9th International Conference on
Interdisciplinary Studies in Food industry and Nutrition Science of Iran
نهمین همایش بین المللی
مطالعات میان رشته‌ای
در صنایـــــع غذایـی 9
علـوم تغذیـه ایــــران
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Green Coatings for a Sustainable Future: A Review of Biopolymer-Based Innovations in Food Packaging

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ABSTRACT

With the environmental problems caused by traditional petroleum-based plastics, green packaging coatings have become an important non-polluting choice. The advances of biopolymer-based packaging materials are reviewed by recent research results in the manuscript, and are categorized fundamentally into three groups: polysaccharides (starch and cellulose), polyesters (PLA, PHA) and proteins (gelatin, whey). More indication depicting that the mechanical and barrier qualities and performances of these coatings can be enhanced much by incorporation with nanomaterials or bioactive compounds has been shown recently. Such modifications have led to active and intelligent packaging systems, with improved antimicrobial, antioxidant, and UV light barrier properties that can extend shelf life and improve the safety of foods. Furthermore, upcycling of agricultural waste conforms to the tenets of a circular economy, which advocates for valorization of low-cost residues into high-value biodegradable packaging. There are plenty of other challenges, not least of which cost, scale and performance on a par with old ingredients, but formulation and processing advances are sitting corners and champions are emerging that can lead us to a greener (in both senses) future for packaging.

Keywords: *Biopolymer packaging, nanomaterials, sustainability, circular economy, food safety*

1. *INTRODUCTION*

With the increasing concern about environmental issues of nonbiodegradable and polluting conventional petroleum-based plastics, green packaging coatings for food and consumer goods have drawn global attention. Among them, the coatings made from renewable biopolymers, dominated by polysaccharides, proteins, and biopolyesters, have many merits including biodegradability, renewability and non-toxicity, and therefore should to be new prospective candidates as alternatives to traditional plastics [1,2]. Nanoscale materials and bioactive agents have been embedded within such biopolymer matrices to improve strength, barrier properties, and functionality, resulting in active and intelligent packaging systems that could be suitable for food preservation with enhanced shelf life extension, food safety enhancement and less depletion waste [3,4]. In addition, the use of upcycled and waste derived materials for green coatings is promoted [5].

Legislations and consumption interest towards ecofriendly innovations, the urge for a reduction of the carbon footprints and the newness to create a better future of the packaging industry have partially paved this path too [1,2]. Although the aforementioned developed bioplastics possess improved performance, they still have difficulties with partially missing scalability, production cost, and obtaining performance equivalent to that of traditional plastics; thus, in-depth studies should be carried out, especially concerning formulation optimization, processing technologies, and environmental regulation [3,6]. Moreover, the advent of antimicrobial, antioxidant or UV barrier multifunctional coating materials opened up new possibilities to enhance food preservation and safety and to reduce food waste [7,8]. Modern green packaging coatings fulfil not only ecological and legal requirements but are also necessary for an environmentally friendly and functional development of modern packaging systems [1,2]. In view of the new concerns regarding environmental problems, this review provides an overview of recent progress in green packaging coatings, *particularly the development of innovative biopolymer-based systems. It will also detail materials from polysaccharides, biopolyesters, proteins, and upcycled resources.*

2. RECENT ADVANCES IN GREEN PACKAGING COATINGS

2.1. POLYSACCHARIDES

Polysaccharides, such as starch, cellulose (including cellulose nanocrystals), chitosan, alginate, pectin and mucilage are the ideal candidates as green packaging materials due to their outstanding combination of characteristics (biodegradability, renewability and film forming) [9,10]. These polysaccharides are attractive as they all exhibit nontoxicity, renewability, and can be modifiable or used in composites by mixing with each other to improve their mechanical and barrier properties, which meets the demand for both food security and environmental friendliness.

2.1.1. Starch

Starch, of natural and low cost from plants, is a hydrophilic and abundant material. Nevertheless, it is able to give rise to films exhibiting acceptable mechanical properties and degree of oxygen-barrier. But such a polymer is not water-proof enough, and the polymer is blended with other biopolymer for improved water resistance [11,12]. Otero-Herrera et al. (2025) Explained the novel development of films and coatings for food packaging from root starches from cassava, yam and sweet potatoes (Fig. 1). They observed, however, that such films are biodegradable and have poor mechanical properties and low vapor barrier. To alleviate these drawbacks, many innovative methods (starch modification, hydrophobic substances addition, and fillers incorporation) have been proposed. The review also shows that, active and intelligent packaging can be fabricated by addition of antimicrobial agents and pH indicators to improve the quality and shelf-life of food products. Thus, these new-coatings are potential alternatives to eco-friendly means of food preservation [13].

Fig. 1. *Application of starches from cassava, yam, and sweet potato in food packaging applications*

Zhang et al. (2025) prepared a bi-functionally-modified starch film on paper packaging by modifying the starch with polyethyleneimine and then grafting with methyl trimethoxy silane. The coated paper obtained exhibited the static water contact angle of ~128°, oil resistant grade >7%, the improvement rate was 46.88% of tensile index and 81.69% of burst index. These show a substantial increase in resistance to water and oil, as well as mechanical strength, suggesting the promise of the coating in terms of lessening plastic use in food packaging [14].

2.1.2. Cellulose (Nanocellulose)

Cellulose and nanocellulose possess high mechanical strength, transparency, and exceptional barrier properties, making them suitable for thermoforming biodegradable and recyclable coatings or films, especially in fiber-based packages [15]. Atta et al. (2022) prepared edible films from bacterial cellulose, carboxymethyl cellulose and glycerol, added olive oil or ginger oil for antimicrobial activity. Water solubility of the films ranged from 10.0 to 41.08%, while inhibition zones against bacteria and fungi ranged from 8.13 to 22cm. Shielding of oranges and tomatoes with these coatings inhibited decay and weight loss, with shelf life being increased up to 9 weeks at different temperatures [16].

Jingxuan et al. (2023) prepared a cellulose nanofiber (CNF) and carboxymethyl cellulose (CMC) coating for molded pulp food trays which resulted in a homogeneous 200µm thick coating. The trays coated with the *coating composition showed significant enhancement in mechanical strength, air and moisture barriers and repellence against grease than uncoated trays. Food storage experiment revealed that the CNF/CMC-coated coating could effectively prolong the shelf-life of raspberries, blueberries and cherry tomatoes [17].*

Baral et al. (2025) isolated cellulose nanocrystals from mixed office wastepaper and applied them as coatings on paper packaging. The water vapor resistance of the coated paper increased by 14 times, air resistance increased by 250 times, and the water contact angle compared to that of the unmodified coated paper (60.13°) was raised to 99.40°. The tensile index increased to 5.28, and all samples degraded completely in 49 days (in soil), indicating good biodegradability (see the process step in Fig. 2) [18].

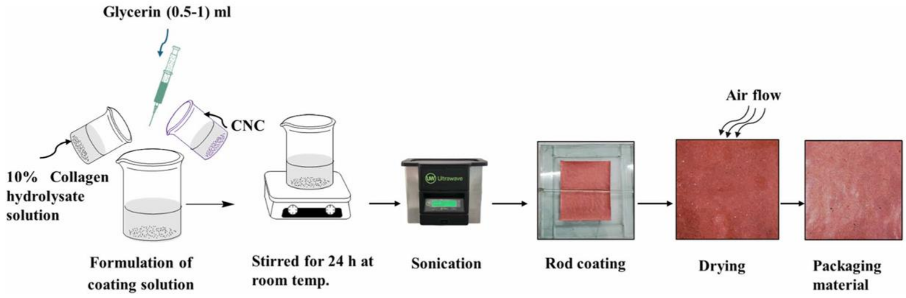

***Fig. 2.** CNC-coated paper is a packaging material for food [18]*

2.1.3. Chitosan

Chitosan from chitin in crustaceous shells has been known to possess antimicrobial ability and high transmittance, as well as barrier properties for gases and UV light, which are beneficial for extending the shelf lives of food products [19]. He et al. (2024) developed a modified quaternary ammonium salt and tannic acid/chitosan composite coating (QCTO) for this purpose. The film exhibited a tensile strength of 69.9 MPa, water vapor permeability rate of 14.3 g·h^{-1}·m^{-2}, and oxygen resistance ratio of 3.5 g·mm·m^{-2} tikah^{-1}. For bananas strawberries mushrooms, shelf life was increased by about 6, 5 and 6 days respectively with lower weight loss and microorganism count (Fig. 3) [20].

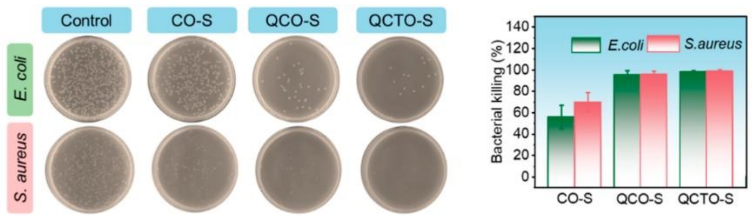

***Fig. 3.** The results of the microbial test in Ref [20]*

Manaswini et al. (2024) investigated the use of chitosan packaging in order to extend shelf-life of food. They demonstrated that chitosan films have an excellent ultraviolet, gas and moisture barrier property and their bactericidal activity can inhibit the bacteria growth. The mechanical performance, flexibility resistance to water and barrier property of the chitosan-based coating was found to increase with an increment in Chitosan concentration or addition system [19].

Jia et al. (2025) prepared a high strength edible film of chitosan, dialdehyde cellulose and proanthocyanidin with the tensile strength 57.47 MPa (114% better than pure chitosan film) and swelling/water solubility each being 115.43%/11.26% at PA concentration of 9%. The scavenging rates in DPPH and ABTS radical of composite film were 92.76% and 99.44%, respectively, increased the shelf life of slices of mango, grape and apple by ninety days relative to the control group [21].

2.1.4. Alginate

Alginate from seaweed produces flexible, transparent films with low oxygen permeability and is biodegradable and biocompatible; however, it also needs to be modified to increase water resistance [22].

Mao et al. (2025) prepared alginate films containing chlorogenic acid carbon dots (CGA-CDs). The UV transmission at 280 nm reduced to 2.66% (88.1% decrease) with the presence of 2% CGA-CDs, whereas the antibacterial rates for E. Coli and S. Aureus were enhanced to 86.0% and 91.6%, respectively. The lowest browning index and mildew of the fresh-cut apples were maintained in the coating treatment, which showed remarkable preservation effects (Fig. 4) [23].

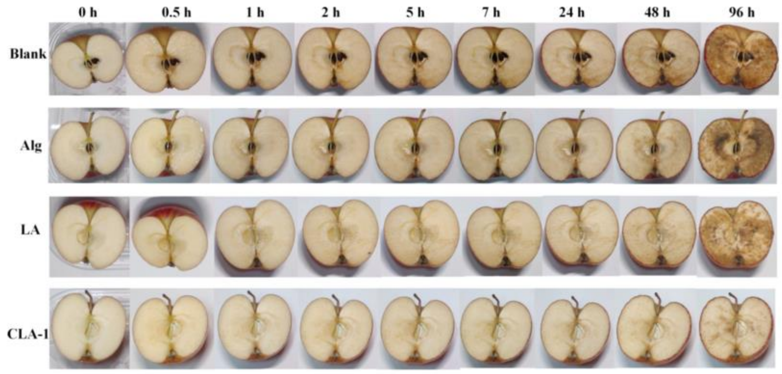

Fig. 4. *Digital photographs of fresh-cut apples were taken at different storage times* [23].

Gouda et al. (2025) developed sodium alginate films incorporated with watercress oil for antimicrobial food packaging. The oils the films or films containing oil, revealed a substantial increase in antioxidant activity from 13.6%dpph inhibition (control) to 92.5%dpph inhibition (highest oil content). The antimicrobial tests showed that the zones of inhibition were up to 27 mm against Salmonella enterica and at least a 6-log reduction in bacterial population after 1 h, indicating excellent antibacterial activity and sustained phenolic release [24]

2.1.5. Pectin

Pectin extracted from fruit peels is desirable because of its film-forming properties and oxygen barrier capability (as well as being water-soluble) and is generally required in mixtures for enhanced applications [22]. Zhang et al. (2023) prepared composite films using pectin-lignin nanoparticles (LNPs). A 3% LNP concentration increased the tensile strength by 164%, water contact angle by 56%, and decreased the water vapor permeability by 25.3%. In addition to the above findings, the films also obstructed nearly all UVB/UVC and most UVA light, and the highest antibacterial inhibition rates of the films were 78.79% for S. Aureus and 47.80% for E. Coli. Strawberry storage in composite films and plastic wraps is shown in Fig. 5 [25].

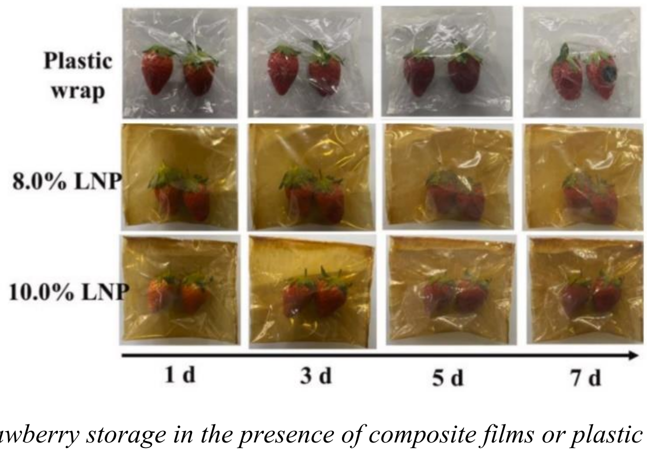

Fig. 5. *Strawberry storage in the presence of composite films or plastic wrap [25].*

El Habbasha et al. (2024) introduced an edible packaging biofilm of pectin/hydroxyethyl cellulose/ZnO nanoparticles. The addition of ZnO NPs decreased WVP (2.55-4.28 × 10^{-12} gm/Pa·s·m^2), increased tensile *strength values (1.2 - 2.6 MPa) and flexibility (4.5 -13 MPa). The films showed high antimicrobial activity with more than 99.96% of reduction of E. coli at 200mg/mL. These biofilms were transparent, flexible, and eco-friendly nature with enhanced barrier and antimicrobial behavior in relation to the ZnO concentrations trending in increasing manner [26].*

Akachat et al. (2025) Optimized food packing application of lemon essential oil-loaded pectin films. The films showed higher elongation at break (20.05%), good flexibility and lower moisture content (28.89%) compared to those in the control samples. The antimicrobial activity assay showed high inhibitory effects of the EtOH extract to Botrytis cinerea (100%) and importantly moderate activity towards Alternaria alternata (50%). Furthermore, pectin–EO film could reduce the TSS loss of apple slices as a packaging film; only after 10 days, the changes in coated and uncoated slices −12.04% and 24.46%, respectively indicated a better preserved effect [27].

2.2. BIOPOLYESTERS

Polylactic acid (PLA), polyhydroxyalkanoates (PHA), and polybutylene succinate (PBS) are renewable biopolyesters that are currently being extensively applied to packaging coatings because of their environmental degradation characteristics and superior mechanical properties of these coatings. These materials can be used as pure materials or in multi-structures and are usually blended to adapt the mechanical and barrier properties to specific requirements for packaging applications, yielding compostable, food-safe solutions that reduce reliance on petroleum-based plastics [28].

2.2.1. Polylactic Acid (PLA)

PLA is a stiff thermoplastic made from fermented plant sugars (e.g., Sugar cane, corn) and features high tensile strength, transparency, and processability; however, it can be brittle with limited barrier properties; mixing with other polymers or additives could improve flexibility and barrier performance [28,29]. Zúniga et al. (2024) developed PLA-based biocomposite films by incorporating modified avocado seed starch (Fig. 6).

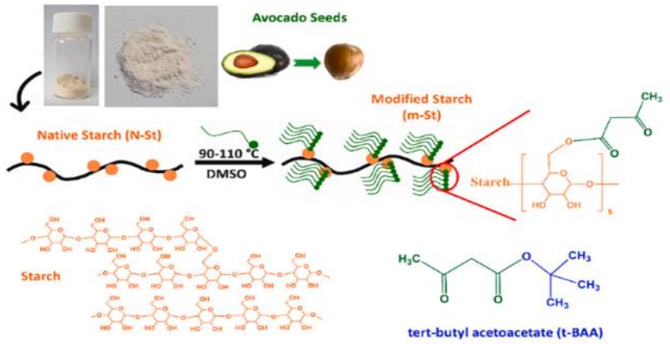

Fig. 6. *Schematic illustration of avocado seed starch transesterification with t-BAA [30]*

The obtained PLA/m-St (1:6) 20 wt% films exhibited a significant increase in the tensile elongation at break from 3.35% (pure PLA) to 27.80% (∼730%). The blockage rate of UVB increased from 16.21% to 83.86%, and oxygen permeability decreased from 1331 to 32.9 cc.m^{-2}. Day^{-1} (97.53%). The water vapor permeability also decreased from 61.9 to 28 g·m^{-2}·day^{-1}, suggesting that its mechanical and barrier properties are significantly enhanced for use as a food packaging material [30].

Dang et al. (2025) formulated polylactic acid (PLA) films covered with emulsions of gelatin-pomelo essential oil for active food packaging. After coating, the water contact angle of PLA was decreased (from 74 ± 3° to 63 ± 1°), and a stronger UV light barrier was reflected; significant antibacterial properties against S. aureus and P. aeruginosa were observed with no cytotoxicity. These findings suggest a possible increased potential and safety of food preservative; however, additional research on large-scale could be necessary [31].

2.2.2. Polyhydroxyalkanoates (PHA)

PHA is a family of polyesters produced by bacteria from sugars or lipids, and it has outstanding biodegradability under different conditions (soil, compost, and water) with non-toxic properties and oxygen and water vapor barriers; thus, it can be used for food packaging that requires safety and is environmentally friendly [28]. It is a flexible, partly bio-based polyester with good elongation, impact resistance, and processability, which can be used to enhance properties, especially the toughness and flexibility of PLA-based blends, although its barrier properties are lower than those of some other biopolyesters [32].

Ferri et al. (2023) had produced totally biodegradable films based on tannins-poly(hydroxybutyrte-co-valerate) (PHBV) blend for food packaging. Films with 5 phr tannin showed good antioxidant and UV protective (gas barrier) performance, retaining transparency as well as basic mechanical strength (Young's modulus: 900–1030 MPa; tensile strength: 20 MPa). The films were thermally stable from room temperature to 200°C, and they were capable of colorimetric recognition of ammonia, suggesting as smart spoilage indicators. Tannins incorporation increased shelf-life and multi-functionality, thus making the PHBV/tannin films a potential alternative to petrochemical plastics [33].

Stublić et al. (2024) reviewed more than 100 articles and suggested that when PHAs are combined with other biodegradable polymers, including PLA, starch, and cellulose, their mechanical properties are improved by up to 40% compared to native materials and barrier properties by 35% (Fig. 7). The inclusion of antimicrobials and essential oils increased the food shelf life by 25%. The environmental impact of the PHA-based coating is approximately 50% less than that of petroleum-based plastics, and the efficiency of production increased by approximately 60% with optimized fermentation [34].

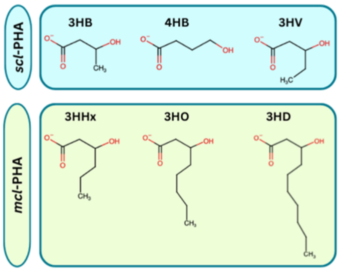

Fig. 7. *Classification of PHAs according to the reference* [34]

2.2.3. Polybutylene Succinate (PBS)

Polybutylene Succinate (PBS) is an aliphatic biodegradable polyester synthesized by addition polymerization between butanediol and succinic acid, both of which can be derived from biomass, the way evolved a compostable food wrapper plastic more environmentally friendly than conventional plastic. PBS has an appropriate balance of mechanical, flexible and thermal processability properties, and it is also internationally biodegradable [35–37]. Their films can act as good barriers and, together with nature additives, they can have antioxidant and antimicrobial properties that succeed in the extension of shelf life food [38].

Hamdani et al. (2023) PBS latex was applied to kraft paper and biodegradable packaging film were prepared. On the PBS-coated paper, the Cobb1800 hydrophobicity was 15.5 ± 0.1 g/m^2 (Fig. 8), the images of oil resistance kit rating were 12/12 and water vapor transmission rate was 112.62±8.04 g/(m2·day). Coated paper also showed a good suitability for thermal sealing, and was comparable or better than commercial references as regards [39].

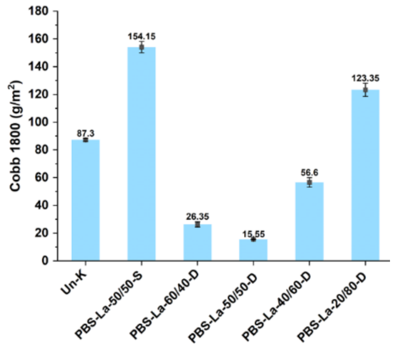

Fig. 8. *Cobb1800 values (g/m^2) of the coated and uncoated paper samples* [39].

Nabels-Sneiders et al. (2023) developed PBS nanocomposites with NFC interlayers for food packaging. One NFC layer (0.35% w/w) achieved WVTR below that of a single layer, up to 5.5-fold, but with increasing number of layers optical transparency decreased (65 to 25%). The increased number of NFC layers resulted in an increased defect rate and lower adhesion, but the laminates enabled a short-term food storage solution with a sustainable high barrier [40].

Cabrini et al. (2023) ultrasonically sprayed polyethylene glycol diglycidyl ether (PEGDE)-crosslinked chitosan/graphene oxide nanocomposite coatings on PBS films. O_2 and CO_2 transmission rates were, respectively, decreased by 85% and 93%, in the presence of coatings containing 1 wt% graphene oxide as compared to uncoated PBS. These coatings were clear, adhered well and enhanced both gas barrier and mechanical resistance for use in high-barrier food packaging [41].

These studies demonstrate how biopolyesters, such as PLA, PHA, and PBS, are engineered into coatings or multilayer structures to significantly enhance the mechanical, barrier, and functional properties of sustainable packaging.

2.3. PROTEINS

Biodegradable packaging films for food have been made using biopolymers such as gelatin, whey, wheat gluten, and soy protein. These proteins may be modified by plasticizers, cross-linkers, or other biopolymers to increase their mechanical and barrier properties. Protein-based coatings are renewable, nontoxic, and biodegradable, thus reducing the reliance on petrochemical-derived plastics [42,43]. They can also be linked to antioxidants or antimicrobials to enhance the shelf life of food and increase safety. The most important drawback is the low water vapor barrier properties, which can be improved by formulation. Therefore, these coatings contribute to sustainability, food safety, and functional performance in current packaging demands [43].

2.3.1. Gelatin-Based Coatings

Gelatin (a collagen derivative) possesses good film-forming properties, transparency, and flexibility, although it has relatively poor water resistance [44]. Zhang et al. (2024) reviewed the development of gelatin films enhanced with plant extracts and nanoparticles. The cycle and importance of protein-based packaging are presented in Fig. 9.

Fig. 9. *The cycle and importance of protein-based packaging [45].*

They reported an improved tensile strength of their packaging materials from 33.7 to 40.9 Mpa after inclusion of catechin, chlorogenic acid and anthocyanin B2 and water permeability was reduced by 40%. Antioxidant capacity of these films was increased and pork spoilage was successfully inhibited upon them. The presence of chitin nano-whiskers (or its chitosan derivatives) enhanced the thermal stability and strength of gelatin matrix, making it to be a multi-functional material for active food packaging systems [45].

Sun et al. (2024) developed gelatin-containing composite films with nanocellulose and coffee leaf extract-Fe^{3+} complex. With 1 wt% extract-metal complex incorporated, the UV barrier, mechanical and barrier properties of PAmBLs were improved and at meantime an antibacterial efficiency over 90% vs. S. aureus and E. coli was realized as well. The films also showed high antioxidant capacity and extended the shelf life of packaged fresh pork for 8 days at 4°C, which was indicative of a great potential in application as active food packaging materials [46].

2.3.2. Whey Protein-Based Coatings

Whey protein from dairy foods forms clear, flexible films with high oxygen barrier properties but poor moisture resistance [47]. Al-Hilifi et al. (2023) prepared chitosan and whey protein hydrolysate composite films for food packaging applications with the aim of enhancing mechanical and antioxidant features. Films containing 1 wt% whey protein hydrolysate showed tensile strength of the order of 26.3 MPa, whereas neat chitosan films exhibited only a value of 10.9 MPa. Antioxidant activity was dose-dependent and the best scavenging (83% DPPH) was achieved at 1 wt.% loading. These affirm improved physicochemical performance and applicability to commercial food packaging [48].

Botalo et al. (2024) fabricated smart edible films based on alginate, whey protein isolates, and curcumin. Whey protein isolates addition increased the hydrophobic and antioxidant properties while curcumin improved UV-barrier and reduced water vapor permeability of the films. More importantly, the coatings could obviously prolong the shelf life of apples with less enzymatic browning and weight loss (Fig. 10), clearly showing their capability for fruit preservation [49].

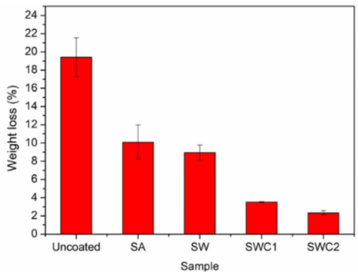

Fig. 10. *Weight loss percentages of incubated apples with and without coatings (SA: Pure alginate film, SW: Alginate and whey protein film, SWC1: Alginate, whey protein, and 0.2 g Curcumin film, SWC2: Alginate, whey protein, and 0.5 g Curcumin film) [49].*

2.3.3. Soy Protein-Based Coatings

Soy protein is a plant-based protein with film-forming properties, mechanical intensity, and biodegradability [50]. Maroufi et al. (2023) developed soy protein isolate (SPI)/kappa-carrageenan/cellulose nanofibril composite films incorporated with Zenian essential oil (ZEO)-loaded MOFs. The addition of more nanofibril decreased water solubility (22.98%), moisture content (21.72%) and water vapor permeability (1.22 g $mm^{-1}s^{-1}pa^{-1}10^{-10}$), improved thermal stability and antibacterial activity. The optimized film could efficiently prevent the pathogenic bacteria and promote the antioxidant capacity, indicating that it had potential application for active food packaging [51].

Zhao et al. (2024) produce 15 biodegradable tannin-based films by cross-linking between SPI and DAS using TA. The tensile strength of the SPI/DAS/15TA film was 208.27% higher than that of the pure SPI film. In addition, the films exhibited good UV-blocking properties, with the absorption range of the SPI/DAS/10TA film reaching 389 nm. TA-modified films also presented strong antibacterial activity (Fig. 11), which indicated the potential of it for food packaging as an environmentally friendly material [52].

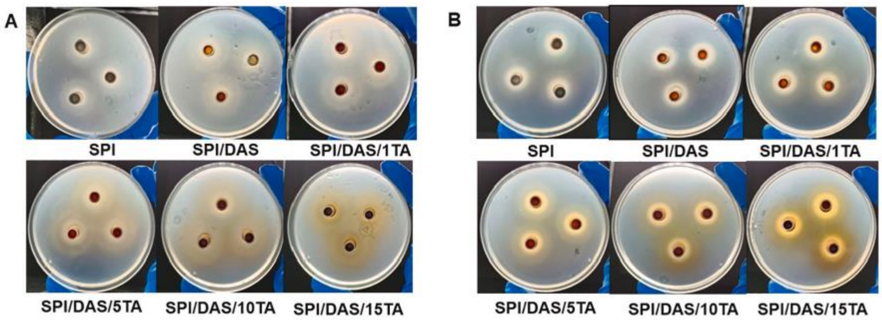

Fig. 11. *Antibacterial activity of the films against (A) S.aureus and (B) E.coli bacterial pathogens (5, 10, 15wt TA) [52]*

2.4. UPCYCLED WASTE MATERIALS

Upcycled waste materials, such as carboxymethyl cellulose (CMC) from sugarcane bagasse, pectin from fruit peels, and cellulose from rice husks, are emerging as sources for developing biodegradable packaging films. These are predominantly polysaccharides (cellulose, starch, and pectin) and some proteins derived from agricultural waste products [53,54], providing a viable renewable alternative to fossil fuel-based plastics. They have the following desirable properties: high biodegradability, good film-forming potential, mechanical strength, flexibility, and compatibility with food systems.For instance, CMC films made from sugarcane bagasse also yielded good tensile strength, elongation, and water vapor barrier properties, particularly in the presence of plasticizers such as glycerol or nano-to-micrometer-sized nanocellulose [55,56]. Some of these films also exhibit antioxidant and antimicrobial properties when combined with fruit or vegetable extracts, which help increase the shelf life of food [53]. The potentialities of such upcycled materials as potential packaging solutions are environmental friendliness, plastic waste reduction, realization of cost-saving strategies by the use of cheap raw materials, and significant contribution to the circular economy with a high value-added use of agricultural waste products. Also, such films are usually transparent, light-weight, and can be form-tailored for particular food applications, meaning they are highly versatile [54]. Overall, with the current global interest in sustainability initiatives, upcycled agricultural by-products offer functional, environmentally friendly, and economically feasible alternatives for food packaging.

2.4.1. Corn Stover-Based Packaging Material

Corn stover-related packaging material is very important, since it utilizes the excess agricultural residue to fabricate an affordable and practical renewable packaging, benefiting the environment and local circular economy. Its application not only creates a sustainable production cycle, but also expands the field of green material design [57].

Li et al. (2023) developed a cellulose nanofiber/corn straw core (CSC) composite films for food packaging, and analyzed the mechanical properties UV, and water vapor barrier of such material. The tensile strength of the CNF/CSC-100 film was up to 8.04 times higher than that of poly (butanediol sebacate butanediol terephthalate), and its water vapor barrier performance was improved by 57.69% compared with raw CNF alone. The film was also a barrier to bacteria until 12 days and promoted an effective preservation of fresh garlic and milk, indicating high potential for use in food packaging applications [58].

Du et al. (2024) fabricated composites based on corn stover reinforced polypropylene (PP) and modified PP (MPP), for food packaging, with the emphasis placed on mechanical and barrier properties. When the corn stover content was 20%, the tensile strength of MPP/CS composite was increased by 120% compared with that of PP/CS, and it demonstrated the best water vapor barrier and preserving performance for vegetables. Less E. coli and S. aureus were grown on the MPP/CS composites, especially with low content of corn stover, which would be beneficial to food safety and shelf-life improvement [59].

Duan et al. (2024) developed a packaging material based on corn stover powder and natural binders, such as glycerin. Their experimental packaging could withstand 500 g of the product and showed acceptable toughness and color stability. Compost ability was integrated into the material, completing a local circular system in which there is no load to take back to recycling after use, reducing the impact on the environment and the production conglomerate [57].

2.4.2. Carboxymethyl Cellulose/Chitosan Composite Films

The combination of CMC and chitosan solution developed into degradable, non-toxic, composite films as green packaging material. Such films are superior replacements of traditional plastics, contributing to food safety and preservation by providing a strong oxygen barrier (due to the presence potential of CMC) as well as its antimicrobial behavior provided with the action of chitosan material [60,61].

Amaregouda et al. (2024), where chitosan nanoparticles from agricultural source were incorporated in Carboxymethyl cellulose/starch-based films for Multifunctional food packaging application. The films containing 9% of chitosan nanoparticle had its tensile strength increased by approximately 81%, with an improvement of 34.5% in UV barrier, and a reduction of moisture content by about 54%. The oxygen and water vapor permeability decreased by 45.9% (OV) and 68.6% (WV), while the refrigerated shelf life of chicken meat reached to 56 hours at room temperature with the use of films [62].

Yu et al.(2025) fabricated CMC/chitosan composite films using a NaOH/urea aqueous solution. The optimum film (1.5% CS, 2% CMC, 2.5% NaOH, and 4% urea) had a tensile strength of 46.08 MPa with an elongation at break of 68%. The barrier property was also good, with a water vapor transmission rate of 0.26×10^{-5} g/(m^2·h·Pa), as shown in Fig. 12, and it was a potential and biodegradable replacement for petroleum film packaging substances [60].

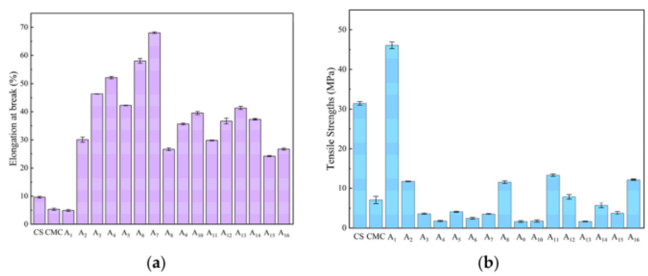

Fig. 12. *Mechanical properties of CS, CMC, and CS/CMC composite films: (a) elongation at break (%), (b) tensile strength (MPa) [60].*

2.6. CONCLUSION

Green packaging coatings, which are environmentally friendly and have been developed in response to oil-based and environmental pollution problems associated with conventional plastics reaching the environment, represent an important paradigm shift toward eco-packing. As discussed, renewable biopolymer-

based materials (e.g., Starch and cellulose among polysaccharides; PLA and PHA from the family of bio-polyesters; and gelatin and whey as example proteins) have a high potential for offering biodegradability, renewability, and non-toxic nature. The addition of nanomaterials and bioactive compounds has further modified these coatings, transforming them into active and smart strategies to enhance food safety and prolong shelf-life. Recent studies have already demonstrated the excellent functional properties of such materials. In fact, a few polysaccharide-based coatings have performed at the level of one-fold improvement in barrier properties and bio-polyester blends have indicated greater than or less than 700% enhancement within tensile strength/flexibility. In addition, protein-based films have been successfully functionalized with natural extracts to obtain antioxidant and antimicrobial capabilities. Moreover, the process reuses waste agricultural oil sources and values them into high-value biodegradable packaging. Yet the cost, scalability and performance parity with traditional plastics are still barriers to widespread adoption. Nonetheless, ongoing efforts are in place to overcome these challenges and formulation optimization as well as innovative processing practices have been developed. As material projects mature out of phase conversion, this is evidence of a collective journey towards a more sustainable, efficient and safe future for our food packaging – one that can only be driven by both regulatory pressures and consumer interest.

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