Sustainable Biopolymer Composites from Banana Pseudostem Cellulose: Integrating Natural Plasticizers and Antimicrobial Agents for Eco-friendly E-commerce Packaging

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Abstract

The rapid expansion of online retail has created urgent demand for sustainable e-commerce packaging that matches the performance of conventional plastics while reducing waste and enabling circular end-of-life options. This review synthesises recent work on converting banana pseudostem - an abundant, underutilised agro-waste - into cellulose feedstock for biopolymer films, and evaluates natural, low-toxicity additives (starch, glycerol and citrus-derived extracts) to impart plasticity, flexibility and antimicrobial function. We summarise extraction pathways (conventional alkali/bleach sequences and emerging green methods such as enzymatic, Deep Eutectic Solvents (DES)/Ionic Liquids (IL) and microwave-assisted approaches), highlight how cellulose purity and crystallinity govern film mechanical and barrier outcomes, and examine plasticisation strategies (starch-based, glycerol and hybrid systems) that tune tensile and elongation behaviour. The review further collates evidence on citrus peel actives (limonene, citral, flavonoids), their extraction routes and routes to incorporate them into cellulose matrices (blending, coating, encapsulation) to deliver active antimicrobial protection relevant to transit and storage in fulfilment logistics. Across these domains we identify recurring sustainability gaps: lack of standardised, pilot-scale solvent recovery and Life Cycle Assessment (LCA) data for extraction routes; insufficient performance benchmarking under realistic humidity/temperature cycles; and sparse techno-economic analyses for feedstock valorisation and scale-up. The paper finds that banana-pseudostem cellulose, combined with waste-derived starch and controlled glycerol dosing plus citrus-based antimicrobials, offers a credible pathway to compostable, hygienic packaging for many e-commerce categories - provided remaining gaps in durability, moisture control and life-cycle validation are addressed.

Keywords: Banana pseudostem cellulose; Sustainable e-commerce packaging; Biopolymer composite films; Natural plasticizers and bioadditives; Circular bioeconomy and biodegradability

1. Introduction

1.1. Background and Motivation

There has been a rapid surge in the volume of packaging being sent out for delivery of goods purchased through e-commerce. Most of these packaging materials are made of plastics and therefore contribute to waste problems associated with landfills and ocean pollution. It is estimated that in 2019, approximately 2 billion pounds of plastic were used for e-commerce packaging [1], [2]. Additionally, this amount is expected to exceed 4 billion pounds in 2025 [3], [4]. Increased return rates in addition to increased packaging volumes, both of which are directly attributed to e-commerce, have significantly contributed to the increasing amount of packaging waste in landfills and to the problem of plastic in oceans [5], [6].

Further aggravating the environmental impact of packaging waste is the fact that the recycling rate of plastics is very low - only approximately 14% of all plastic packaging is recycled globally [7], with only about 5% of plastic packaging being reused in new products.

Thus, there is a rapidly growing need to develop packaging films made from biodegradable, renewable source materials, that meet performance requirements, but also support circular-bioeconomy objectives.

One of the most promising feedstocks for production of bio-based materials is agro-industrial by-product waste. Banana plants produce a large quantity of waste material, specifically banana pseudostems. Banana pseudostems represent a readily available lignocellulosic biomass source, that is produced annually during banana harvesting. The chemical composition of banana pseudostems have been studied, and studies indicate that they contain significant amounts of cellulose and have minimal economic utilization outside of composting [8].

Moreover, conversion of banana pseudostem biomass into bio-based packaging films will provide a valuable opportunity to convert waste biomass into a product that will help to fulfill the circular economy i.e. "waste-to-resource" paradigm and leverage the regional advantages that exist for tropical banana producing regions [9]. Therefore, conversion of banana pseudostem cellulose into bio-based packaging films represents a convergence of three key sustainability strategies: minimizing waste generation; substituting non-renewable packaging materials with renewable biomass; and utilizing locally sourced biomass. The focus of this literature review will be on this convergence and will target the following topics: extraction of cellulose from banana pseudostem biomass; incorporation of natural plasticizers and antimicrobial agents into cellulose films; and meeting e-commerce packaging requirements.

1.2. Sustainability Perspective and Relevance

For the e-commerce sector, the sustainability of packaging has been defined by three, interrelated dimensions: renewability of feedstocks; biodegradability upon end-of-product life; and minimized carbon footprint as part of a circular-bioeconomy paradigm [10]. The renewability dimension is achieved by using cellulose sourced from agro-residue materials instead of relying on polymers made from fossil fuels (like petroleum-based plastics). The biodegradability dimension will assist in avoiding long-term negative environmental impacts [11]. The impact on the environment must be considered across all dimensions of the development of bioplastics, including feedstock selection, processing and functionalization [12]. Therefore, the objective of this review is to consider the integration of the development of bioplastics with green extraction techniques, the use of natural plasticizers such as starch or glycerol, and the incorporation of bio-antimicrobial agents such as extracts from citrus plants for both enhanced functionality and for their compatibility with eco-design principles and reducing reliance on toxicological or fossil chemical products. Studies have shown that biopolymer composites, when they are developed with consideration of the end-of-product life cycle and are incorporated into circular supply chain models, can provide a significant reduction in environmental footprint in comparison to traditional petroleum-based plastic films used in the e-commerce sector [13]. As such, the value of this review stems from its integrated approach from resource, to product, to end-of-product life in an e-commerce packaging model, and supports a transition toward environmentally friendly packaging that adds value and supports circular-bioeconomic goals.

1.3. Objectives and Scope of the Review

The study reviewed all the steps from a raw material to a functionally active film. The study was based on four interconnected areas: (1) cellulose from agricultural waste (banana pseudostems) used as a source for film production; (2) plasticization of cellulose-based matrix using bio-sourced plasticizers (starch and glycerol); (3) the addition of antimicrobial agents derived from citrus fruits to provide functionality in films; and (4) mechanical, barrier, degradability and antimicrobial properties of the laboratory scale films in an e-commerce context. The review has been limited to laboratory scale composite materials which could be relevant for fulfilling e-commerce packaging needs within the circular bio-economy paradigm. To accomplish its objectives, the review identified studies that focused on: (i) renewable feedstock sources, (ii) green processing methods, (iii) additive functions incorporated into the final product and (iv) comparative testing of film properties. These aspects will allow the synthesis of existing knowledge and identification of research gaps driven by sustainability concerns. In addition, the review identifies possible pathways toward the development of scalable eco-designed packaging films for the rapidly increasing global online retail market.

2. Extraction of Cellulose from Banana Pseudostem: Methods and Sustainability Gaps

2.1. Composition and Structure of Banana Pseudostem

The pseudostem of banana plants is a lignocellulosic matrix chiefly composed of cellulose, hemicellulose and lignin, whose proportions vary with cultivar, growth stage and anatomical region [14], [15]. Reported cellulose contents in pseudostem fibres typically range between ~55–65 %, while hemicellulose often lies between ~15–25 % and lignin between ~10–15 % [16], [17], [18]. Higher cellulose contents — reaching up to approximately 71% — have been reported in banana pseudostem fibers, particularly in inner sheath fractions or selectively extracted fiber portions, where lignin and hemicellulose contents are relatively lower [19], [17]. Importantly, the outer sheaths of the pseudostem exhibit higher lignin and ash burdens compared to inner sheaths, reflecting greater structural support loads and older tissue maturity [14]. Therefore, a better-quality cellulose can be produced using the selective fractionation of the pseudostem. The inner region of the pseudostem has less lignin than the outer region and has greater access to cellulose than the outer sheaths; these areas have the ability to respond to chemical delignification methods more easily, allowing for the most effective removal of lignin from the cell wall. Consequently, higher yields of purer cellulose are obtained [15]. Understanding this spatial heterogeneity is critical for process design, since higher lignin/hemicellulose contents increase chemical, energy and solvent demands for pulp-like delignification stages, thereby influencing the sustainability of downstream film-making.

2.2. Conventional Extraction Techniques

The conventional method of extracting cellulose from the banana pseudostem begins with an alkali treatment, then is treated with bleaches, followed by optional acid hydrolysis to degrade the hemicelluloses and lignin found within the lignocellulosic matrix [20]. During the alkaline treatment step, solutions of NaOH or KOH are utilized at elevated temperatures to cleave ester and ether bonds found in hemicellulose, pectins and in lignin-carbohydrate complexes [21]. Afterward, bleaching is performed using H_2O_2 or $NaClO_2$ to oxidize any remaining lignin chromophores enabling fiber delignification [20]. Finally, some researchers will use acid hydrolysis (such as H_2SO_4) to further degrade amorphous cellulose regions or remove any residual non-cellulosic polysaccharides [8]. The order of treatments (alkali → bleach → acid) has become standard practice primarily because they are relatively simple and produce high yields of cellulose compared to untreated biomass.

Although this sequence of treatments is currently the most common way of processing plant material into cellulose, there are many reasons why this process is unsustainable. For example, strong alkalis and bleaching agents have to be heated and washed out of the system requiring a great deal of energy; strong chemicals create large amounts of chemically contaminated wastewater that require extensive neutralization prior to being discharged into waterways [20]; and in addition to generating acidic waste streams (which can also include partially degraded cellulose), acid hydrolysis reduces the crystallinity of cellulose [8]. Furthermore, it is possible for residual lignin fragments to remain on the surface of the fibers after incomplete treatment, resulting in impurities in the isolated cellulose [20]. Therefore, the lack of efficiency in the conventional extraction process presents a significant challenge to achieving sustainable production of cellulose for film and packaging applications. Consequently, while the traditional alkali/bleach/acid extraction process remains the baseline, its very high chemical energy requirements and the toxic nature of the effluent produced necessitates the search for milder alternative approaches to achieve better sustainability.

Table 1. Summary of Conventional Cellulose Extraction Techniques from Banana Pseudostem

Technique	**Typical Conditions**	**Reported Yield / Outcome**	**Key Limitations**	**References**
Alkali Treatment	NaOH (2–10 % w/v), 60–90 °C, 1–4 h; multiple washing steps	High removal of hemicellulose; increases relative cellulose proportion (50–70 % yield depending on pre-treatment)	High chemical consumption; large wash-water volumes; caustic effluent requiring neutralization	[20], [21]
Bleaching (oxidative)	H_2O_2 or NaClO-based bleaching at 40–80 °C, pH control; 1–3 cycles	Improves whiteness and reduces residual lignin; modest cellulose loss possible	Use of strong oxidants; formation of chlorinated by-products (with NaClO); energy intensive	[20]; [8]
Acid Hydrolysis	H_2SO_4 (1–64 % w/w depending on goal), 30–90 °C; short reaction times for nanocellulose	Removes amorphous regions; used for nanocellulose; reduces degree of polymerization	Corrosive acids; acidic effluent generation; risk of cellulose degradation and low DP	[8]; [17]

Combined Alkali → Bleach → Acid (Conventional Sequence)	Sequential application of the above steps, optimized per feedstock	High cellulose purity achievable; conventional benchmark for lab-scale extraction	Cumulative chemical and energy footprint; significant effluent treatment needs; limited sustainability	[20], [8], [18]

2.3. Emerging Green Extraction Methods

The adoption of novel "green" extraction techniques is growing, as well as interest in their ability to isolate cellulose from renewable feedstocks through the use of sustainable processes. Green extraction includes the use of enzymes, deep eutectic solvents (DES) and ionic liquids (ILS) and/or microwave-assisted extraction, which can provide a more environmentally friendly alternative to traditional extraction methods currently employed in the production of cellulose from agro-waste sources like banana pseudostems [22], [23]. The enzymatic process employs cellulase or other degradative enzymes that degrade hemicelluloses and lignins under mild conditions, thereby minimizing the use of harsh chemicals and resulting effluents [8]. Although enzymatic treatment of banana pseudostem produces relatively small amounts of cellulose, it results in highly crystalline cellulose with enhanced thermal stability. DES are non-toxic, biodegradable mixtures of hydrogen bond donors (HBD) and acceptors (HBA) (e.g. ChCl / urea) that represent an alternative to strong alkali or acidic solvents. Recent reviews have demonstrated that DES can effectively break down lignin-carbohydrate networks, providing high cellulose yield with the capability of recycling and reusing the solvents [23]. Ionic Liquid System (ILS), particularly those based on imidazolium cations, also allow for the dissolution or swelling of cellulose, facilitating subsequent delignification and extraction at reduced total chemical load; moreover, ILS can be recycled, thus decreasing waste [24], [22]. Furthermore, microwave assisted pretreatment can accelerate delignification and improve mass transfer, therefore reducing reaction time and energy compared to conventional heating [22]. Overall, the implementation of these green extraction technologies result in significantly less water and energy use, fewer effluent burden and increased extraction efficiency. However, the literature indicates only a limited number of pilot scale studies on the extraction of cellulose from banana pseudostems, and there is little available information on the recovery of solvents used in these studies. Therefore, if green extraction protocols are adopted into the e-commerce packaging supply chain early on, they will help support the circular bioeconomy model by using fewer resources, generating less waste, and creating cellulose materials for biopolymer film that exhibit superior performance characteristics.

2.4. Comparative Analysis of Extraction Approaches

A comparative assessment of extraction techniques from the Banana pseudostem underscores trade-offs between yield, purity, crystallinity and environmental footprint. For example, an alkaline–acid method achieved cellulose yields of just ~3.4 % (dry-basis) yet still retained substantial residual hemicellulose and lignin, resulting in relatively low crystallinity (~13.5 %) [8]. In contrast, emerging enzymatic or TEMPO-oxidation routes delivered higher crystallinity indices (~69 %) though yields remained modest (~14.6 % dry basis) [8]. When comparing more conventional chemical pretreatments with green methods, the conventional route may achieve higher nominal mass recovery in some cases but at the expense of intensive chemical use and effluent generation [17], [25].

Crystallinity improvements, critical for film performance, are clearly higher in green treatments; for instance, nanocellulose from banana biomass showed crystallinity in the 57-69 % range when DES or ILs were used and yielded recycled or reusable solvents [22]. However, scalability remains a challenge: while the chemical sequence (alkali→bleach→acid) is still widely used at pilot scale for banana pseudostem valorization [25], full life-cycle assessments (LCA) reveal higher embodied energy and water usage, and higher effluent toxicity compared to green alternatives [22]. Some LCA-type comparisons for lignocellulosic-based extraction (though not specific to banana pseudostem) show that solvent-recovery and energy-reuse loops reduce environmental impact by up to 30 % relative to conventional pulping [23]. Thus, for a packaging-film feedstock envisioned in sustainable e-commerce use, the selection of extraction route must balance output (yield + purity + crystallinity) and environmental metrics (chemical load, energy, water, effluent). The emerging green processes show promise but need rigorous scale-up and full LCA validations before commercialization.

2.5. Research Gaps and Future Directions

Despite considerable advances in extracting cellulose from the pseudostem of banana plants, several critical gaps hinder full sustainability translation. First, although green extraction protocols such as DES, ILS and enzymatic methods are described, standardisation is lacking: different studies use varying pretreatment times, temperatures, biomass pretreatments or solvent recovery strategies, making cross-comparison difficult and replication at scale uncertain [16], [22]. Second, many studies remain at bench-scale; pilot-scale or industrial-scale validation is rare, and quantitative solvent-recovery and recycling data are seldom reported. For example, yield and crystallinity improvements are noted but solvent lifecycle metrics (reuse cycles, energy for recovery, actual effluent loads) remain undocumented for banana pseudostem specifically [26]. Third, the opportunity exists to embed extraction processes into closed-loop biorefinery frameworks: pseudostem contains not only cellulose but significant hemicellulose, lignin and extractives, which could be valorised (e.g., lignin as bio-polymer or energy source) to raise overall process economics and reduce waste. Works proposing circular-bioeconomy alignment emphasise this integrated value-chain but few studies implement it for banana pseudostem [25], [27]. To move toward commercial e-commerce-packaging film feedstocks, future efforts should prioritise: (i) establishing harmonised metrics and benchmarking extraction routes (yield, purity, crystallinity, solvent reuse, energy/water use); (ii) carry out life-cycle assessments (LCA) specific to pseudostem-derived cellulose including cradle-to-gate impacts; and (iii) design extraction and downstream plasticisation/functionalisation in an integrated biorefinery concept that uses all biomass fractions, recovers reagents and minimizes effluent emissions. Addressing these gaps will facilitate the translation of laboratory-scale extraction into sustainable, scalable feedstocks for packaging-grade cellulose films.

3. Natural Plasticizers for Cellulose-Based Composites: Role of Starch and Glycerol

3.1. Need for Plasticization in Cellulose Films

Cellulose-derived films inherently suffer from brittleness and low flexibility due to the dense hydrogen-bonding network between cellulose chains, which limits chain mobility and results in poor elongation and fracture toughness [28]. As a consequence, pure cellulose films often exhibit high tensile strength but very low strain at break, making them unsuitable for packaging applications where flexibility is required to absorb mechanical stresses and accommodate handling during e-commerce logistics [29]. The integration of plasticisers into the cellulose matrix provides a mechanism to interrupt inter- and intra-molecular hydrogen bonds, enhance chain mobility and thereby improve flexibility and film-forming behaviour [30]. For instance, low-molecular-weight polyols such as glycerol are widely used to reduce modulus and increase elongation, enhancing the film's ability to bend and resist crack propagation [28]. In the context of packaging films derived from agro-waste cellulose such as banana pseudostem, plasticisation is essential to bridge the gap between rigid biopolymer structures and the performance demands of e-commerce packaging - namely durability, deformability and resilience to drop or stack forces. Therefore, understanding the role of plasticisers is a critical precursor to exploring starch- and glycerol-based systems in subsequent sections.

3.2. Starch as a Bio-based Plasticizer

Starch is an attractive bio-based component for improving the flexibility of cellulose-derived films because it is abundant, low-cost and inherently film-forming. Native starch is composed of two polymers - linear amylose and branched amylopectin - and the amylose/amylopectin ratio strongly governs film behaviour: higher amylose content generally promotes stronger, more cohesive films with higher tensile strength and greater crystallinity, whereas amylopectin-rich starches yield more extensible but less mechanically robust films [31]. When starch is blended into cellulose matrices, its hydroxyl-rich chains can form hydrogen bonds with cellulose hydroxyls, promoting miscibility and a continuous film morphology if processing (gelatinisation, casting/thermoplasticisation) is optimised [32].

The functional influence of starch in cellulose-based films is multifaceted. Small-to-moderate starch loadings can improve film transparency and gloss by filling micro-voids and reducing light scattering; however, excessive starch content (particularly amylopectin-rich fractions) can lead to retrogradation and phase separation, causing opacity and embrittlement over time [33]. Mechanically, many studies report an optimum starch fraction where tensile strength is retained or slightly improved while elongation at break increases - beyond that point, brittleness or decreased modulus may occur depending on gelatinisation and drying histories [34]. Starch also tends to increase hydrophilicity and water-uptake; this raises the need for compatibilisation (e.g., via crosslinking, incorporation of hydrophobic co-polymers, or controlled plasticiser blends) to manage dimensional stability under humid e-commerce logistics [32].

Crucially for sustainability, starch-containing cellulose films show improved biodegradability in composting and soil environments compared to many fossil-derived plasticisers and synthetic polymer blends [35]. This end-of-life advantage, together with the availability of non-food starch sources and agricultural residues, makes starch an attractive co-component for banana pseudostem cellulose films. Nevertheless, the choice of starch type (amylose ratio), processing route and the starch–cellulose interaction window remain under-explored specifically for banana-derived cellulose, and warrant targeted study to optimise performance for e-commerce packaging.

3.3. Glycerol and Polyols as Flexibilizers

Low-molecular-weight polyols such as Glycerol play a pivotal role in enhancing flexibility of cellulose-based films, primarily via disruption of inter- and intra-molecular hydrogen bonds within the hydroxyl-rich cellulose network [30], [36]. Glycerol molecules intercalate between cellulose chains, increasing free volume and chain mobility, thereby reducing rigidity and enabling higher elongation at break [37]. Mechanistically, glycerol-cellulose hydrogen bonding replaces some of the stronger cellulose–cellulose interactions, leading to lower glass transition temperature and softening of the film matrix [38], [39].

However, the effect of glycerol (and other polyols such as sorbitol or polyethylene glycol) on mechanical and barrier performance is strongly concentration-dependent. For instance, cellulose films plasticised with 10-30 wt% glycerol show marked improvements in elongation but a concomitant decline in tensile strength and modulus [38]. Higher loadings (≥ 40-50 wt%) often yield increased water vapour permeability and reduced crystallinity, undermining barrier performance [37]. In a recent study on cellulose acetate films with up to 50 wt% glycerol, films remained crack-free and flexible, though water vapour transmission increased and glycerol migration remained a key concern [40].

Blending of glycerol-plasticised systems with cellulose–starch matrices further illustrates trade-offs. The presence of glycerol in a cellulose–starch blend allows lower modulus and higher elongation, yet the overall barrier to moisture often suffers unless additional cross-linking or co-plasticiser strategies are employed [41]. For e-commerce packaging films derived from banana pseudostem cellulose, optimising glycerol content is therefore critical: too little plasticiser fails to improve flexibility; too much degrades mechanical integrity and barrier stability. Future work should therefore map the glycerol (or polyol) concentration versus performance landscape specifically in banana-derived cellulose blends, addressing migration, ageing, humidity sensitivity and synergistic effects with starch-based plasticisers.

3.4. Hybrid Plasticization Strategies

Hybrid plasticization strategies that combine starch-based and glycerol (or other polyol) plasticisers are increasingly explored to tune flexibility, strength and moisture behaviour of biopolymer films. In such systems, a starch matrix provides structural integrity and biodegradability, while glycerol provides chain mobility and softness - together offering a balanced performance [42]. For example, a co-plasticised starch film with glycerol and isosorbide exhibited improved elongation and moderate strength compared to glycerol alone, by exploiting combined hydrogen-bond disruption and polymer-plasticiser compatibility [43]. In cellulose–starch–glycerol composite films, blending starch and glycerol allows modulation of modulus: lower starch/glycerol ratios yield high flexibility but reduced tensile strength, while higher starch content preserves strength but limits deformability [44]. A key trade-off arises: increasing glycerol improves flexibility and film forming, but also increases moisture uptake and water-vapour permeability because the plasticiser increases free volume and hydrophilic sites [45]. Meanwhile, higher starch–glycerol blends sometimes lead to retrogradation or starch recrystallisation over storage, undermining long-term strength [46]. For our target of packaging films based on banana pseudostem cellulose, a hybrid plasticiser route is advantageous: the cellulose backbone offers rigidity, starch adds biodegradability and glycerol enables flexibility. However, because packaging films for e-commerce must resist moisture, drop-impact and stacking, the moisture sensitivity of glycerol-rich hybrid films must be addressed - for instance by optimising plasticiser ratio, incorporating humidity-barrier coatings or blending with moisture-resistant fillers. Thus, hybrid strategies offer a route toward tunable film properties, but must be designed with an explicit view toward the strength–moisture-sensitivity axis for sustainable packaging functionality.

3.5. Sustainability and Research Gaps

Hybrid and bio-plasticiser strategies for cellulose-based films show potential, but important sustainability and knowledge gaps remain. First, many plasticisers used (even natural ones) can derive from food-competing crops (e.g., starch from maize) or involve energy-intensive purification, raising questions about feedstock renewability and land use - thus, the ideal plasticiser would originate from non-food, waste-derived sources [46]. Second, plasticiser-modified films often show sensitivity to humidity or moisture: glycerol-rich films tend to absorb more water, soften or degrade under high humidity, reducing mechanical integrity and barrier performance [42]. Such environmental instability is a major challenge for packaging films used in variable e-commerce logistics conditions. Third, while the functional benefits (flexibility, elongation) of plasticisers are well documented, very few studies provide full life-cycle assessment (LCA) of these composite films including the plasticiser stage, use-phase moisture effects and end-of-life disposal. Recent reviews show LCA data for many biopolymer systems is limited, especially when additives/plasticisers are included [47], [48]. For banana pseudostem-derived cellulose films, the effect of starch/glycerol plasticisers on the cradle-to-grave carbon footprint, water footprint and end-of-life emissions is unquantified. To support true sustainable packaging, future research should therefore: (i) source plasticisers from agricultural or industrial residues rather than dedicated crops; (ii) assess performance under realistic humidity/temperature cycles to gauge durability; and (iii) integrate LCA and techno-economic analysis of plasticiser-modified cellulose films under e-commerce packaging use cases. Addressing these gaps will strengthen the environmental credibility of biopolymer film solutions for online-fulfilment packaging.

4. Natural Antimicrobial Agents for Cellulose Composites: Citrus-Derived Additives

4.1. Importance of Antimicrobial Functionality in Packaging

With increased e-commerce delivery distances and time spans, it has become increasingly important to incorporate antimicrobial properties into packaging films to protect products during transportation under various conditions. Antimicrobial packaging films can help extend the shelf life of food products by preventing microbial growth on the surface of products and/or within the head space of packages and therefore also minimize waste due to spoilage [49]. Additionally, increasing demands for consumer assurance of product cleanliness and safety combined with consumer reluctance to utilize synthetic preservatives are shifting interest toward using natural antimicrobial agents in packaging materials [50]. Natural-agent embedded films provide consumers with cleaner labeling and meet hygiene standards associated with direct-to-consumer delivery systems when used to replace or lessen the amount of synthetic antimicrobial additives. With cellulose-based films that are made from agro-residue sources such as banana pseudostems, incorporation of citrus-derived natural antimicrobial agents can contribute to both bio-based packaging material structures and provide active antimicrobial protection. Therefore, citrus-derived natural antimicrobial agent based cellulose films represent a dual benefit for modern e-commerce packaging and address both sustainability and hygiene functions.

4.2. Citrus Peel Extracts and Their Active Components

Citrus peel, which is often considered to be an agri-industrial waste, is a rich source of bioactive compounds including monoterpenes (limonene, citral); flavonoids (hesperidin, naringin) and other phenolics that can inhibit microorganisms. The broad-spectrum antibacterial efficacy of limonene, the major volatile in many citrus peel essential oils, can be explained by its ability to disrupt the integrity of bacterial cell membranes and cause leakage of cellular contents [51]. Citral (geranial + neral) exerts its antimicrobial action through disruption of bacterial cell membranes and/or cell wall structure, especially on Gram-positive microbes [52]. In addition to acting as membrane-disrupting agents, flavonoids like hesperidin and naringin inhibit the enzymatic activity of microbes and affect the permeability of their cell walls [53].

The recovery of these compounds from citrus peels is becoming increasingly less reliant on traditional solvent extraction and hydrodistillation processes, with a focus on more sustainable alternatives. For example, supercritical CO_2 extraction (with ethanol as a co-solvent) was successful for recovering volatiles from Citrus grandis peels at high levels of purity (~95.6%) and for recovering naringin with excellent antimicrobial properties [51]. Ultrasound-assisted solvent extraction and microwave-assisted solvent extraction were effective for recovering flavonoids and volatiles from citrus peels with good yields and short process times [52], [54]. Additionally, solvent systems like deep eutectic solvents (DES) show great potential for the green extraction of flavonoid-terpenoid fractions from citrus waste [54]. These new methods create a pathway towards sustainability in packaging by enabling the use of citrus-derived extracts, not only to add value to waste materials, but also to introduce natural antimicrobial active components into cellulose-based packaging, thereby extending shelf life and maintaining hygiene standards for e-commerce packages.

4.3. Incorporation into Cellulose Matrices

Citrus-derived antimicrobial agents blended into cellulose-based matrices involve several established methods - blending, surface coating and encapsulation/impregnation - each influencing film morphology, optical clarity and mechanical properties in unique and varied manners. When using the blending method, citrus peel extract or essential oils are simply added into a cellulose solution (or dispersion) before being cast into a film to provide an even distribution of the active. For example, studies have shown that when orange-peel powder was blended into polysaccharide films there were improvements to the antimicrobial activity however, as the concentration of the blend increased so did the phase separation of the blend which affected both the films optical clarity and tensile strength [55]. The surface coating technique allows for an antimicrobial coating to be applied on top of a previously formed cellulose film. This allows the mechanical properties of the cellulose film to remain intact while still providing an antimicrobial coating at the interface between the two layers, however, it is necessary to manage the adhesive characteristics of the antimicrobial coating to prevent migration of the antimicrobials [56]. Encapsulation and/or supercritical-CO_2 impregnation of citrus actives into cellulose matrices post-film formation allows for controlled release of the citrus actives while minimizing the disturbance to the film's physical structure [52].

Microscopically, incorporation of citrus extracts may affect the micro-structure of the film. For example, SEM images of cellulose acetate membranes loaded with tangerine peel extract indicated that the membrane exhibited smoother surfaces and lower porosity than non-loaded films due to interactions between the extract and the polymer; however, these membranes had decreased tensile strength and increased dimensional variability [57]. If the essential oil droplets form aggregates or crystals, then the optical clarity of the film may decrease. Therefore, it is important to achieve a uniform distribution of the citrus actives at low concentrations (< 5 wt %). Antimicrobial loading typically decreases the modulus and strength of the film but increases the elongation and toughness if the distribution of the actives is good and plasticization is appropriate [58]. Moreover, the development of a bio-degradable film made from cellulose-based materials derived from banana pseudostem with incorporated citrus actives provides an opportunity to develop a sustainable and renewable product with the capability to provide hygiene functions for e-commerce packaging products. However, obtaining a transparent film, one with sufficient mechanical properties and minimal active migration will continue to be a technological challenge. To further evaluate the performance of coatings, blends and impregnations in banana-cellulose matrices under realistic handling and storage conditions will require future research efforts.

4.4. Antimicrobial Efficacy and Mechanisms

Natural citrus actives (limonene, citral, flavonoids) exert antimicrobial effects via multiple, often complementary, mechanisms. The primary and best-documented pathway is membrane-targeting: lipophilic monoterpenes (e.g., limonene, citral) partition into and disrupt phospholipid bilayers, increasing membrane fluidity and permeability and causing leakage of ions, ATP and macromolecules, which rapidly compromises cell viability [59], [60]. Secondary mechanisms include perturbation of energy metabolism (inhibition of oxidative phosphorylation), enzyme inactivation and induction of oxidative stress through reactive oxygen species generation, particularly for polyphenolic fractions [59]. Comparative studies have demonstrated that although some of the essential oil components work much faster than the polymeric antimicrobials (such as chitosan) as membrane disruptors, chitosan acts on the cell membranes through an electrostatic attraction to the negative charge of the cell membrane, creating a physical barrier that interferes with cell metabolism and has been shown to cause cell aggregation and lysis - actions which are dependent upon pH and can be additive (synergistic) when used in combination with essential oils [61], [62]. A critical advantage of using different modes of action in developing formulations for packaging, is that they allow for development of formulation strategies: the volatile nature of the terpenes allows for very rapid contact inactivation (surface hygiene), while the chitosan or flavonoid rich fractions will allow for longer term, contact mediated protection and slow release. Complementary mechanisms can be optimized through understanding how to utilize them together (e.g., using a fast acting terpene with a film bound layer of chitosan) to achieve optimal immediate antimicrobial effectiveness and long term protection in cellulose based packaging systems.

4.5. Sustainability Gaps and Future Directions

Standardization of antimicrobial testing for packaging systems remains fragmented: methods adapted from clinical Antimicrobial Susceptibility Testing (AST) (disk diffusion, broth microdilution) or food-pathogen assays produce inconsistent results for volatile, hydrophobic citrus actives, complicating comparability across studies and product development [63], [64]. Early-stage research therefore often reports efficacy that is not translatable to real packaging conditions [65].

Economic feasibility is another key barrier. Several techno-economic studies show promising valorisation routes for citrus peel (extraction of essential oils, flavonoids, pectin), but profitability depends heavily on process scale, co-product valorisation and local supply chains; pilot- and plant-scale cost data are still scarce [66], [67]. Without reliable TEA inputs, circular-economy claims for citrus-derived antimicrobials remain tentative.

Finally, integrated environmental assessments are limited: although some LCAs exist for citrus by-product valorisation, few studies examine the combined impacts of extraction, incorporation into biopolymer films, and end-of-life behaviour. Ex-ante/prospective LCA frameworks can help, but have rarely been applied to citrus-derived active packaging at pilot TRLs [68], [69]. To advance sustainable deployment, the field needs (i) harmonized antimicrobial testing protocols suited to volatile plant actives, (ii) transparent pilot-scale TEA data for citrus valorisation chains, and (iii) prospective LCAs that link process scale-up to realistic end-of-life scenarios.

5. Lab-Scale Evaluation of Composite Films: Mechanical, Barrier, and Biodegradation Properties

5.1. Mechanical Performance

Mechanical performance of composite films is routinely assessed via tensile strength, elongation at break and Young's modulus, usually following ASTM D882 or ISO 527 standards for thin films. Typical biopolymer film tensile strengths vary from ~10–70 MPa, elongation from ~2–30 % and modulus from ~500–2000 MPa depending on formulation and processing [70], [71], [72]. In cellulose-based films derived from agro-residues such as banana pseudostem, higher purity cellulose correlates with higher tensile strength and modulus due to strong hydrogen-bond networks, but may reduce elongation [70], [71]. The addition of plasticisers (e.g., starch or glycerol) typically decreases modulus and strength while increasing elongation: for example, glycerol-plasticised regenerated cellulose films exhibited tensile strengths above 80 MPa at low plasticiser loadings, but strengths dropped when plasticiser content exceeded ~30 % [72]. In cellulose-starch-glycerol matrices the plasticiser ratio becomes critical—lower ratios (≤20 %) maintain strength (30–50 MPa) while enabling elongation (10-20 %), whereas higher plasticiser loadings result in elongations >30 % but strength below 20 MPa [30]. For e-commerce packaging applications, a balance is required: film must resist handling stresses (modulus and strength) while offering flexibility to absorb shock and bending. Thus in banana pseudostem cellulose-based composites the mechanical testing provides insight into how extraction purity and plasticiser loading affect ultimate performance and guide formulation towards packaging-grade behaviour.

5.2. Barrier Properties

The barrier properties of films made from biopolymers are very important for packaging applications; particularly for e-commerce customers, because moisture can enter through a film and cause deterioration in the product, while oxygen entering through a film can contribute to spoilage of perishable products. The two most commonly used parameters to measure barrier properties are the water vapour transmission rate (WVTR), which is expressed in units of $g/m^2/24h$ at specified levels of humidity, and oxygen permeability (OP or O2P), which is measured in units of $cm^3/m^2/24hr/atm$. Typically, cellulose based films have WVTR values that range between approximately 15-60$g/m^2/24hr$ at moderate humidity conditions, and the oxygen transmission rates of cellulose films can be less than 1$cm^3/m^2/24hr/atm$ with high crystallinity and high density films [71], [73]. The addition of plasticizers, such as glycerol or starch into cellulose films will influence their barrier properties significantly: an increase in glycerol concentration will result in increased free volume and hygroscopicity of the cellulose film, resulting in an increase of the WVTR value of up to 40% relative to unplasticized cellulose films [28]. Conversely, higher starch content at fixed plasticiser loading can reduce WVTR by promoting tighter network formation and lesser free volume [74]. Moreover, addition of citrus-derived antimicrobial extracts or essential oils can further modify barrier behaviour - small amounts (≤ 5 wt %) of limonene-rich citrus peel extract blended into cellulose films reduced Oxygen Permeability (O_2P) by ~30 % due to filling of micropores and increased tortuosity, but increased WVTR modestly due to increased hydrophilicity from extract residues [55]. Thus, in banana-pseudostem cellulose-based composite films the balance between plasticiser ratio (starch/glycerol) and active-agent inclusion becomes a design lever: lower WVTR and O_2P favour packaging robustness, but trade-offs may emerge in flexibility or transparency. For e-commerce packaging of moisture-sensitive goods, formulations with starch-rich matrices, low glycerol loadings and carefully dispersed citrus actives appear most promising. Future work should report standardized barrier data (ASTM E96, ASTM D3985) under packaging-realistic humidity and temperature cycles.

5.3. Biodegradability Assessment

Biodegradability testing of cellulose-based composite films is essential to validate end-of-life credentials and compare with conventional plastics. Common laboratory methods include soil burial tests, composting trials and enzymatic degradation assays; each environment imposes different microbial, temperature and moisture conditions relevant to real disposal pathways [75]. For instance, soil-burial experiments on regenerated cellulose films demonstrated complete decay within 63 days in summer and 112 days in spring under controlled moisture, compared with hundreds of years required for conventional fossil-derived plastics [76]. Composting protocols typically measure CO_2 evolution or mass-loss under thermophilic conditions; biopolymer films may reach 70-90 % mass loss over 90 days, whereas polyethylene films show negligible change [77]. Enzymatic degradation tests provide mechanistic insight but are less representative of field conditions. Plasticiser type and load affect biodegradation kinetics: films plasticised with glycerol and starch tend to degrade faster as plasticiser migration creates porosity and increases microbial access [78]. However, inclusion of hydrophobic additives or citrus-derived antimicrobials can slow degradation by reducing moisture uptake and microbial colonisation [79]. For packaging applications, especially in the e-commerce sector, composite films derived from banana pseudostem cellulose must demonstrate a reliable biodegradation profile under realistic soil or compost conditions. Moreover, standardized reporting (mass loss %, CO_2 evolution, residuals) and direct comparison with conventional plastics such as LDPE or PP are urgently needed to support sustainability claims.

5.4. Antimicrobial Testing Methods

To evaluate antimicrobial action in packaging film accurately, you need to use a method that simulates the physical phenomena of contact, diffusion, and release. Disk (or agar) diffusion is still one of the most popular ways to do this; you place a thin disc made of the packaging film, or an extract impregnated into the disc, onto pathogen-inoculated agar, allow for incubation and measure the diameter of the inhibition zone as evidence of antimicrobial action [80]. While the disk diffusion assay is useful because of its convenience, it is primarily suited to assessing diffusable agent activity and may therefore underrepresent the effectiveness of films against contact-killing. Contact-killing assays better model how packaging materials interact with microbes (the film is inoculated with bacterial suspensions, incubated, and then the number of colony-forming units are counted); Microbial growth inhibition assays (e.g., broth micro-dilution or film extract in suspension) provide a means of quantifying the effects of citrus extracts that have been incorporated into films at varying concentrations [81], [82]. The concentration of citrus-based antimicrobials (e.g., limonene, citral), however, can have a substantial impact upon the outcome of such studies; several studies demonstrate that there exists a concentration dependent threshold level (wt% ~0.5-5 wt%) below which little-to-no significant zone of inhibition can be detected, while above this threshold level activity will plateau due to either saturation of the film matrix by the active agent(s), or disruption to the structure of the film matrix [83]. Therefore, consistent normalization of test conditions (i.e., inoculum size, incubation time, humidity, temperature) and reporting standards (e.g., log reduction, inhibition zone mm, release kinetics) continue to be a major issue across the field of antimicrobial packaging research, thereby making comparative analysis of results between different studies problematic. Hence, when evaluating cellulose-based composite films prepared using banana pseudostem and incorporating citrus-based antimicrobials, it is essential to assess each film using a combination of disk diffusion, contact-killing and microbial growth inhibition assays simultaneously, and to collect and present both concentration response data and release profiles to support the validity of claims regarding their antimicrobial performance.

5.5. Integration Toward E-commerce Packaging Requirements

For e-commerce packaging, composite films based on banana-pseudostem cellulose must align with real-world demands: flexibility to accommodate handling and drop stresses; shelf-life extension via robust barrier and antimicrobial performance; cost-effectiveness; and scalability of production [84]. Flexibility is especially critical in fulfilment-logistics contexts where packaging is widely stacked, bent or compressed - conventional plastics deliver elongation rates of 200 %+, but biopolymer films often achieve only 10–30 % [85]. Trade-offs therefore emerge: adding plasticisers or antimicrobial agents improves flexibility and hygiene but may raise cost or complicate manufacture. Cost-models indicate that raw-material cost contributes up to 40 % of film cost in biopolymer systems, and scale reduces this only when roll-to-roll converters achieve > 500 tonnes annual output [86].

Future challenges include effective moisture control (given that e-commerce packages transit variable climates), durability under repeated handling, and recyclability or compostability at end-of-life. Many biopolymer films demonstrate composting performance, but few have demonstrated full circularity [87]. Moreover, integration with existing packaging lines (heat-sealing speeds, print compatibility) remains under-explored [86]. To fulfil this transition, banana pseudostem-based film solutions must not only meet mechanical, barrier and antimicrobial benchmarks in the laboratory but also pass pilot-scale validation in fulfilment-logistics environments and couple with cost-and-life-cycle assessments to ensure true economic and environmental viability.

6. Conclusion and Future Outlook

This review positions an integrated sustainability pathway: adopt green extraction to recover high-quality cellulose from banana pseudostem → apply natural modification (starch, glycerol, hybrid plasticisers) to tune mechanical and barrier properties → functionalise films with citrus-derived antimicrobials to extend shelf life and hygiene. When these stages are designed together within a circular-bioeconomy framework - valorising co-products (hemicellulose, lignin, pectin), recovering solvents, and prioritising waste-derived plasticisers - the resulting films can displace single-use fossil plastics in many e-commerce segments while offering compostable end-of-life routes. However, moving from laboratory promise to industrial translation requires focused action on three fronts.

First, scale-up and pilot validation: laboratory reports must be translated into roll-to-roll pilot lines that demonstrate consistent film casting, active dispersion, heat-sealing performance and compatibility with existing fulfilment-line equipment. Pilot studies should capture solvent-recovery efficiency, energy consumption and actual throughput to inform realistic techno-economic assessments.

Second, performance benchmarking under realistic logistics: standardized test batteries (mechanical shock/drop, cyclic bending, ASTM/ISO barrier protocols under variable RH and temperature, and sustained antimicrobial challenge tests) are required to define target specifications that match real e-commerce handling and storage windows.

Third, integrated sustainability and regulatory validation: comprehensive cradle-to-grave LCAs and transparent TEAs must accompany scale-up to quantify carbon, water and waste benefits versus incumbent plastics. Regulatory acceptance (food contact, antimicrobial claims, biodegradation certification) must be pursued early to de-risk market entry.

In short, banana pseudostem-derived cellulose films with natural plasticisers and citrus actives offer a technically and environmentally promising route to sustainable e-commerce packaging. Realising this potential mandates coordinated research-to-pilot programs, harmonised testing frameworks, and economic+LCA evidence to support industrial adoption and policy incentives that accelerate circular, bio-based packaging solutions.

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