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Natural-based food packaging from banana leaves: Innovation toward sustainable and circular food systems

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ABSTRACT

Background: Global food waste and the extensive use of non-biodegradable plastics in food packaging remain among the most pressing environmental challenges, contributing to greenhouse gas emissions, resource depletion, and economic losses. In response, bio-based and biodegradable materials derived from agricultural residues have gained attention as sustainable alternatives. Among these, banana leaves offer great potential due to their abundance, biodegradability, and mechanical strength. This study was conducted to synthesize current advancements, challenges, and future directions in the development of banana-leaf-based materials for sustainable food packaging applications, with particular attention to food protection and quality preservation. **Methods**: This study employs a systematic literature review that integrates material, environmental, and policy perspectives to evaluate the feasibility, performance, and sustainability of banana-leaf-based food packaging. **Findings:** Technological advancements such as enzymatic pulping, nanocellulose extraction, and hybrid biopolymer formation have enhanced the mechanical, thermal, and biodegradation properties of banana-leaf composites, while also improving barrier and antimicrobial functionalities relevant to food safety and shelf-life extension. Life cycle assessments show reduced energy use and emissions compared to plastic packaging, while socioeconomic analyses highlight benefits for rural livelihoods. Policy reviews emphasize the need for regulatory harmonization to accelerate industrial adoption. **Conclusion**: Banana-leaf-based materials demonstrate strong potential as eco-friendly food packaging that not only aligns environmental, social, and economic sustainability goals, but also supports food safety, reduces spoilage, and contributes to food quality preservation when supported by technological innovation and coherent policy frameworks. **Novelty/Originality of this article:** This study presents an integrated synthesis of material performance, food safety relevance, environmental assessment, and policy implications, positioning banana-leaf packaging as a viable and scalable approach toward sustainable food systems and circular economy transitions.

KEYWORDS: agro-waste valorization; banana leaf packaging; biodegradable food packaging; circular economy; sustainable materials.

1. Introduction

Globally, food waste remains one of the most critical sustainability challenge, with an estimated 1.05 billion tonnes of food discarded in 2022, equivalent to 132 kilograms per person annually. Approximately 60% of this waste originated from households, 28% from food service, and 12% from retail sectors (Forbes et al., 2024). Beyond environmental and economic consequences, food loss and waste are closely linked to food safety risks, deterioration of food quality, and reduced nutritional value, as inadequate storage and packaging conditions can accelerate microbial growth and nutrient degradation (FAO, 2019; WHO, 2022).

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In Indonesia, food loss and waste are estimated at annually, or approximately 115–184 kilograms per capita per year, indicating substantial inefficiencies in the nation's food production and consumption system. This inefficiency contributes to severe environmental and economic impacts, including resource depletion, increased greenhouse gas emissions, and financial losses estimated at IDR 213–551 trillion annually—equivalent to about 4–5% of Indonesia's Gross Domestic Product (GDP) (Yananto et al., 2021). At the same time, inadequate and unsustainable food packaging practices may exacerbate food safety concerns and negatively affect consumer health. The migration of chemical substances from food packaging into food not only affects food safety and quality but also poses a significant risk to public health due to potential toxicity (Seref & Cufaoglu, 2025).

In light of concerns about food safety and the limitations of conventional petroleum-based plastics, research has increasingly focused on biobased and biodegradable packaging materials derived from renewable resources such as cellulose, starch, and chitosan. These natural biopolymers have been shown to play a functional role in preserving food quality and extending shelf life, while offering improved environmental performance compared to traditional plastics. For example, biobased films and coatings can contribute to maintaining the mechanical and barrier properties necessary for food protection, potentially reducing both food spoilage and reliance on non-renewable packaging materials. However, challenges related to achieving consistent barrier performance, mechanical strength, and scalability remain important areas of ongoing research (Nilsen-Nygaard et al., 2021; Shi et al., 2025).

The global challenge of food waste is closely linked not only to environmental sustainability but also to food safety and quality outcomes, which are strongly influenced by the choice of food packaging materials. The widespread use of non-biodegradable plastics in food packaging, which exacerbate environmental pollution and resource inefficiency. To address these interconnected issues, bio-based and biodegradable packaging materials inspired by natural resources have emerged as a promising solution, offering improved sustainability, reduced carbon footprint, and compatibility with circular economy principles (Hu et al., 2025). However, the widespread adoption of biodegradable packaging remains limited due to challenges in large-scale production, inconsistent material performance, and a lack of supportive policy frameworks. Strengthening collaboration among researchers, industries, and policymakers is therefore crucial to accelerate the global shift toward sustainable food packaging solutions (Teixeira et al., 2025). These challenges highlight the need for interdisciplinary research that combines material science, chemistry, environmental assessment, and economics to optimize biodegradable packaging and promote sustainable market adoption.

Recent advances in biopolymer research have strengthened the feasibility of converting agricultural residues into high-performance packaging materials. Agricultural by-products such as husks, peels, cobs, and lignocellulosic fibers contain substantial amounts of cellulose, starch, lignin, and proteins that can be transformed into biodegradable films with promising mechanical and barrier properties comparable to conventional plastics (Selvam et al., 2025). Improvements in extraction techniques, green solvent systems, polymer modification, and nanocomposite reinforcement have further enhanced the stability, flexibility, and functional performance of waste-derived biopolymer packaging, increasing their potential for industrial adoption (Sharma et al., 2025). These developments collectively demonstrate that agricultural waste is not merely a disposal burden, but a valuable renewable resource capable of supporting global transitions toward sustainable biobased packaging solutions.

Among various natural resources, banana leaves possess strong natural fibers and inherent biodegradability, making them a promising raw material for developing eco-friendly food packaging applications. Their fiber structure provides good mechanical strength and environmental compatibility, supporting their potential use as a sustainable alternative to plastic-based packaging (Jumaidin et al., 2021). Recent studies have demonstrated that banana plant residues, particularly pseudostems, can be converted into molded food packaging with favorable strength and durability while maintaining full biodegradability. This valorization of banana waste not only reduces environmental impact compared to conventional polystyrene packaging but also supports circular economy principles by transforming agricultural by-products into value-added materials (Castillo et al., 2023). Such valorization of agricultural waste not only mitigates environmental burdens but also supports circular economy principles, converting low-value residues into sustainable, value-added products.

Building upon these developments, this study aims to analyze the potential of banana leaves as an eco-friendly food packaging material through a structured review of scientific literature. The theoretical framework integrates concepts from sustainable materials engineering, biopolymer chemistry, and circular economy theory to identify both opportunities and limitations in the development of banana leaf-based packaging. The objectives are to synthesize current research findings on material properties, food packaging performance, and environmental performance; to evaluate policy and market readiness for biodegradable packaging adoption; and to identify research gaps and propose future directions for material optimization and sustainability assessment. By bridging interdisciplinary perspectives, this study contributes to the state of the art in sustainable food packaging and supports the transition toward bio-based materials as a strategic solution to reduce food waste and environmental pollution globally.

2. Methods

This study employed a systematic literature review approach to ensure a structured and transparent synthesis of existing research on sustainable food packaging innovations, with a specific focus on banana leaves and related agricultural by-products. The review aimed to identify technological developments, environmental implications, and research gaps associated with biodegradable food packaging materials within a circular economy framework. Scientific literature was retrieved from major academic databases, including Scopus, ScienceDirect, MDPI, Web of Science, and Google Scholar. The search strategy utilized combinations of keywords such as *"banana leaves," "banana waste," "biodegradable films," "bio-based food packaging,"* and *"eco-friendly packaging,".* Only peer-reviewed journal articles and review papers published between 2020 and 2025 were included to ensure scientific relevance and currency (Kumari et al., 2025b). The search strategy was designed to capture studies relevant not only to material sustainability but also to food packaging functionality and food safety considerations.

The review process adhered to the general principles of the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to ensure transparency and reproducibility (Page et al., 2021). After removing duplicate records, articles were screened based on title, abstract, and full-text relevance to the study objectives. Inclusion criteria required studies to address the use of banana leaves or other natural fibers for food packaging applications, including assessments of material properties, biodegradability, environmental performance, and food packaging functionality. Exclusion criteria comprised non-peer-reviewed publications, conference abstracts, and studies lacking methodological clarity or sufficient empirical evidence. Quality assessment of the selected studies considered the clarity of experimental or analytical methods, relevance to food packaging applications, and contribution to sustainability and material performance evaluation. A thematic synthesis approach was subsequently applied to organize findings into key analytical categories, including material extraction and processing, physicochemical and functional properties, environmental assessment, and circular economy implications (Snyder, 2019). This thematic synthesis also enabled the identification of evidence related to food–packaging interactions, food quality preservation, and potential implications for food safety within sustainable food systems.

3. Results and Discussion

3.1 Technological innovations in banana leaf-based sustainable packaging

Recent progress in natural-based food packaging technologies has increasingly positioned banana leaves as a promising renewable substrate due to their wide availability, biodegradability, and long-standing use in tropical regions as natural food wrappers. The transition toward eco-friendly materials derived from banana leaves is viewed as a viable strategy to replace petroleum-based plastics, especially in regions with abundant banana biomass. Several innovative approaches have been developed to improve the functionality, mechanical integrity, and durability of banana-leaf-based materials through optimized thermal and mechanical processing. One strategy involves the fabrication of multilayer structures reinforced with natural binders such as corn starch, resulting in biocomposites with enhanced stability and flexibility. The process is mention on Figure 1, includes sequential preparation, thermoplastic blending, and compression molding to yield composite sheets suitable for sustainable packaging. These advancements offer a low-cost, chemical-free pathway aligned with circular-economy principles and promote the valorization of agricultural residues into high-value materials (Arumugam et al., 2023).

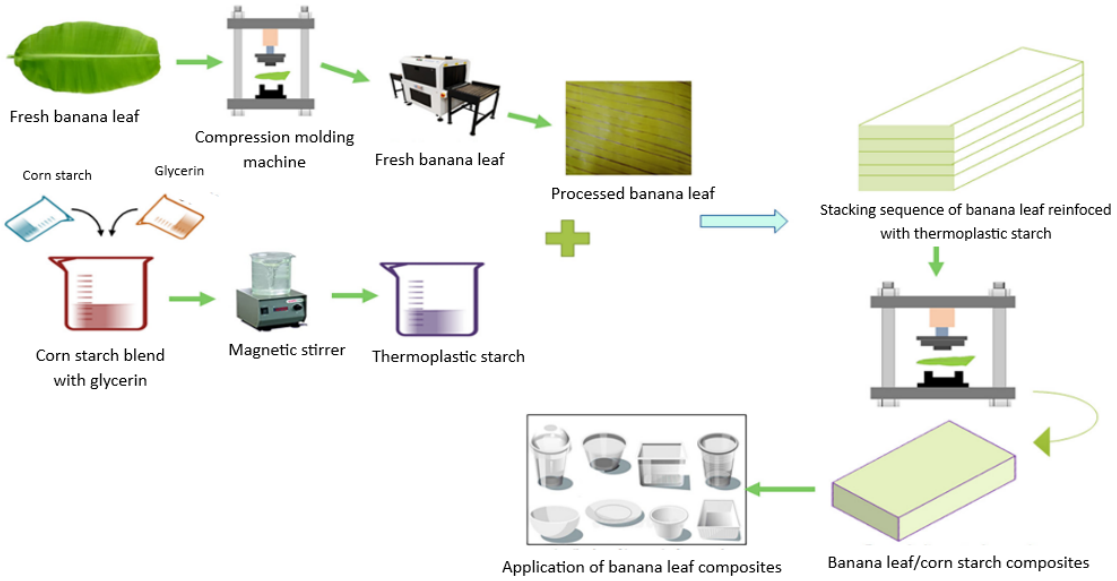

Fig. 1. Schematic illustration of the fabrication process of banana leaf/corn starch (BL/CS) sustainable composites, showing the sequential stages of leaf preparation, starch–glycerin blending, and compression molding for eco-friendly packaging applications (Arumugam et al., 2023)

Building on these developments, further innovations have explored enzymatic processing routes to convert banana leaves and sheaths into biodegradable packaging sheets. This eco-friendly method replaces conventional chemical pulping with enzyme-assisted biopulping and biobleaching, significantly reducing energy consumption and chemical discharge. The resulting pulp is then blended with starch derived from other agricultural residues to improve strength and flexibility, followed by the application of a biodegradable bioplastic coating that enhances water resistance and structural durability. Notably, the coating decomposes naturally within a few months, minimizing post-consumer waste and supporting food safety requirements. This approach represents a sustainable and economically feasible strategy for transforming banana plant biomass into functional food packaging materials consistent with circular resource flows (Jeenusha & Amritkumar, 2020).

Advancements in the field have also shifted toward converting banana leaves into high-value nanostructured materials to improve performance within next-generation biodegradable packaging systems. Through microbial fermentation processes, bacterial nanocellulose (BNC) has been produced using hydrolysates from banana leaf biomass as the primary carbon source. The resulting nanocellulose films demonstrate outstanding mechanical strength, high transparency, and superior water-retention capacity, characteristics essential for food-contact and biodegradable applications. When integrated into biopolymer matrices, nanocellulose enhances barrier properties against moisture and gases while maintaining compostability. This technique not only valorizes agricultural waste but also represents a major step toward advanced biopackaging solutions that unite renewability, high functionality, and environmental compatibility (Dáger-López et al., 2024).

Complementary assessments have examined the biodegradability and practical performance of banana leaf-based packaging under real environmental conditions. Comparative soil-burial tests between banana leaf wraps and cassava-based bioplastic packaging revealed significantly faster decomposition of banana leaf materials, with approximately 84% weight loss observed within 90 days. This rapid degradation demonstrates the material's natural compatibility with organic waste management systems. Moreover, banana leaf wraps offer adequate tensile strength and moisture protection suitable for short-term food storage and transport. These results confirm that banana leaf-based packaging not only serves as an environmentally sound substitute for synthetic plastics but also exhibits promising functionality for integration into sustainable and circular food supply chains (Myle Coratchia et al., 2024).

Expanding the technological scope of banana leaf valorization, recent studies have emphasized biochemical modification and nanostructural engineering as pathways to enhance material performance. Shiam et al. (2024) demonstrated that biodegradable films prepared from banana peel starch and plasticizers such as glycerol and citric acid can achieve tensile strengths of up to 10.56 MPa and undergo complete degradation within one week. Enzymatic treatments and nanocellulose reinforcement further enhance tensile, thermal, and barrier properties, resulting in biopolymers that compare favorably with conventional plastics in durability and gas resistance. In parallel, Hasan et al. (2024) optimized bioplastic synthesis from banana peels using controlled hydrolysis with hydrochloric acid and sodium hydroxide. Optimal hydrolysis time (15 minutes) and reagent concentration (0.5 N HCl and NaOH) produced bioplastics with improved elasticity, tensile strength (0.4086 MPa), and slower biodegradation over two months, demonstrating suitability for disposable packaging and agricultural mulch applications. These findings highlight the potential of mild chemical hydrolysis and controlled polymer modification to produce cost-effective, high-performing, and biodegradable packaging materials.

Further demonstrating the versatility of fruit-derived residues, Suntararak & Boonkate (2025) successfully produced biodegradable films from mixed fruit fibers—including carrot, guava, and banana peel—using alginate as a binding polymer. The optimal formulation (60% guava + 1.8% alginate) yielded tensile strength of 0.50 N/m^2 and elongation of 55.6%, while soil-burial tests confirmed rapid degradation within 30 days. Their findings underscore the feasibility of hybridizing banana peel fibers with other plant-based polysaccharides to enhance film integrity, flexibility, and environmental safety. Collectively, these technological innovations mark a transition from simple fiber utilization toward multi-component, bio-derived packaging systems capable of meeting industrial performance standards while supporting waste valorization and circular-economy objectives.

These technological innovations also create opportunities to enhance food quality preservation through improved packaging functionality. Advanced biodegradable packaging systems, particularly those incorporating multilayer structures and active or bioactive components, have been shown to play a crucial role in maintaining food quality during storage by controlling moisture transfer, oxygen permeability, and microbial growth. According to recent findings, improved barrier properties and the integration of antimicrobial or antioxidant functionalities in biodegradable packaging can effectively slow oxidative degradation and microbial spoilage, thereby extending shelf life and enhancing food safety. Such functional improvements highlight that innovations in sustainable packaging materials are not only environmentally beneficial but also directly contribute to preserving food quality and protecting consumer health (Wang et al., 2022).

3.2 Material characterization and functional properties banana leaf based packaging

Understanding the intrinsic material properties of banana-leaf-derived composites is essential for optimizing their performance in sustainable food-packaging applications. Recent studies on banana fiber–reinforced composites (BFRCs) provide extensive insights into the structural, mechanical, and thermal characteristics responsible for their functional behavior. The performance of BFRCs is influenced by multiple factors, including fiber content, surface treatment, fibril orientation, and matrix compatibility. Chemical modifications—particularly alkaline or silane treatments—have been shown to enhance fiber–matrix adhesion by removing surface impurities and increasing surface roughness, resulting in notable improvements in tensile, flexural, and impact strength. Hybridization with other natural or synthetic fibers has further strengthened stiffness and toughness, while the incorporation of nanofillers and multilayered composite structures has significantly improved thermal stability, heat resistance, and degradation temperature. Collectively, these findings underscore the importance of systematic characterization in understanding structure–property relationships and guiding the development of banana-fiber composites suitable for food-contact and biodegradable packaging applications (Özkan, 2024)

Building upon mechanical and thermal evaluations, researchers have increasingly turned to microstructural and crystalline analyses to better understand the performance of banana-derived materials. Nanocellulose extracted from Musa acuminata (*Kepok*) banana peel through delignification, bleaching, and controlled acid hydrolysis exhibits characteristic cellulose I crystallinity, with particle dimensions ranging from 1.71 to 1.98 nm and a crystallinity index between 53% and 56%. X-ray diffraction (XRD) patterns display dominant peaks around 2θ = 22°, confirming the presence of ordered cellulose regions, while scanning electron microscopy (SEM) images reveal irregular lump-like morphologies typical of hydrolyzed cellulose. These microstructural features indicate that controlled hydrolysis effectively tailors nanoscale architecture, enhancing the transparency, strength, and barrier efficiency of biodegradable films, is mention on Figure 2 (Putri et al., 2023).

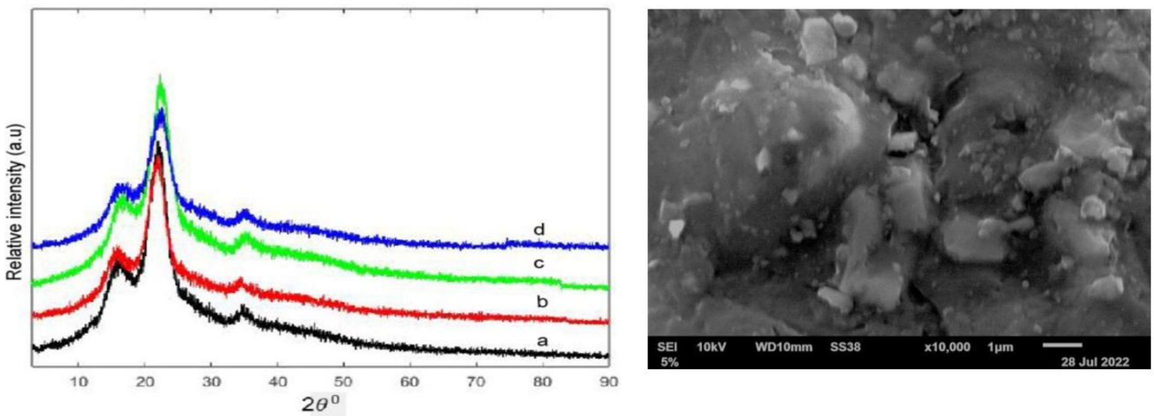

Fig. 2. (a) XRD pattern (b) SEM micrographs of nanocellulose extracted from *Kepok* banana peel, showing cellulose I peaks (2θ ≈ 22°) and irregular lump-like morphologies typical of acid-hydrolyzed cellulose
(Putri et al., 2023)

Advances in nanocomposite engineering have further highlighted the importance of nanoscale dispersion in determining functional performance. Transmission electron microscopy (TEM) analyses of cocoyam starch–banana peel nanocomposite films show uniformly dispersed nanocellulose particles embedded within the starch matrix, demonstrating strong interfacial bonding and effective stress distribution. The coexistence of elongated fibrils and spherical nanoparticles suggests partial exfoliation of nanocellulose, which improves matrix interlocking and reinforces mechanical strength. This nanoscale network structure enhances tensile properties, reduces film permeability, and increases thermal resistance, is mention on Figure 3. These observations provide direct evidence that banana-derived nanocellulose acts as an efficient reinforcement agent capable of improving film compactness, stability, and functional performance during processing and storage (Fadeyibi et al., 2022).

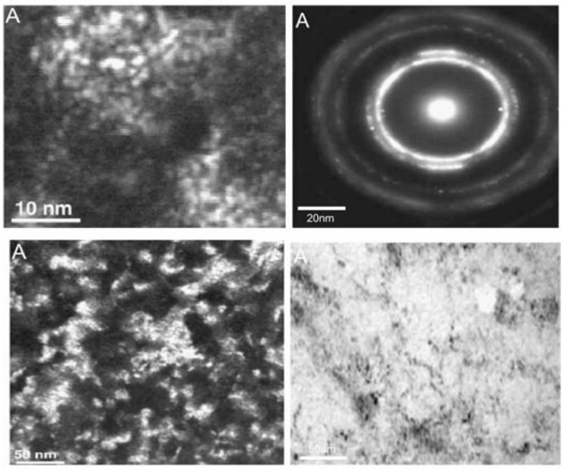

Fig. 3. TEM of banana-peel nanocomposite films showing uniform nanocellulose dispersion within the starch matrix and evidence of fibrillar network formation (Fadeyibi et al., 2022)

Parallel research has explored the bioactive functionality of banana-based films, particularly their antimicrobial properties. Films produced from banana starch and enriched with banana peel extract show significant antibacterial activity against both Gram-positive and Gram-negative pathogens. Clear inhibition zones against Escherichia coli O157:H7 and Staphylococcus aureus (TISTR 1466) demonstrate a concentration-dependent antimicrobial effect. Increasing extract concentration from 1% to 5% (w/v) significantly enhances antimicrobial activity, approaching the inhibition effectiveness of standard antibiotics such as ampicillin (30 μg/disc). The antimicrobial mechanism is attributed to phenolic compounds—including gallic acid, catechin, and epicatechin—which disrupt bacterial membranes, interfere with metabolic pathways, and inhibit cellular replication. These findings confirm that integrating banana peel extract into starch-based matrices enhances bioactive performance while offering a natural, biodegradable alternative to conventional antimicrobial packaging, is mention on Figure 4 (Taweechat et al., 2021).

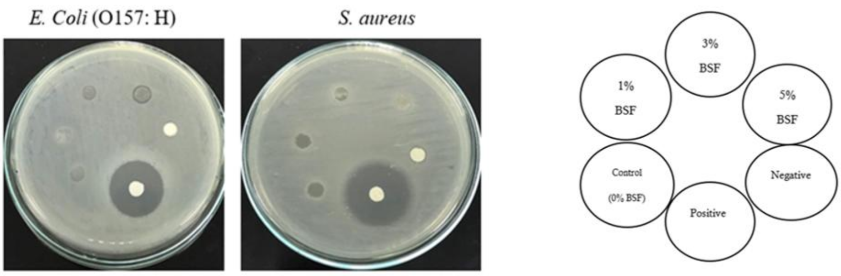

Fig. 4. Antimicrobial activity of banana-starch films containing banana-peel extract against E. coli O157:H7 and S. aureus (TISTR 1466), showing concentration-dependent inhibition zones (Taweechat et al., 2021)

Complementary studies on fiber-reinforced biocomposites further reinforce the mechanical and thermal benefits of incorporating banana fibers into polymer matrices. Mechanical testing consistently shows substantial increases in tensile, flexural, and impact strength due to improved stress transfer between the fiber and the matrix. SEM analyses reveal uniform fiber distribution and strong interfacial adhesion, supporting enhanced load-bearing capacity. Thermal analyses using thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) demonstrate elevated decomposition temperatures and increased char residue, indicating improved thermal stability and resistance to heat-induced degradation. Soil-burial studies confirm that these materials maintain high biodegradability, degrading significantly within a few months—an essential attribute for environmentally responsible food packaging. The cumulative evidence positions banana-fiber-reinforced composites as durable, biodegradable materials suitable for modern packaging applications (Kusić et al., 2020).

In summary, comprehensive material characterization demonstrates that banana-plant-derived substrates exhibit the mechanical resilience, thermal stability, biodegradability, and bioactivity required for sustainable food-packaging applications. Improvements in pretreatment strategies, nanofiller dispersion, surface modification, and film-forming techniques have significantly enhanced their structural and functional performance. However, challenges remain in scaling production, standardizing fiber quality, and ensuring consistent interfacial properties across different processing methods. Further research is therefore needed to refine fiber-matrix compatibility, optimize processing conditions, and establish standardized quality parameters to support industrial adoption. These insights form the basis for examining how material performance integrates with broader industrial and policy considerations in the subsequent section (Juani & Navaranjan, 2023). In addition to mechanical and barrier properties, the functional performance of banana leaf–based packaging materials is closely related to food quality preservation. Active and antimicrobial biodegradable packaging systems have been shown to inhibit microbial growth, delay spoilage processes, and extend shelf life while maintaining food safety and quality. These findings indicate that material performance should be evaluated not only from a structural perspective but also in terms of its effectiveness in supporting food quality preservation and shelf-life extension (Fadiji et al., 2023).

3.3 *Environmental and life cycle assessment*

Evaluating the environmental performance of banana-leaf-based packaging requires a holistic assessment of impacts across the entire value chain. Recent reviews on processed banana leaves and leaf-derived packaging materials highlight their potential to reduce plastic waste, conserve natural resources, and mitigate greenhouse gas emissions. Life Cycle Assessment (LCA) has therefore become a critical analytical framework for quantifying environmental indicators—including energy demand, water consumption, waste generation, and carbon emissions—when substituting petroleum-based plastics with renewable alternatives. Incorporating LCA early in material development ensures that sustainability gains are genuine and avoids unintended burden shifting to other stages of the product life cycle (Arumugam et al., 2023; Merino et al., 2022)

A comprehensive LCA typically follows a cradle-to-grave structure, accounting for raw material extraction, processing, production, distribution, use, and end-of-life stages. For banana-derived materials, relevant processes include banana cultivation, leaf or peel harvesting, preprocessing (washing, drying, pulping), biopolymer synthesis, and waste management through composting or biodegradation. Within this framework, the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) stages play central roles in defining system boundaries and quantifying material, energy, and emission flows. Prior assessments of the banana value chain indicate that agricultural and transportation activities disproportionately influence total carbon footprint, reinforcing the need for precise scope definition and accurate boundary setting (Bockel et al., 2018). Comparative

LCAs further demonstrate the potential of banana residues to reduce environmental impacts. Incorporating banana-rachis fibers (5–20 wt%) into recycled high-density polyethylene (rHDPE) composites has been shown to decrease life-cycle energy demand and greenhouse gas emissions while improving mechanical and thermal properties (Cabrera et al., 2023). Similarly, LCA studies on banana-waste-based bioplastics report lower global warming potential and cumulative energy demand compared with fossil-derived plastics, particularly when renewable energy inputs are used during processing (Patil et al., 2024) Collectively, these findings validate that valorizing banana residues within circular-economy frameworks can simultaneously enhance material performance and advance global sustainability targets.

Despite these advantages, methodological and practical challenges continue to limit the consistency and comparability of LCA results for banana-derived packaging materials. A key limitation is the scarcity of region-specific inventory data for banana leaf and fiber processing, which often forces researchers to rely on generic or secondary datasets that may not capture local agricultural practices or energy sources accurately (Veliz et al., 2022). Variability in cultivation methods, climate conditions, and post-harvest handling further contributes to differences in energy use and emission profiles, complicating cross-study comparisons. Additionally, allocating environmental burdens between banana fruit production and by-product utilization (e.g., leaf-based packaging) remains a significant challenge in LCA modeling (Rodríguez et al., 2020). Many assessments also simplify end-of-life modeling by assuming ideal composting conditions, which often do not reflect actual waste-management infrastructure and can lead to optimistic environmental projections (Merino et al., 2022). Addressing these data limitations through harmonized methodologies, standardized system boundaries, and open-access regional datasets is essential for producing robust, transparent, and policy-relevant LCA outcomes.

Recent applications of LCA have increasingly focused on evaluating trade-offs between environmental benefits and potential burdens in banana-fiber-based biocomposites. (Rodríguez et al., 2020) conducted a comparative LCA of coffee jar lids manufactured from banana fiber, poly (lactic acid) (PLA), and high-density polyethylene (HDPE). Their findings showed that biocomposites containing 40% banana fiber outperformed pure PLA in several environmental categories; however, agricultural activities contributed notably to eutrophication and land occupation due to fertilizer use and biomass processing. These results highlight the need for process optimization, sustainable biomass sourcing, and efficient waste-valorization strategies to ensure that material substitution yields net environmental gains, is mention on Figure 5.

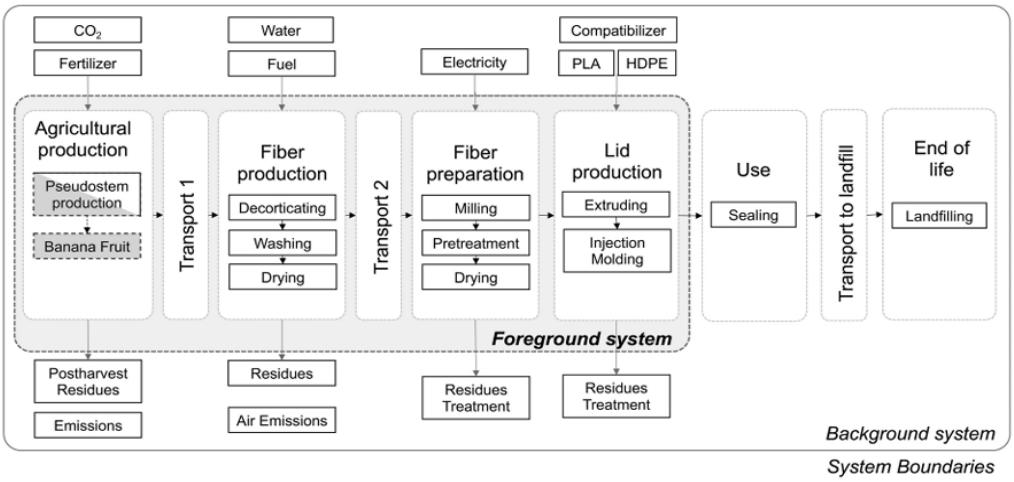

Fig. 5. system boundaries for the life cycle assessment (LCA) of banana-fiber-based biocomposite packaging materials, illustrating stages from raw material cultivation to end-of-life management (Rodríguez et al., 2020)

Complementary studies using comparative LCAs emphasize that biodegradable materials do not automatically guarantee superior environmental performance. The sustainability outcomes of bio-based packaging depend heavily on agricultural practices, energy sources, and end-of-life conditions. Intensive monoculture cultivation, chemical pretreatments, or non-renewable energy inputs can increase impacts in categories such as land occupation, eutrophication, or ecotoxicity. Therefore, integrating LCA results with circular-design principles—such as renewable energy adoption, regional biomass sourcing, and realistic disposal modeling—is essential to reduce total life-cycle burdens and avoid unintended environmental shifts (Senga et al., 2024).

In summary, valorizing banana plant residues through biocomposite production provides a promising pathway to reduce the environmental footprint of food-packaging systems. Incorporating banana fibers into polymer matrices enhances several life-cycle indicators, including global warming potential, fossil resource depletion, and cumulative energy demand. When agricultural waste such as banana pseudostems and leaves is converted into biodegradable composites, it supports waste reduction, material circularity, and renewable-resource utilization. Optimized composite formulations containing up to 40% banana fiber have demonstrated strong biodegradability and satisfactory mechanical performance, positioning them as viable alternatives to petroleum-based plastics. Future research should focus on refining pretreatment processes, enhancing fiber–matrix compatibility, and conducting comprehensive, multi-scenario LCAs across diverse production, transportation, and disposal contexts to validate long-term ecological benefits (Figueroa-Enriquez et al., 2025; Naik et al., 2025). Overall, life cycle assessment studies indicate that banana-derived biodegradable packaging can reduce environmental impacts, particularly when improved packaging performance helps preserve food quality and minimize spoilage. By linking material sustainability with food waste reduction, banana-based packaging supports resource efficiency and more sustainable food systems, provided that production and end-of-life conditions are properly optimized (Kumar et al., 2025a).

3.4 Socio-economic and policy implications

The socio-economic potential of leaf-based packaging extends far beyond its environmental advantages, offering tangible benefits for local communities and small-scale enterprises. In India, the collection, stitching, and marketing of leaves for disposable plates and food wrappers serve as vital sources of income for rural and tribal women, representing a decentralized circular-economy model grounded in renewable natural resources. Collaborations between community producers and international partners—such as Germany's Leaf Republic—illustrate how traditional practices can evolve into scalable, export-oriented industries that preserve cultural heritage while fostering economic empowerment (Kora, 2019). Comparable initiatives in Taiwan's Kavalan region demonstrate that integrating banana fibers into local handicrafts, supported by indigenous knowledge and sustainable-design principles, can stimulate rural innovation, strengthen cultural identity, and enhance community resilience (Lin & Lin, 2022).

Public perception and consumer acceptance play a decisive role in determining the market viability of biodegradable and leaf-based packaging. Empirical studies indicate that cultural familiarity, environmental awareness, and aesthetic perception significantly influence purchasing behavior and the willingness to adopt eco-friendly alternatives. Surveys conducted in Cameroon reveal a strong consumer preference for traditional leaf packaging due to its natural appearance, biodegradability, and perceived food safety (Guillaume et al., 2024). Broader assessments of biodegradable packaging emphasize that consumer trust depends on transparent labeling, verifiable environmental claims, and affordable pricing strategies. Reinforcing eco-labeling systems, strengthening consumer education, and improving communication of environmental performance are therefore essential steps to increase social acceptance and market penetration of banana-leaf-based packaging (de Oliveira et al., 2023).

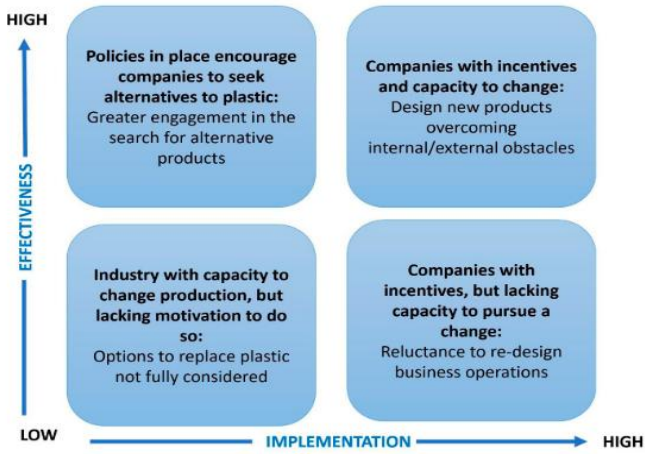

Fig. 6. Conceptual framework illustrating the interaction between biodegradability policies, certification systems, and market adoption pathways for sustainable packaging (Leal Filho et al., 2025)

Policy frameworks and regulatory mechanisms remain critical to accelerating the transition toward bio-based and biodegradable packaging. Governments in the European Union, the United States, and various Asian countries have adopted policies such as extended-producer-responsibility (EPR) schemes, eco-labeling requirements, and fiscal incentives to stimulate innovation in sustainable materials. However, disparities in enforcement and gaps in certification standards hinder international harmonization. Scholars underscore the need for unified terminology and globally accepted definitions of "biodegradable" and "compostable" to ensure fair trade practices and regulatory coherence (Thapliyal et al., 2024). Differences in biodegradability testing protocols and labeling criteria across jurisdictions further create market uncertainty for manufacturers and consumers. Addressing these inconsistencies through international collaboration and cross-sector regulatory alliances is essential for enabling large-scale adoption of renewable packaging systems, is mention on Figure 6 (Leal Filho et al., 2025).

The ongoing transition toward sustainable packaging demands an integrated policy approach that combines regulatory clarity with technological and economic incentives. Effective governance should extend beyond end-of-life waste management to include research investment, certification infrastructure, and industrial scaling for renewable feedstocks. Strengthening collaboration among government bodies, academic institutions, and private industries can help bridge policy gaps and accelerate innovation across the supply chain. With the support of coherent institutional mechanisms, banana-leaf-based materials can demonstrate how natural substrates align with circular-economy objectives and low-carbon development pathways (Cruz et al., 2022).

Integrating banana-leaf-based packaging into circular-economy systems highlights how agricultural by-products can be transformed into high-value materials while minimizing waste. Establishing a circular banana value chain enables the conversion of biomass residues—such as leaves, pseudostems, and peels—into renewable feedstocks for biopolymers, biodegradable packaging, and bioenergy (Krungkaew et al., 2023). This closed-loop approach enhances resource efficiency by reinserting organic waste into production cycles and reducing reliance on fossil resources. Complementary research on agro-food waste valorization further demonstrates that such strategies spur bio-innovation, reduce carbon footprints, and reinforce the role of banana-derived materials in global sustainability transitions (Carnaval et al., 2024).

Ultimately, advancing banana-based packaging solutions within the circular bioeconomy requires coordinated action across technological, economic, and policy dimensions. Integrating banana waste streams into renewable-material value chains, supported by biorefinery infrastructure, market incentives, and heightened public awareness, can facilitate the replacement of fossil-based plastics with biodegradable alternatives. These strategies highlight the potential of banana-leaf- and banana-peel-derived materials to contribute to inclusive, low-carbon economic growth. Realizing this potential will depend on policy coherence, international collaboration, and sustained investments in innovation to align local production systems with broader global sustainability ambitions (Fiallos-Cárdenas et al., 2022; Serratos et al., 2025). From a sustainable food systems and food safety perspective, advances in biodegradable and smart food packaging demonstrate that bio-based materials can simultaneously support environmental sustainability and effective food protection. Biodegradable films formulated from food-grade polymers have been shown to reduce chemical migration risks associated with conventional plastics while providing adequate barrier, antimicrobial, and freshness-preserving functions that help maintain food quality and safety during storage and distribution. By extending shelf life and reducing spoilage, such packaging solutions contribute to lower food loss across the supply chain and support consumer access to fresher, higher-quality foods. In the long term, the availability of safer and more sustainable packaging may positively influence dietary practices and encourage more responsible consumption patterns within resilient and circular food systems (D'Almeida & de Albuquerque, 2024; Kumar et al., 2025a).

3.5 Research gaps and future perspectives

Despite notable progress in utilizing banana-derived fibers as sustainable reinforcements for composite materials, several technological and structural limitations continue to impede their optimization for packaging and industrial applications. Existing fabrication techniques—such as hand lay-up, compression molding, and filament winding—remain predominantly manual, resulting in limited scalability and inconsistent mechanical outputs. Variability in fiber morphology, moisture content, and diameter further contributes to fluctuations in tensile and flexural properties, thereby reducing the reliability of finished composites. Although surface modification strategies such as alkaline, acidic, and enzymatic treatments have improved fiber–matrix bonding, most optimization efforts remain empirical rather than guided by predictive modeling. Overcoming these limitations will require the adoption of data-driven design tools, advanced hybridization methods, and nanotechnology-based reinforcement approaches to enhance strength, durability, and water resistance while preserving environmental compatibility (Heena et al., 2023).

Recent investigations into banana-leaf-based composites have highlighted both their substantial potential and persistent bottlenecks. While banana leaf fibers offer inherent advantages—including biodegradability, renewability, and low density—their heterogeneous structure and limited interfacial adhesion with polymer matrices hinder consistent performance at scale (Saxena & Chawla, 2020). Fiber extraction and processing methods remain labor-intensive and insufficiently standardized, resulting in inconsistent fiber quality across batches. Similarly, research on converting banana leaf ash into pozzolanic additives for construction reveals promising pathways for agricultural waste utilization, but compositional variability and limited long-term durability data restrict broader industrial adoption (Stel'makh et al., 2024). These challenges underscore the need for standardized protocols covering fiber preparation, pretreatment, and quality evaluation to ensure reproducible and reliable composite properties.

A significant gap persists between laboratory-scale innovations and industrial-level production. Existing studies largely focus on fiber treatment optimization, filler incorporation, and hybrid formulations under controlled laboratory settings, while standardized and scalable manufacturing methods remain underdeveloped (Imran et al., 2023). Labor-intensive extraction and pretreatment steps constrain production throughput, and the absence of automation contributes to inconsistent material performance. Although promising mechanical and thermal properties have been demonstrated in banana fiber nonwoven composites through specialized pre- and post-treatment techniques (Motaleb et al., 2021) these approaches remain unsuitable for continuous, high-volume production. Bridging this divide requires standardizing operational procedures and designing automated, cost-efficient technologies capable of delivering consistent material quality at industrial scales while maintaining environmental sustainability.

Ensuring the sustainability of banana-based composites also requires multidimensional assessment frameworks that integrate environmental, economic, and social dimensions. Evaluating bio-based materials solely through biodegradability or mechanical performance provides an incomplete picture of their sustainability outcomes. For instance Naik et al. (2023) found that although banana-fiber-reinforced epoxy composites exhibited promising biodegradability, the introduction of nanofillers influenced decomposition behavior and resource efficiency, revealing complex sustainability trade-offs. Likewise, Nagaraja et al. (2024) emphasized that sustainable material innovation should consider socioeconomic indicators—such as rural livelihood enhancement, equitable value distribution, and agricultural waste valorization—in addition to environmental performance. These findings highlight the importance of holistic Life Cycle Assessment (LCA) approaches that integrate energy consumption, emissions, waste generation, and end-of-life scenarios with social and economic benefits.

Progress toward widespread adoption of banana-leaf-based composites also depends on coherent policy frameworks and market transformation. Regulatory fragmentation, inconsistencies in biodegradability standards, and limited fiscal incentives continue to constrain industrial uptake. Harmonizing certification systems, establishing transparent labeling requirements, and implementing supportive policy instruments are essential to enable banana-derived materials to compete effectively with conventional plastics while ensuring regulatory integrity and industrial feasibility (Friedrich, 2024). Furthermore, policies must encourage investments in research and development, biorefinery infrastructure, and market incentives to accelerate the transition toward renewable packaging systems.

Future research should prioritize multidisciplinary and cross-sectoral approaches. Advancing the performance stability of natural fiber–biopolymer composites requires deeper insight into environmental interactions, degradation pathways, and long-term behavior under real-world conditions (McKay et al., 2024). As highlighted by Nagaraja et al. (2024) integrating structural engineering, biological modification, and socio-environmental perspectives will support the development of technically robust and socially inclusive materials. Such frameworks will help researchers move beyond laboratory experimentation toward community-centered and globally scalable material solutions.

Strengthening cross-country collaboration among tropical regions—including Indonesia, India, Thailand, several African nations, and Latin American countries—will be essential for scaling innovation and harmonizing standards. These regions share similar climatic conditions and possess abundant lignocellulosic biomass resources, facilitating shared technological development and cross-regional knowledge exchange. Establishing transnational networks can generate inclusive value chains, empower smallholder farmers, and enhance understanding of fiber behavior under diverse environmental conditions (Puttegowda, 2025).

Looking ahead, digital technologies such as artificial intelligence (AI) and machine learning (ML) are expected to play transformative roles in accelerating research on banana-based composites. AI-driven predictive modeling can estimate key performance metrics—including tensile strength, moisture resistance, and degradation kinetics—while reducing reliance on trial-and-error experimentation. Machine learning algorithms can support rapid screening of fiber formulations, optimization of processing conditions, and forecasting of long-term performance under variable environmental scenarios. Integrating these data-driven tools will enhance precision in material design, reduce innovation timelines, and improve decision-making in circular-economy applications (Karuppan et al., 2025; Uddin et al., 2025) Ultimately, the future of banana leaf–based composites will depend on the convergence of multidisciplinary research, cross-regional collaboration, and digital innovation to develop scalable, socially responsible, and environmentally resilient material solutions. In addition, future studies should extend performance evaluation beyond mechanical and environmental aspects to include food–packaging interactions under real storage conditions. Collectively, these findings suggest that banana-leaf-based packaging materials have the potential not only to reduce environmental burdens, but also to indirectly support food quality preservation by improving barrier performance and reducing exposure to harmful packaging-derived contaminants.

4. Conclusions

This review synthesizes recent technological, environmental, and socio-economic advances in banana-leaf-derived materials for sustainable food packaging. Innovations such as enzymatic pulping, nanocellulose extraction, and hybrid biocomposites have improved the mechanical, thermal, and barrier properties of banana-based substrates, supporting their technical feasibility for packaging applications. Life cycle assessments further demonstrate that valorization of banana residues can reduce greenhouse gas emissions, energy demand, and waste generation, aligning these materials with circular economy and low-carbon development objectives.

Beyond material performance, banana-leaf-based packaging shows meaningful socio-economic potential in banana-producing regions by supporting rural livelihoods and agricultural waste valorization. However, large-scale adoption remains constrained by regulatory fragmentation, limited industrial standardization, and scalability challenges. From a food science and public health perspective, banana-leaf-based packaging highlights the importance of developing food-contact materials that simultaneously support food safety, quality preservation, and environmental sustainability. For industry stakeholders, regulators, and nutrition policymakers, coordinated efforts in pilot-scale implementation, harmonized safety and biodegradability standards, and supportive policy frameworks are essential to enable responsible commercialization and integration of banana-based packaging into sustainable food systems.

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Author Contribution

The author, Ajeng Putri Ardiani, was solely responsible for the conceptualization, methodology, data analysis, and manuscript preparation, including writing, reviewing, and editing all sections of this paper.

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This study did not involve human participants, animal experiments, or sensitive data collection; therefore, ethical review and approval were not required. The research was conducted in accordance with academic integrity principles and followed standard ethical practices for literature-based studies.

Informed Consent Statement

This study did not involve human participants or the collection of personal data; therefore, informed consent was not required. The research relied solely on previously published academic literature and secondary data sources.

Data Availability Statement

This study did not generate any new datasets. All data supporting the analysis and discussion were obtained from previously published scientific articles and publicly available sources cited in the reference list.

Conflicts of Interest

The author declares no conflict of interest.

Declaration of Generative AI Use

The author utilized ChatGPT (OpenAI, San Francisco, CA, USA) to support the preparation of this manuscript, particularly in identifying relevant scholarly literature, paraphrasing academic content, and enhancing language clarity and coherence. All generated outputs were critically reviewed, verified, and edited by the author, who assumes full responsibility for the accuracy, originality, and integrity of the final manuscript.

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