose derivatives from agricultural residues and plant compounds has led to diverse biodegradable products.	Ethyl cellulose (EC) micro-encapsulated systems are studied for extended drug release and protection of the core substance from degradation.
[47]	Review of recent developments, applications, and potential of cellulose-based functional materials across various fields.	• Cellulose has made the most progress in biological applications, water treatment, sensors, and as a reinforcing agent. • Greater focus is needed on energy applications due to rapid advances in energy storage materials.	• Enhanced application of lignocellulosic fibres in bioplastics. • Research on the Interfacial and Interaction mechanism compatibility between matrix and other materials. • Use of solvents and acids to improve mechanical processing.
[48]	Magnetic composite films were synthesized using cotton and sugarcane bagasse to produce cellulose biopolymers.	• Cellulose-based smart bioplastic films with adsorbed magnetic nanoparticles were fabricated for optical and magnetic applications.	Other methods of extraction to be explored.

		• Films remained thermally stable regardless of extraction source or nanoparticles. • Optical transmittance was largely unaffected, and nanoparticles retained superparamagnetic behavior in the composite.	
[49]	The molecular structure was analyzed by ATR-FTIR, chemical composition quantified using pulp and paper industry techniques (IPAT), and thermal properties assessed via TGA/DSC.	• Banana fibers have a diameter of 80–125 μm, density of 0.32–0.66 g/cm^3, and moisture content of 11.26–13.20%. • They are hydrophilic with water absorption of 232–396% and contain functional groups from cellulose, hemicellulose, pectin, and lignin. • Chemical composition: Cellulose 59.15%, Hemicellulose 14.42%, Lignin 10.70%, Pectin 3.79%, Extractives 11.81%, Ash 0.55%; thermally stable up to 180 °C.	