Development of Biopolymer Packaging Material Derived from Pineapple Peel: A Comprehensive Review

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***Abstract*—This review highlights recent advancements in the development of biopolymer packaging materials derived from cellulose extracted from pineapple peel, emphasizing its potential as a sustainable and eco-friendly alternative to conventional plastic packaging. Cellulose, the most abundant natural polymer, is known for its biodegradability, renewability, and non-toxicity, making it an ideal candidate for green packaging applications. Pineapple peel, a commonly discarded agricultural waste, is rich in cellulose and represents a promising raw material for producing biodegradable films. The review examines the sources of cellulose with a particular focus on pineapple peel and evaluates various extraction techniques, including chemical and environmentally friendly methods, aimed at optimizing yield and quality. It also explores modifications of cellulose through physical and chemical treatments to enhance mechanical, thermal, and barrier properties essential for packaging functionality. The versatility and biodegradability of cellulose-based films, along with their potential to reduce plastic waste, are discussed, as well as challenges related to scalability and production cost. Emerging applications in food packaging and other sustainable material uses are considered. Future research directions include improving extraction efficiency, enhancing film properties through biopolymer blending, and expanding the application scope of pineapple peel-derived cellulose films. Overall, this review underscores the potential of pineapple peel cellulose as a low-cost, sustainable biopolymer for packaging materials, contributing meaningfully to the reduction of plastic pollution.**

***Index Terms*—Pineapple peel, cellulose extraction, biopolymer packaging, biodegradable film, sustainable materials.**

1. INTRODUCTION

Packaging plays a vital role in the modern food supply chain. At its core, packaging material serves as a protective barrier that preserves food quality, extends shelf life, enhances safety during transportation and storage, and ensures consumer convenience [1]. With growing global food demand, packaging has become more than just a container it is an indispensable part of food distribution and marketing [2]. Traditionally, synthetic plastics such as polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polyvinyl chloride (PVC) have dominated the packaging industry due to their affordability, durability, lightweight nature, and ease of processing [3]. However, these materials come with a major drawback: they are derived from non-renewable fossil fuels and are non-biodegradable, causing long-term ecological damage.

The widespread use of plastic packaging has led to severe environmental consequences. Globally, over 400 million tonnes of plastic are produced annually, and around 40% of this is used for packaging purposes most of which is discarded after a single use [4]. India alone generates more than 5 million tonnes of plastic waste every year, and over 40% of this waste remains uncollected or mismanaged, contributing to land, water, and air pollution [5]. These plastics persist in the environment for hundreds of years, leaching toxic chemicals and entering the food chain, impacting more than 600 terrestrial and marine species, and raising concerns about human health [6,7]. As awareness of these environmental issues grows, so does the call for sustainable, biodegradable alternatives to conventional plastic packaging. Food packaging in particular demands solutions that are not only eco-friendly but also food-grade, safe, mechanically sound, and capable of preserving food quality [1]. Several biodegradable materials such as starch, chitosan, polylactic acid (PLA), and polyhydroxyalkanoates (PHA) have emerged as potential substitutes [8]. Among these, cellulose stands out due to its biodegradability, film-forming ability, high mechanical strength, and natural abundance [9].

Cellulose is the most abundant organic polymer on Earth, comprising approximately 1.5 trillion tonnes in the biosphere annually, sourced from plants, algae, and agricultural waste [10]. It can be chemically modified and blended with plasticizers or natural polymers to enhance its film-forming properties, making it highly suitable for packaging applications. Furthermore, the integration of bioactive compounds such as essential oils can provide antimicrobial and antioxidant properties to cellulose-based films, enhancing their functionality and extending food shelf life [11]. While primary sources like wood pulp are traditionally used for cellulose extraction, the valorisation of agro-industrial waste is a more sustainable and cost-effective approach. Among various options such as banana peels, corn husks, sugarcane bagasse, and rice straw, pineapple peel emerges as a particularly promising candidate. Pineapple peel constitutes 30–35% of the fruit's total weight, and is typically discarded or used as low-value compost [12]. However, it is rich in cellulose, hemicellulose, lignin, and bioactive compounds like bromelain, making it an underutilized but highly potent resource for packaging applications [13].

Moreover, pineapple cultivation is widespread in tropical countries like India, the Philippines, Thailand, and Brazil. India ranks among the top five pineapple producers globally, and generates substantial volumes of peel waste, especially from juice processing and canning industries [14]. Utilizing this waste not only supports the circular bioeconomy but also adds value to agricultural residues, aligning with India's sustainable development goals and Plastic Waste Management Rules (2016, amended in 2022).

Advances in green extraction methods such as ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), and enzymatic hydrolysis have further enhanced the sustainability and efficiency of cellulose recovery from pineapple peel, reducing chemical usage and environmental impact [15,16].

With the global biodegradable packaging market valued at USD 89 billion in 2023 and expected to exceed USD 140 billion by 2030 [17], there is immense potential for innovations in cellulose-based packaging. This review seeks to explore the viability of pineapple peel-derived cellulose as a next-generation biodegradable material for food packaging. It emphasizes current extraction methods, film formulation techniques, performance attributes, and the broader implications for environmental sustainability and industrial scalability. By advancing the utilization of pineapple waste, this research supports the global shift toward eco-conscious packaging solutions, aiming to reduce plastic dependency and promote sustainable living [18].

The objective of this review is to provide a comprehensive overview of the potential of pineapple peel-derived cellulose in the development of biodegradable packaging materials. It covers the various extraction techniques for isolating cellulose, and its formulation into functional packaging films. The scope extends to evaluating mechanical, thermal, and barrier properties, as well as real-world applications, commercial viability, and environmental impact. By consolidating current research findings, this review aims to highlight the scientific advancements, challenges, and prospects associated with the valorisation of pineapple peel as a sustainable packaging solution.

2. OVERVIEW OF CELLULOSE SOURCES

Cellulose is the most abundant renewable biopolymer found in nature, accounting for nearly 50% of the dry weight of plant biomass and playing a crucial structural role in plant cell walls [20]. It is primarily obtained from wood (40–50%), cotton (up to 90%), agricultural residues, and non-wood sources such as flax, hemp, jute, bamboo, and grasses. Among these, wood pulp remains the dominant industrial source, while cotton linters provide the purest form of cellulose. Additionally, significant quantities of cellulose are extracted from agro-industrial wastes like sugarcane bagasse, wheat straw, rice husk, and fruit peels, which offer a sustainable and low-cost alternative [20, 21]. Cellulose can exist in various morphologies and degrees of polymerization depending on its source and extraction method. These include microcrystalline cellulose (MCC), nanocrystalline cellulose (CNC), and cellulose nanofibrils (CNF). CNCs and CNFs have drawn attention due to their excellent mechanical strength, surface area, and ability to reinforce biodegradable films [22]. For example, CNCs extracted from tunicates exhibit the highest crystallinity (~90%), while those from wood and cotton range between 60–80% [21]. The selection of source and treatment method significantly influences the crystallinity index, aspect ratio, and thermal stability, all of which impact the final application in packaging and biomedical fields. A comparative summary of various cellulose sources, their composition, crystallinity, common additives, and application relevance is presented in Table 1, emphasizing the suitability of pineapple peel as a high-potential raw material for biodegradable packaging.

The incorporation of additives and polymeric blends further enhances the performance of cellulose-based materials. For instance, glycerol, sorbitol, and polyethylene glycol (PEG) are widely used as plasticizers to improve flexibility and processability, although they may reduce water resistance [22]. Natural additives such as essential oils, plant extracts, and chitosan are increasingly used to impart antimicrobial and antioxidant properties, making cellulose films suitable for active packaging. Furthermore, chemical surface modifications like esterification, oxidation, and etherification allowing for tailored hydrophobicity, barrier properties, and compatibility with other biopolymers [20].

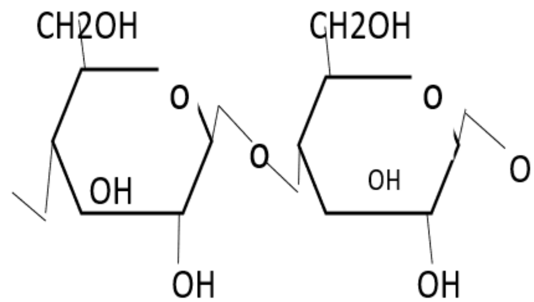

Fig 1: Structure of cellulose

With their high abundance, tunable structure, and biodegradability, cellulose and its nanostructured forms present an ideal platform for developing functional materials. The global shift toward sustainable and bio-based alternatives further amplifies the importance of exploring diverse cellulose sources and optimizing them for packaging, healthcare, and composite applications [19,22].

Table 1: Comparison of Cellulose Sources Based on Content, Crystallinity, Additives, and Application Suitability

Cellulose Source	Cellulose Content (%)	Crystallinity Index (%)	Notable Additives or Blends	Application Suitability	Reference
Cotton Linters	~90	70–80	PEG, glycerol	High-purity films, medical applications	[19]
Wood Pulp (Hardwood)	40–50	60–70	PLA, starch	Paper, packaging, composite boards	[20]
Hemp/Flax Fibers	60–77	65–75	PLA, chitosan	Composites, reinforcement fillers	[22]
Banana Peel	25–30	~60	Glycerol, sorbitol	Biodegradable films, low-cost packaging	[21]
Rice Husk	30–35	~70	Epoxy, PVA	Reinforced plastics, insulation materials	[19]

Pineapple Peel	41.8–48	80.9	Starch, CMC, turmeric oleoresin	High-performance biodegradable packaging films	[23,24]

3. PINEAPPLE AS A PROMISING SOURCE OF CELLULOSE

In the pursuit of sustainable cellulose resources, fruit processing residues have emerged as valuable agro-waste candidates. Among these, pineapple (*Ananas comosus* L. Merr.) peel constituting approximately 30–35% of the fruit's mass offers substantial potential for value addition [25]. Rich in fibre-rich fractions (FRFs), including cellulose (up to 48 g/100 g dry weight), hemicellulose, lignin, and pectin, pineapple peel not only supports the development of biodegradable materials but also contributes to circular bioeconomy goals [26]. Its physicochemical properties, such as high water- and oil-holding capacities (7.94–12.3 mL/g and 5.84–8.64 g/g), and cation-exchange capacity (102–120 meq/kg), further reinforce its suitability for material applications. The peel is also nutritionally rich, containing carbohydrates, vitamin C, minerals (Ca, K, Mg), and bromelain an enzyme with proven therapeutic and digestive functions [25,27]. Due to its fermentable sugars and nutrient content, pineapple peel is also used as a microbial substrate in biosurfactant and protein-rich feed production through solid-state fermentation [28,29]. These multifaceted uses position pineapple peel as a key agro-industrial residue for resource valorisation. In terms of biopolymer development, pineapple peel has shown comparative advantages over other fruit peels. Studies revealed that pineapple peel yielded cellulose with a crystallinity index of 80.9%, outperforming banana and papaya peels, which had significantly lower values. This higher crystallinity contributes to improved mechanical and thermal properties critical factors in biofilm applications [23]. Moreover, bleaching treatments applied to pineapple peel resulted in enhanced thermal stability, making the extracted cellulose more suitable for industrial-scale processing. Fig 2 illustrates the comparative crystallinity index of cellulose extracted from various fruit peels, emphasizing the structural advantage of pineapple peel for film development.

In another comparison, pineapple peel exhibited higher hemicellulose content and better removal efficiency under alkaline conditions, which allowed to produce pure cellulose with improved mechanical strength [30]. Cold plasma-assisted pretreatment using Fe^{2+} ions further improved the quality of cellulose nanofibrils from pineapple peel, outperforming similar treatments applied to banana and papaya [24]. These advancements underscore pineapple peel's superior behaviour in both extraction and processing techniques.

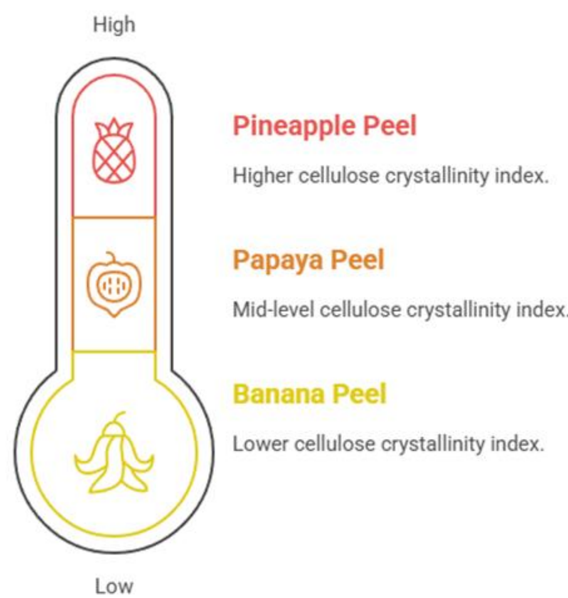

Fig 2: Comparing fruit peels based on cellulose crystallinity index.

Beyond cellulose, the broader composition of pineapple biomass including crown, stem, leaves, and pomace also holds potential for producing a spectrum of value-added products such as bioethanol, biofertilizers, enzymes (e.g., bromelain), and biopolymers [31, 32, 33]. The integration of green technologies such as microwave-assisted extraction (MAE), enzymatic hydrolysis, and hydrothermal pretreatment has improved the sustainability of these conversion processes [34, 45].

4. EXTRACTION TECHNIQUES OF CELLULOSE FROM PINEAPPLE PEEL

As the demand for biodegradable materials intensifies, the extraction of cellulose from agro-industrial residues like pineapple peel is gaining considerable traction. Pineapple peel, rich in lignocellulosic content, requires carefully optimized processes to isolate high-purity cellulose for biofilm development. Various methods, including chemical, mechanical, and enzymatic treatments, have been explored to improve extraction yield, crystallinity, and material quality while aligning with sustainability goals.

4.1 CHEMICAL METHODS

Studies have explored a range of chemical extraction protocols for isolating cellulose from pineapple peel, with variations in reagent concentration, treatment duration, and resulting yield. For instance, alkaline treatment conditions were optimized using 5% NaOH at 80°C for 2 hours, achieving a cellulose yield of approximately 41.8%, along with improved thermal and structural properties of the resulting biofilm [23]. In comparison, certain studies reported a higher crystallinity index of 80.9% using a combined NaOH and H_2O_2 bleaching strategy, underscoring the significance of sequential chemical processing for enhancing cellulose purity and morphology [24]. Also, demonstrated that extended bleaching (up to 6 hours) with H_2O_2 resulted in significant lignin removal and increased brightness, crucial for packaging aesthetics [36]. Similarly, various others emphasized the role of sulfuric acid hydrolysis in producing CNCs with uniform nanoscale dimensions (<1000 nm) and high crystallinity, making them suitable for reinforcement in active food packaging [37]. Their protocol also highlighted the thermal stability and reduced agglomeration of CNCs under optimized hydrolysis conditions.

Furthermore, it was stressed process simplification by integrating low-chemical-use protocols while maintaining cellulose yield and quality, aligning with green chemistry principles. Their method achieved enhanced film-forming ability with CMC and starch blending, which improved mechanical performance compared to unmodified films. In comparison to these studies, the combined use of alkaline mercerization, H_2O_2 bleaching, and acid hydrolysis, when optimized, not only yields high-purity cellulose but also minimizes chemical input and environmental burden of demonstrating a balance between performance and sustainability [38].

4.1 MECHANICAL AND ENZYMATIC METHODS

Several studies have explored the potential of mechanical and enzymatic methods as sustainable alternatives to conventional chemical extraction. For instance, ultrasonication was employed and high-pressure homogenization to disrupt the pineapple peel matrix, enhancing surface area and facilitating cellulose release [23,24]. Their results indicated that mechanical pre-treatment significantly increased the accessibility of cellulose fibres, leading to improved hydrolysis efficiency and a more uniform microstructure in the final material. In contrast, enzymatic treatment was evaluated using cellulase and xylanase, emphasizing its specificity in removing hemicellulose and lignin without damaging the cellulose backbone [38]. Though slower than chemical methods, this approach preserved the native crystalline structure and minimized by-product formation of an advantage for producing functional films with higher transparency and mechanical uniformity. Certain researches demonstrated that the combination of enzymatic hydrolysis with mechanical stirring and grinding improved cellulose yield and reduced treatment time when applied to fruit and vegetable residues. Their hybrid method reduced chemical dependency and energy consumption by nearly 30%, highlighting its feasibility for sustainable scale-up [39]. Similarly, it was observed to have enhanced crystallinity and thermal resistance in nanocellulose derived from enzymatically treated biomass compared to chemically extracted counterparts.

4.2 YIELD, PURITY AND EFFICIENCY

Various studies have evaluated the yield, purity, and efficiency of cellulose extraction from pineapple peel, demonstrating consistent improvements through optimized protocols. Studies reported an initial cellulose content of around 24–30% in raw pineapple peel, which was enhanced to over 80% purity following alkaline delignification and bleaching treatments. Their approach resulted in a purified cellulose yield close to 20% by weight of dry peel, confirming the effectiveness of sequential chemical processes [23]. In agreement, it was also found to have achieved similar extraction efficiency using a stepwise method involving alkaline treatment, bleaching, and acid hydrolysis [37]. Their cellulose product exhibited high crystallinity and thermal stability, indicating excellent potential for biodegradable packaging films.

The study also emphasized the importance of controlled bleaching times to maximize lignin removal without compromising yield. Further researches also highlighted that employing double bleaching steps significantly enhances cellulose purity by reducing residual lignin content, which also improves the optical and mechanical properties of films made from extracted cellulose [24, 36]. These studies reported increased reproducibility and product consistency when bleaching was carefully optimized. Moreover, coupling chemical extraction were demonstrated with mechanical pretreatment techniques such as ultrasonication and grinding not only increased cellulose yield but also reduced chemical consumption, improving overall process sustainability. This combined strategy resulted in higher extraction efficiency compared to chemical methods alone [38].

5. FILM FORMATION FROM CELLULOSE EXTRACTED FROM PINEAPPLE PEEL

Once high-purity cellulose is extracted from pineapple peel, the next critical step involves its transformation into functional biodegradable films. Film formation relies on optimizing matrix composition, plasticizers, polymer blends, and functional agents to improve mechanical, thermal, and barrier properties. These biofilms not only provide a sustainable packaging alternative but also offer antimicrobial, antioxidant, and moisture-resistant characteristics when combined with suitable additives.

5.1 ROLE OF PLASTICIZER

Previous research has extensively evaluated the impact of plasticizer type and concentration on the mechanical and barrier properties of cellulose-based films, particularly those derived from pineapple peel. Studies demonstrated that glycerol, when blended with starch and CMC (carboxymethyl cellulose), significantly improved film flexibility and transparency, producing smooth films with high elongation at break [23]. However, the study also noted a decline in water resistance due to glycerol's hygroscopic nature. Similarly, it was also found that glycerol enhanced film formability and ductility, but higher concentrations led to excessive moisture absorption and plasticizer migration, which negatively affected storage stability [38]. On the other hand, sorbitol was evaluated as an alternative and observed that its lower hygroscopicity improved the film's moisture barrier properties, making it suitable for packaging applications where water sensitivity is a concern [39]. However, films containing sorbitol were stiffer and less elastic than those plasticized with glycerol, requiring careful formulation to maintain flexibility. The role of glycerol was explored in nanocellulose-reinforced films and highlighted a trade-off between flexibility and water vapor permeability, suggesting the need for composite blends to balance these attributes [37]. In contrast, it was also reported that the use of binding agents like starch and CMC not only improved the dispersion of plasticizers within the cellulose matrix but also increased mechanical strength and homogeneity, especially at lower plasticizer concentrations [40]. Comparatively, these studies affirm that glycerol is optimal for softness and flexibility, while sorbitol is better suited for improved barrier function. Blending plasticizers with film-forming agents like CMC or starch is crucial to tailor properties for specific food packaging applications, highlighting the need for formulation strategies that balance mechanical performance with environmental resistance.

5.2 BLENDING WITH OTHER POLYMERS

Cellulose derived from pineapple peel, while mechanically robust, can benefit significantly from blending with other natural polymers. Previous studies have underscored the synergistic benefits of blending cellulose extracted from pineapple peel with natural co-polymers such as starch and carboxymethyl cellulose (CMC) to enhance film functionality. Studies demonstrated that incorporating starch into cellulose-based matrices improved film elasticity and processability, while also lowering production costs. However, the study noted that films with high starch content exhibited increased moisture sensitivity, necessitating optimal cellulose-to-starch ratios for packaging durability [38]. In comparison, it was also highlighted that starch cellulose blends significantly enhanced tensile strength and thermal stability, enabling application in high-moisture food environments. Their research emphasized that the addition of glycerol as a plasticizer further improved film flexibility, though it slightly compromised water vapor barrier properties [23]. Some focused-on CMC cellulose blends, finding that CMC's strong hydrogen bonding capacity promoted film uniformity and reduced surface cracks. These films demonstrated superior optical clarity and mechanical integrity, particularly when used with nanocellulose [37]. Moreover, it was observed that CMC contributed to enhanced stress tolerance and reduced shrinkage during drying, making it suitable for active packaging applications [39]. Collectively, these studies confirm that starch blends offer cost-effective reinforcement, but are best suited for dry product packaging, while CMC blends yield stronger, more flexible films with improved moisture resistance. The choice of blending polymer must be aligned with the intended application, balancing mechanical strength, barrier function, and environmental stability.

5.3 INCORPORATION OF ACTIVE AGENTS

Comparative analysis of previous studies highlights the promising role of bioactive agents particularly essential oils in enhancing the functionality of cellulose-based films derived from pineapple peel. Incorporation of cinnamon essential oil into cellulose nano papers derived from pineapple pomace not only improved film elongation by 46%, but also significantly extended the shelf life of coriander leaves under both ambient and refrigerated conditions [41]. This study emphasized the antimicrobial and antioxidant capabilities of cinnamon oil, which are crucial for controlling spoilage and extending food freshness. In alignment, research has reported that essential oils such as clove and turmeric improved oxygen barrier properties and mechanical flexibility of cellulose films [42]. These films were especially effective in limiting oxidative degradation, thereby reducing discoloration and textural changes in packaged produce. Meanwhile, research have also highlighted the broad-spectrum efficacy of plant polyphenols and essential oils, noting their contribution to film bioactivity and consumer appeal due to natural origin and safety [43].

Additionally, nanotechnology-enhanced methods were introduced such as electrospinning and nanoparticle encapsulation that stabilize volatile essential oils and enable controlled release. These techniques improve both shelf-life extension and film integrity, overcoming limitations such as oil evaporation and phase separation [44].

Collectively, these studies confirm that the integration of active agents into cellulose-based packaging films not only enhances mechanical, antioxidant, and antimicrobial performance, but also aligns with the dual goals of food preservation and environmental sustainability. The selection and stabilization of bioactive agents, along with the delivery method, play a key role in optimizing these multifunctional films for commercial use.

6. PROPERTIES OF DEVELOPED FILM FROM PINEAPPLE PEEL CELLULOSE

Biodegradable films developed from pineapple peel cellulose exhibit diverse functional properties essential for food packaging applications. The performance of these films depends on factors like cellulose crystallinity, the type of additives used, and formulation strategies such as blending and incorporation of active agents [45]. Key functional parameters include mechanical strength, thermal behaviour, biodegradability, biocompatibility, and barrier efficiency.

6.1 MECHANICAL PROPERTIES

Comparative evaluation of previous research underscores the mechanical robustness and adaptability of cellulose-based materials across diverse applications. The bacterial cellulose, due to its high crystallinity and purity, exhibited superior tensile strength and modulus, making it ideal for biomedical applications [46]. Similarly, it was also demonstrated that incorporating cellulose nanocrystals (CNCs) into biopolymer matrices significantly enhanced tensile strength, Young's modulus, and toughness, particularly in biodegradable packaging. In the case of pineapple peel-derived cellulose, mechanical performance is notably improved through nanocellulose incorporation and polymer blending [45]. The role of nano fibrillated cellulose (CNF) in imparting tear resistance and flexibility due to its long fibre length and high aspect ratio, attributes essential for sustainable packaging solutions. Additionally, emphasized the benefits of chemically modified cellulose-based hydrogels, which displayed self-healing elasticity and enhanced stretchability, thus extending potential applications into wound dressings and soft-tissue engineering [47]. Moreover, studies have affirmed that tailored mechanical behaviour through the strategic use of plasticizers (e.g., glycerol) and reinforcing fillers (e.g., starch, CMC) yields films with optimized elongation at break, tensile strength, and elasticity, making them viable eco-friendly alternatives to conventional plastics [16,48]. The mechanical strength of cellulose-based films can be enhanced by incorporating CNCs or CNFs, which improve flexibility and tensile strength. As shown in Table 2, blending with CMC or starch and optimizing plasticizer use also contributes to improved elasticity and durability, making the films suitable for packaging and structural applications.

These findings collectively suggest that pineapple peel cellulose, when processed with suitable reinforcement and modification strategies, can achieve comparable or superior mechanical properties relative to other biomass sources enabling versatile use in both food packaging and biomedical sectors.

6.2 THERMAL STABILITY

Various previous studies reveals that thermal stability of cellulose-based films is highly influenced by crystallinity, chemical treatments, and incorporation of nanofillers. Native cellulose typically decomposes in two major stages, with crystalline regions exhibiting higher thermal resistance than amorphous segments [49]. This baseline observation aligns with findings that demonstrated that pretreated and bleached pineapple peel cellulose, due to its increased crystallinity index (~80.9%), shows superior thermal resistance suitable for food contact applications [50]. Further researches reported that chemical modifications, such as esterification and incorporation of halloysite nanotubes, act as thermal insulators, delaying degradation onset by forming a barrier to heat transfer [51]. This mechanism is comparable to findings where nano clay-enhanced films exhibited improved thermal integrity, with decomposition temperatures shifting to higher ranges [52]. Similarly, integrating starch and cellulose blends with cross-linkers significantly enhanced thermal resistance, enabling application in heat-sensitive packaging processes [53]. Collectively, these studies confirm that pineapple peel-derived cellulose, especially when chemically treated or blended with suitable additives, exhibits thermal behaviour comparable to or exceeding other agro-waste-based biopolymers [54]. This positions it as a promising candidate for high-temperature applications in food packaging, agriculture, and biodegradable containers, offering both functional and environmental benefits. As illustrated in Table 2, cellulose films derived from pineapple peel show enhanced thermal stability when subjected to treatments like bleaching, esterification, and nanoparticle addition. These modifications increase crystallinity and provide thermal resistance up to 400°C, enabling their use in heat-exposed environments such as food processing.

6.3 BIODEGRADABILITY AND BIOCOMPATIBILITY

Studies consistently emphasize the biodegradable and biocompatible nature of cellulose, including that derived from pineapple peel. it was also cellulose degrades naturally through microbial enzymatic action, breaking down into non-toxic byproducts such as water, CO_2, and biomass [22]. This property is supported by research that observed complete degradation of cellulose films within a few weeks under composting conditions, especially when blended with biodegradable polymers like starch and CMC [23,38]. The degradation rate was found to depend on crystallinity, with amorphous regions breaking down faster, a pattern consistent with observations [37]. In terms of biocompatibility, studies established cellulose as non-toxic and non-immunogenic, suitable for wound dressings, tissue scaffolds, and drug delivery systems [55]. This aligns with findings in which it was demonstrated that chemically modified cellulose, particularly with surface functionalization (e.g., carboxyl or amino groups), enhanced cell adhesion and proliferation [56]. These biomedical applications are further supported by the mechanical tunability and film-forming ability observed in pineapple peel cellulose [36] which renders it adaptable for both environmentally friendly packaging and biomedical uses. Table 2 emphasizes that the biodegradability and biocompatibility of cellulose films depend on factors such as crystallinity, film thickness, and chemical modification. These characteristics allow the films to degrade naturally while maintaining safety and compatibility for biomedical use, including wound dressings and drug delivery systems. Thus, when benchmarked against other agro-waste sources, pineapple peel cellulose not only meets but often exceeds biodegradation and compatibility standards, offering a dual benefit: reducing plastic waste and expanding into sustainable healthcare solutions.

6.4 BARRIER PROPERTIES

Barrier properties of cellulose-based films have been extensively explored in recent studies, especially in the context of food packaging [57]. Studies have highlighted the exceptional oxygen barrier performance of nanocellulose (CNFs, CNCs) in dry environments, a finding was reinforced where certain researches demonstrated that acid-hydrolyzed CNCs from pineapple peel significantly reduce oxygen permeability [24,37]. However, cellulose's hydrophilic nature poses challenges under high-moisture conditions. To counteract this, multi-layered composites and blends with hydrophobic polymers or derivatives, such as hydroxypropyl cellulose (HPC) and methylcellulose (MC), have been employed [58,59]. This approach aligns with the report that improved moisture barrier properties when cellulose was combined with starch and plasticizers in optimized ratios. Moreover, it was observed that cellulose-based films reinforced with CNFs lower peroxide formation in lipid-containing food systems and inhibit microbial growth, supporting the dual role of these materials as passive and active packaging agents [60,61]. Comparatively, it was also found that extended bleaching improved not just optical clarity but film compactness, further reducing water vapor permeability (WVP) [36]. The barrier performance of cellulose films, particularly against oxygen and moisture, can be significantly improved by reinforcing with CNFs and blending with other biopolymers, as highlighted in Table 2. These enhancements extend shelf life and reduce spoilage in food packaging applications, supporting sustainability and food safety goals [62]. These outcomes position pineapple peel-derived cellulose films—especially when reinforced and blended as superior sustainable alternatives to conventional plastics in extending food shelf life through effective oxygen and moisture barriers.

Table 2: Summary of functional properties and enhancement strategies of cellulose based films.

Property	Key Features	Performance Enhancement	References
Mechanical	High tensile strength, flexibility, elasticity	Add CNCs/CNFs, blend with CMC/starch, optimize plasticizer	[42,48]
Thermal Stability	Stable up to 400°C, improved with crystallinity	Bleaching, esterification, nanoparticle reinforcement	[49,51]
Biodegradability	Microbial degradation into CO_2, H_2O	Control via crystallinity, thickness, and additives	[50,62]
Biocompatibility	Non-toxic, safe for medical use	Surface modification enhances tissue integration	[55]
Oxygen / Moisture Barrier	Low permeability to gases and vapor	Add CNFs, blend with starch/chitosan, use multilayers	[57,61]

7. APPLICATIONS AND SUSTAINABILITY IMPACT OF PINEAPPLE PEEL CELLULOSE FILMS

The transition toward sustainable packaging systems has accelerated the development of cellulose-based biofilms derived from agricultural waste. Among these, pineapple peel cellulose films stand out for their mechanical strength, barrier properties, biodegradability, and compatibility with bioactive additives. These functional attributes make them especially suitable for food packaging, shelf-life extension, and broader environmental and economic contributions.

7.1 APPLICATIONS IN FOOD PACKAGING

Cellulose-based biofilms have gained traction as viable alternatives to synthetic plastic packaging, owing to their structural integrity, environmental compatibility, and functional adaptability. In comparison with earlier studies, the application of cellulose films derived from pineapple peel aligns with the broader trend of substituting petroleum-based plastics with sustainable alternatives. While there was research that highlighted the impressive tensile strength and thermal resistance of CNCs from coconut coir, similar mechanical and functional enhancements were observed in pineapple-derived films, especially when blended with bioactive agents [63]. The antimicrobial properties reported with PPE-incorporated chitosan films are in line with earlier findings [41] in which it was demonstrated similar benefits using cinnamon essential oil for microbial control and shelf-life extension. Furthermore, the incorporation of carnauba wax [64], parallels previous techniques involving nanocellulose reinforcement and multilayer coatings was found to offer improved barrier performance under humid conditions [57]. The rapid biodegradation of durian rind and pineapple fibre composites also confirms trends supporting eco-design targets and fast decomposition [22,56,65]. These collective outcomes affirm that pineapple peel cellulose not only matches but often complements the performance of other lignocellulosic sources, making it an accessible and efficient choice for sustainable food packaging.

7.2 SHELF-LIFE EXTENSION AND ANTIMICROBIAL PERFORMANCE

The use of pineapple peel-derived materials for shelf-life extension is consistent with findings from earlier studies that focus on the integration of functional bioactive compounds into biopolymer matrices. Studies have reported significant shelf-life improvements in bananas using CMC-based edible coatings from pineapple peel and crown biomass [66], correlating with increased crystallinity similar to enhancements observed in the bleaching treatments [36]. This connection between crystallinity and film stability also parallels the findings where CNC formation was linked to thermal and mechanical robustness [37]. Further it was demonstrated that chitosan PPE composites could extend dairy product freshness [67], aligning with earlier reports where incorporation of essential oils into films to achieve antioxidant and antimicrobial benefits [41]. Certain nanocomposite work supports previous conclusions on enhanced barrier and mechanical properties through the integration of waxes and nanocellulose [64], which mimic the multilayer film strategies [57]. Lastly, probiotic encapsulation study has broadened the scope of pineapple cellulose applications beyond traditional packaging, reinforcing cellulose's known biocompatibility and protective [55,68]. Collectively, these studies confirm that pineapple peel-derived films can be effectively engineered for food preservation, combining antimicrobial action, shelf-life extension, and even probiotic delivery within sustainable packaging systems.

7.3 ENVIRONMENTAL AND ECONOMIC BENEFITS

The valorisation of pineapple peel offers significant environmental and economic advantages, especially when integrated into circular economy models. In Costa Rica, the adoption of pineapple waste for biomedical applications and biopolymer development has contributed to post-pandemic economic resilience and reduced environmental waste [69]. Pineapple peel has also demonstrated promise in water treatment, where its cation exchange and adsorption properties are used to remove heavy metals and organic pollutants, contributing to sustainable waste management strategies [70]. Additionally, reviews have highlighted its potential for producing biofuels, bromelain, enzymes, and antioxidants, promoting agricultural waste-to-wealth conversion [71]. From an economic perspective, using pineapple peel and juice as fermentation substrates for bacterial cellulose synthesis significantly reduces the input cost of biopolymer production, offering a scalable, low-cost approach to manufacturing sustainable materials [72]. Fig 3 highlights recent innovations in pineapple peel cellulose films, showcasing enhancements in strength, barrier properties, and active functionality for sustainable packaging. These combined benefits reinforce the commercial viability and ecological relevance of pineapple biomass utilization.

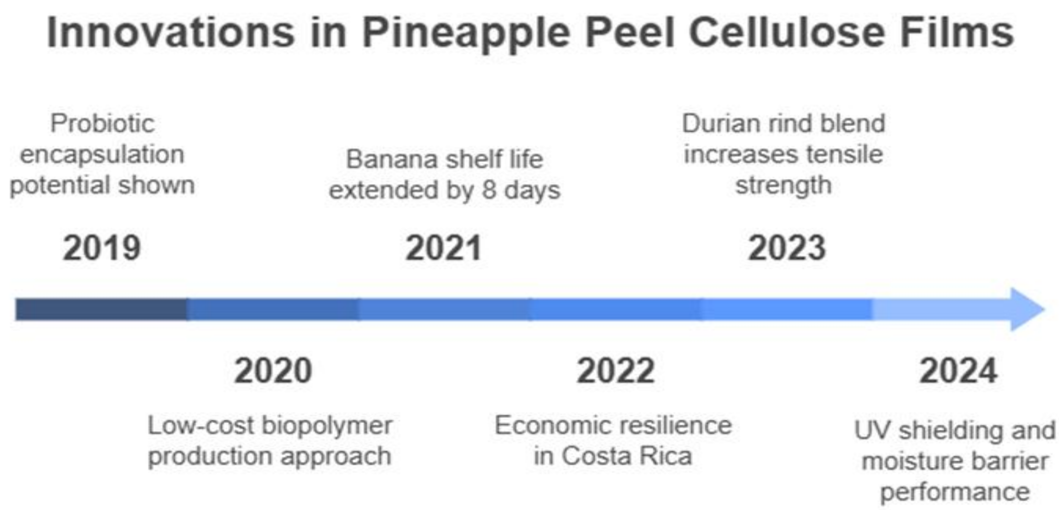

Fig 3: Innovations in pineapple peel cellulose films.

8. FUTURE SCOPE AND STRATEGIC OUTLOOK OF PINEAPPLE PEEL CELLULOSE UTILISATION

As demonstrated throughout this review, the valorisation of pineapple peel into cellulose-based films holds significant promise for sustainable packaging and allied applications. However, to transition from promising lab-scale innovations to widespread commercial adoption, critical challenges must be addressed through a multipronged future strategy. Scaling up cellulose extraction remains a key hurdle, as the industrial translation of processes like alkaline treatment, bleaching, and acid hydrolysis faces limitations due to high energy demands, chemical costs, and inconsistent feedstock composition linked to varietal and processing differences [23,30,70]. Moreover, pretreatment steps often require significant optimization to be both cost-effective and environmentally sustainable. Future advancements in enzyme-assisted, microwave-assisted, and biorefinery-based extraction systems coupled with decentralized processing units near pineapple-growing regions offer scalable and region-specific solutions [24,69]. From a techno-economic perspective, the use of pineapple waste as a low-cost, renewable feedstock can help offset production costs associated with reagents, transportation, and infrastructure [66]. The feasibility of co-producing high-value compounds such as bromelain, bioethanol, and bacterial cellulose (BC) through integrated biorefineries further enhances the economic viability and circularity of these systems [68,72]. However, the development of cost-effective microbial platforms, modular reactor designs, and multi-product valorisation frameworks is still at an early stage and requires significant research and policy support. There is also a pressing need for further scientific investigation to standardize extraction protocols, improve film formulation, and ensure reproducibility across diverse raw materials and production scales. The underutilized multifunctionality of pineapple biomass encompassing cellulose, hemicellulose, lignin, sugars, and enzymes opens new avenues for expanding its application beyond food packaging [45]. Future studies should explore the development of pineapple-derived materials for biomedical use (e.g., wound dressings, scaffolds), adsorbents for water purification, and biofuels, supported by robust lifecycle assessments and safety evaluations [70]. Finally, transitioning from innovation to implementation will require a multidisciplinary and systems-level approach combining materials science, process engineering, environmental biotechnology, and policy frameworks. The convergence of these fields will be essential to harness the full potential of pineapple peel as a commercially viable, environmentally benign, and socially beneficial resource, transforming agro-waste into impactful green technologies for the future [69,72].

9. CONCLUSION

The escalating environmental concerns associated with conventional plastic packaging have underscored the urgent need for sustainable, biodegradable alternatives. This review highlights the transformative potential of pineapple peel, an agro-industrial waste, as a viable source of cellulose for the development of eco-friendly packaging films. Rich in fibre and bioactive compounds, pineapple peel offers a cost-effective and renewable substrate that aligns well with circular economy principles. The paper comprehensively examined various cellulose extraction techniques, emphasizing chemical, mechanical, and enzymatic approaches, and their respective impacts on yield, purity, and environmental sustainability. It also explored the critical role of plasticizers, polymer blends, and bioactive additives in enhancing the functional performance of cellulose-based films particularly in terms of mechanical strength, barrier efficiency, thermal stability, and biodegradability. Beyond material formulation, the review showcased diverse applications of pineapple peel cellulose films in food packaging, where they not only provide structural protection but also offer antimicrobial and shelf-life-extending functionalities. Their potential extends further into probiotic delivery, wastewater treatment, and biomedical applications, establishing pineapple peel as a truly multifunctional biomass. Nevertheless, realizing the full commercial potential of these innovations demands targeted future efforts. Key areas include scaling up extraction processes, improving cost-effectiveness, and expanding multifunctional applications through integrated biorefinery models. Addressing current limitations through green processing, standardization, and public-private collaboration will be pivotal in driving industrial adoption.

In conclusion, pineapple peel-derived cellulose offers a promising pathway toward sustainable material development, contributing meaningfully to plastic reduction, waste valorisation, and environmental protection. With continued research and strategic investment, this underutilized biomass can be transformed into a cornerstone of future biodegradable packaging and green technology solutions.

10. ACKNOWLEDGEMENT

The author would like to express sincere gratitude to the Research Department and the Department of Food Technology, Ramaiah University of Applied Sciences, for their continuous support and guidance throughout the development of this review article. This article has been written as part of author's ongoing research and dissertation work at the college.

11. CONFLICTS OF INTERESTS

The authors declare that there is no conflict of interest.

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LIST OF FIGURES

LIST OF TABLES