Shah *et al.*
Biotechnology for Sustainable Materials (2024) 1:2
https://doi.org/10.1186/s44316-024-00002-1

Biotechnology for Sustainable Materials

MINI REVIEW

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Advancements in the biopolymer films for food packaging applications: a short review

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Abstract

Plastic-based films that are commonly used in the food packaging industry are tough to recycle due to their sorting issue and these films do not decay as they photodegrade into microplastics. These microplastics transport from the air and accumulate in soil, storm drains, and waterways. Recent initiatives in the food packaging industry have led to the development of edible and biodegradable films as sustainable alternatives to synthetic polymer-based plastics. These films, which are biocompatible, biodegradable, and serve as protective coatings on food surfaces, are designed to enhance shelf life by guarding against oxidation, moisture, and microbial spoilage. Recent advancements in polymeric films resulted in the development of high-performance, UV-blocking, nano-engineered, and intelligent pH-sensitive films, along with multilayer, heat-sealable, and active variants. These advanced materials not only prevent food deterioration but also facilitate the early detection of spoilage. However commercial success of these films which have been developed at a lab scale is still challenging due to unsatisfactory mechanical, barrier, thermal, and optical properties than synthetic films. Furthermore, an in-depth understanding related to human interaction, biodegradability, safety studies, scalability, and machinability is required to develop sustainable bioplastic films.

Keywords Biopolymers, Coating material, Edible films, Food packaging

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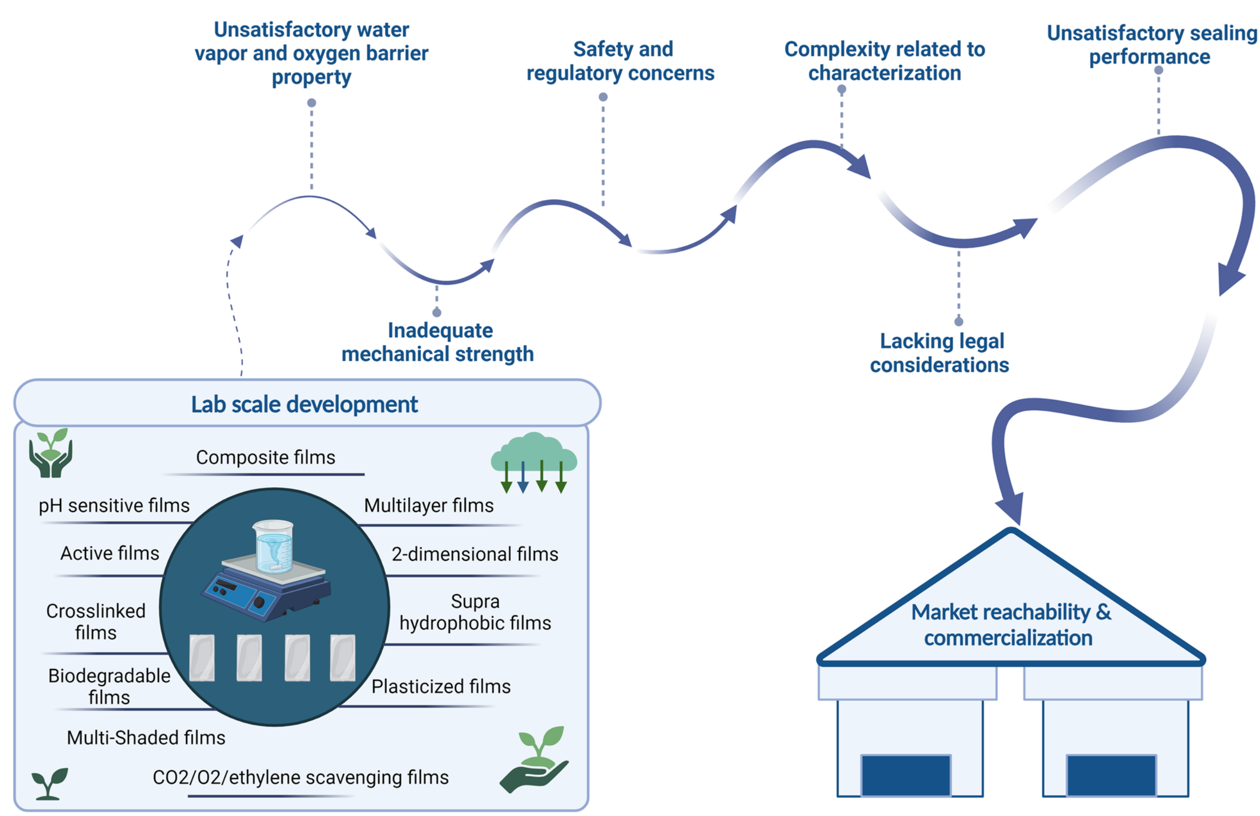
Graphical Abstract



Introduction

Recently, a wide range of films have been extensively studied for their diverse applications in the food packaging industries. The ultimate goal of these films is to prevent food spoilage and extend its shelf life [1]. At the same time, films offer an efficient solution in replacing polyethylene terephthalate, polypropylene, low-density polyethylene, linear low-density polyethylene, medium-density polyethylene, high-density polyethylene, polypropylene, polycarbonate, polyvinyl chloride, polyvinylidene chloride, polyamide/nylon. The multiple solutions offered by biopolymeric films in terms of improving the quality, preventing spoilage and shelf life, and decreasing plastic load always attract researchers to advance their knowledge in edible films. As plastics-based films can be easily molded, sealed, printed, resistant against pathogenic microorganisms, and more durable, they are still leading the food packaging industry. However, due to the movement of microplastics from plastic material into foods as well as its possible concerns on human health and challenges in recycling these materials, biodegradable films are assessed as a substitute for synthetic plastics. Thus, due to consumer awareness and a mounting requirement for "green" alternatives, researchers are more focused on the development of sustainable films [2].

Most of the studies related to films emphasize the improvement of thermal, mechanical, barrier, optical, antioxidant, and antimicrobial properties. These films are made up of natural polymers such as gelatin, sodium alginate, casein, chitosan, starch, cellulose, etc. and thus they are biodegradable. These natural films are thin with a thickness of $\leq$ 0.25 mm and act as an efficient barrier against the movement of moisture, oxygen, and solute. Edible films are often confused with edible coatings. Edible films typically refer to thin layers of edible materials that can encapsulate or cover food items, whereas edible coatings are directly applied onto the surface of food products. Innovation in biopolymer films resulted in the development of a different range of films such as composite films, 2D materials, 3D printed films, superhydrophobic/hydrophilic films, smart and intelligent pH sensitive films, mono or multilayer films, nano-engineered films, active films, plasticized and cross-linked films (Fig. 1). Such advancement helps in offering efficient solutions

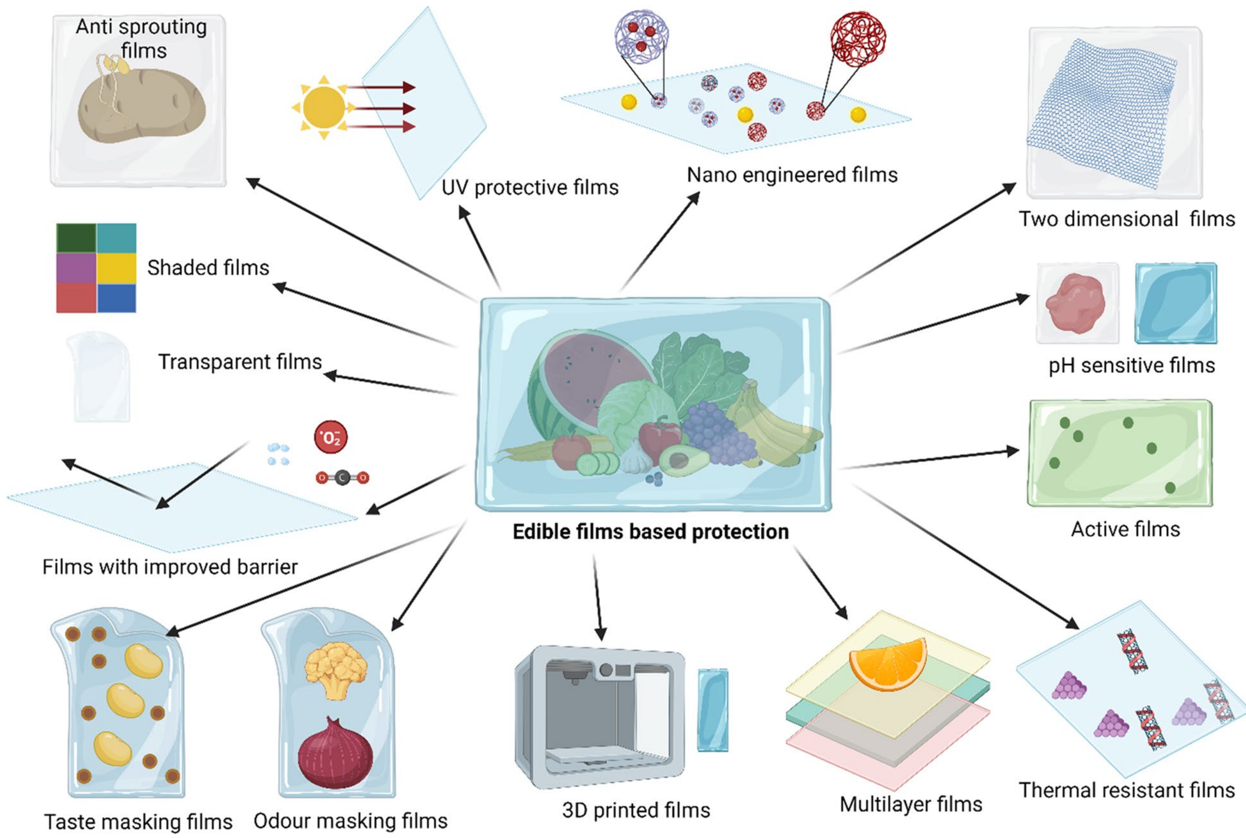


Fig. 1 Comprehensive spectrum of biodegradable films utilized in food packaging applications

against food contamination, spoilage and at the same time it also helps in understanding whether these natural polymeric films are comparable to plastic films or not. This short review article provides systematic information about the recent advancements in biopolymeric films.

Different range of films

Anti-sprouting films

The polymeric materials used in the films serve as carriers to deliver natural anti-sprouting agents such as essential oils. As conventional fogging with chlorpropham causes several health and environmental problems thus fogging with essential oils is considered as an alternative approach. Wider acceptance of essential oils such as spearmint (*Mentha spicata L.)* as an efficient anti-sprouting treatment in postharvest storage of potatoes [3] is also evidenced. However high volatile nature of these oils restricts their applications as potential fogging agents. Thus, loading essential oils in a polymeric delivery system such as films that will allow extended release of essential oils would be advantageous in preventing targeted food sprouting during the storage and supply chain. A recent study showed the development of active carboxymethyl cellulose films loaded with citral could be considered an effective anti-sprouting film to maintain potato quality and storability during marketing and household storage [4].

High-performance UV-blocking films

Ultraviolet rays deteriorate food by encouraging photooxidation and changing the nature of photosensitive components present in the food. Thus, high-performance UV-blocking films can act as a protective screen to prevent the photooxidation of packaged food. The incorporation of UV-blocking agents such as nanomaterials, phytochemicals, or natural plant extracts in polymeric matrix improved the shielding ability of the films. Curcumin, ZnO, TiO_2, silver nanoparticles, and several plant-based extracts have been studied as potential UV-blocking agents with different polymeric matrixes [5].

Nano-engineered films

Nanocomposite material enhances the surface area, thus improving the loading volume of active components, its thermal stability, and the mechanical properties of the films. These nano-engineered materials can significantly improve the physicochemical, mechanical, thermal, optical, and bioactive properties of films. Several nanomaterials including multi-walled carbon nanotubes, organic (nano-cellulose) and inorganic (metal and metal oxide nanoparticles) with exclusive properties such as light barrier, adhesion, anti-oxidative and antimicrobial effects have been used in films and coating materials [6].

Two-dimensional materials films

Two-dimensional materials such as nano-cellulose, metal nanoparticles, and carbon nanotubes have been studied to enhance the barrier, thermal, and mechanical properties of food packaging materials. Several 2D materials have been studied in the form of graphene, transition metal dichalcogenide, hexagonal boron nitride, layered double hydroxides, graphitic carbon nitride, transition metal carbides, and nitrides in food packaging. These two-dimensional materials offer optoelectronic characteristics, large surface area, and good photocatalytic and electrocatalytic, antioxidant, and antimicrobial properties [7].

Multi-shaded films

A recent study showed the application of food color in developing gelatin and starch-based multi-shaded films which can enhance consumer acceptability, especially in confectionary industries for products like candies. This study showed the effect of different food color on the physical and chemical properties of gelatin and starch-based films [8].

Such colorful eye-catching films can attract the consumer's attention and at the same time can be utilized in differentiating similar food products. Colorful packaging material also helps in presenting brand recognition, and product quality, differentiating the diverse range of food products.

Taste masking or modifiers coated films

Masking or modifying food taste is one of the challenging tasks of the flavor trade. There is a wide range of taste modifiers studied before. Some retain high sweetness and others exhibit slight or no sweetness response. There are several taste modifiers such as glycyrrhizin, neohesperidin dihydrochalcone, thaumatin, neotame, miraculin, maltol, ethyl maltol, lactisole, alanine, glycine, lysine, adenosine monophosphate. Excessive salty, sour, bitter, astringent, etc. food, that is highly nutritious, needs taste masking treatments to improve consumer acceptability in terms of health, convenience, and good flavor. These taste modifiers (natural or food-grade synthetic) can be incorporated into the coated films to increase consumer acceptability towards unpleasant food. At the same time encapsulating these flavoring agents in the suitable polymer and coating food with respective polymer can offer the controlled release of flavoring agents. Moreover, the inclusion of flavoring agents can improve the mechanical, thermal, barrier, and other crucial properties of the coated material [9]. Unfortunately, so far, such films or coated materials are not available yet, however, coated materials or films can bring a revolution in the food industry for food which were not accepted by the consumers because of unpleasant taste.

Odor-masking films or coating materials

Edible films and coating materials can be potentially used to mask the undesirable odor of highly nutritious food or vegetables such as onion, garlic, durian, tempeh, harzer cheese, hákarl, and sulfur-containing vegetables. Vinegar, essential oils, herbs and spices, and many other agents have been used to modify the odor of the food [10]. Edible films or coating materials' potential has not been explored yet as odor-masking edible films for food that have an undesirable odor. Using films or coating materials loaded with masking agents for unpleasant food smells could be considered a reliable approach in offering the control and prolonged release of masking agents. At the same time, this type of treatment can improve the physical, chemical, and biological properties of the films.

Oxygen, water, and carbon-dioxide resistant films

Gas as well as water vapor barrier features of a film differ significantly with morphology (pinholes), composition, architecture (mono-multilayer), thickness, and occurrence of bubbles in the films. Water-soluble polymeric films made up of protein and polysaccharides usually display excellent gas barrier properties. Films fabricated from proteins and polysaccharides are likely to display outstanding oxygen barrier properties. This is because of the tightly packed, well-organized hydrogen-bonded network structure. Thus, spoilage of food due to respiration reactions as well as degradative oxidation can be possibly controlled by using such polymers [11]. However, at the same time, they display unsatisfactory water barrier properties due to their hydrophilic nature. Thus, the addition of hydrophobic substances such as lipids, beeswax, oils, and fatty acids could be a reliable approach to restrict the migration of water vapors across the materials. However, such modification can result in films with poor mechanical properties [12].

Other approaches such as fabricating multilayer films or composite films (protein-lipids-polysaccharide), reducing water activity and pH have been also studied to improve the barrier properties of these films [13]. Oxygen from the environment can pass through the membrane during the drying phase, called retort shock [14]. The incorporation of oxygen scavengers or absorbers such as antioxidants, photosensitive dyes, enzymes (oxidase, laccase, and oxalate oxidase), and nano-iron in the food packaging material have been also studied to restrict the migration of oxygen. Oxygen scavenging films can also be prepared by surface immobilization [14]. Nano-active oxygen-absorbing films such as nano-iron-containing kaolinite incorporated into HDPE films as an active oxygen-scavenging film, along with polyolefin nanocomposites have recently been studied [15].

Carbon dioxide is valuable for the modified-atmosphere packaging of foods, however high level of carbon dioxide in the packaging material could be harmful to the food quality and the reliability of the packaging material. This is mainly observed among foods that produce CO_2 including fresh produce and fermented foods. In such cases, it is important to add CO_2 absorbers in food packaging material to preserve the quality of the food and the integrity of the package. Besides chemical absorbers like calcium hydroxide, sodium carbonate, amino-acid salt solution, and calcium oxide, physical adsorbents such as zeolite and activated carbon can be used to adsorb CO2 gas. CO2-absorbing material can be added to films for their application in the food packaging industry. Such absorbent can be added to the films to enhance the CO_2 absorption capability of the films and study their effect on their physical and chemical properties [16]. Incorporation of hydrophobic substances, cross-linkers, fabrication of multiple layer films, using water-resistant polymers (such as milk protein, ethyl, cellulose, PLA, etc.), treatment with divalent ions and other approaches can improve the water barrier property of the films [17, 18]. However, the addition of hydrophilic substances like plasticizers increases film hydrophilicity, which in turn encourages water vapor permeability [19].

Heat-sealable or thermal-resistant films

Heat sealing is a simple and cost-effective approach to processing films into soluble pouches, bags, packets, or sachets. Unfortunately, several neat polymers displayed poor heat sealability which restricts their applications in the food packaging industry. Recent research showed that the addition of nano clay can enhance the seal strength of the films. Similarly, the addition of nanomaterials such as inorganic nano compounds, nanofibers, nanotubes, nanocrystals, and crosslinkers can improve the thermal stability of films [20, 21]. However, the addition of such nanomaterials raised safety concerns as well.

Transparent films

Transparency of the films or coating material is an important attribute as it allows the visual inspection of food such as meat and meets the consumer requirements. Starch, gelatin, chitosan, cellulose derivate (hydroxyethyl cellulose), and other polymer-based films are transparent [22–24]. Ultra transparent glossy and stable films can be prepared using the right biopolymer in the films. For an instance starch, gelatin, and cellulose can result into whitish, yellowish, and translucent films whereas using polylactic acid transparency can be improved.

2D and 3D printed films

The classical casting approach used for the preparation of films always resulted in films with significant variations in thickness. Recent advancements in printing technology allowed the improvement of films in terms of uniformity in thickness and other morphological attributes which can be further confirmed by SEM. This attempt to print films requires the proper selection of printable biopolymers and their understanding related to rheological consideration [25, 26].

Super-hydrophobic/hydrophilic films

Non-wetting surfaces offered by super-hydrophobic coating materials display excellent anti-fouling as well as self-cleaning properties. The idea of fabricating such materials was stimulated by lotus leaves. Ideal super-hydrophobic material for food packaging applications must be cost-effective, simple, and restrict the migration of hydrophobic substances into the food. Several approaches have been used to synthesize the super-hydrophobic coating material. The addition of micro/nanoscale structures as well as low surface energy can provide a high-water contact angle and a small sliding angle. The addition of fluorinated materials and electrostatic spinning of hydrophobic polymers were utilized to fabricate super-hydrophobic coatings. However, due to the high cost and unsuitability of electrospinning for the large-area coating and the recent classification made by the U.S. Environmental Protection Agency for fluorinated materials as "emerging contaminants", both procedures seem unsuitable. Waxes obtained from natural sources such as candelilla wax, beeswax, and rice bran wax can be utilized as ideal super-hydrophobic coatings for food packing. As incorporation of such materials has not compromised the thermal stabilities of super-hydrophobic coatings materials [27, 28].

However, super-hydrophilic films can also be utilized where anti-fogging surfaces are sometimes preferred or food surfaces are highly hydrophobic. Hydrophilic polymers, using plasticizers or any hydrophilic agent are enriched with hydroxyl-, carbonyl-, carboxyl-, amino, sulfhydryl-, and phosphate groups and can be used to make the surface water loving. Plasma treatment is frequently used to synthesize hydrophilic films, at least temporarily.

Smart and intelligent pH-sensitive films

pH-responsive smart packaging biopolymers-based films loaded with natural food colorants consist of solid matrix and pH-sensitive dye. Biopolymer serves as a solid matrix whereas pH-sensitive dye (synthetic or natural) provides color response to the film. Curcumin, anthocyanins, and phycocyanin are used as natural dyes, however, still researchers are looking forward to natural and safe colorimetric indicators, which must be highly sensitive, reliable, and responsive. Such smart and intelligent pH-sensitive films have been used to detect food spoilage caused by undesirable microorganisms and their metabolites. This approach allows the real-time monitoring of food quality and spoilage. This advancement in colorimetric techniques allows for efficient real-time quality monitoring of packaged foods by detecting noticeable color changes [29].

Multilayer films

Changing the architecture of the films significantly impacts the films' physical and chemical properties. For instance using engineering approaches like supramolecular thin films, stimuli-responsive nano- or micro-particles, and multifunctional hydrogel can result in films with advanced features [30]. Polymer structure/architecture alteration, modification in crystallinity, melting blending /multi-layer co-extrusion, nanotechnology, and surface coating have been used to make food packaging material with advanced properties [31]. Multilayer films consisting of barrier, active, and control layers can also improve the functional performance of the films. The barrier layer acts as a shield against moisture, oxygen, and microorganisms present in the environment whereas the active layer contains antioxidants, antimicrobials, or nutrients which can be designed in a way to retain active components and provide control/prolong supply. These active components migrate from the control layer to the food at the desirable rate.

The innermost control layer is in direct contact with food and is intended to control the release rate of active components. The performance of these layers can be adjusted depending on the external environment (humidity, temperature, food properties) and internal properties. Polymer features (such as hydrophilicity, crystallinity, swelling, thermal stability, and barrier properties) and active constituent features (such as molecular mass, ratio, and solubility) are considered internal environment features [32].

Active films

Active films are those films that contain active constituents such as antimicrobials, antioxidants, and nutrients to prevent microbial growth and oxidation reactions and improve the nutritional value of the food. In the majority of the research natural products have been used as active ingredients in various films, without considering the fact related to safety, complexity, and the release kinetics of their components. Active packaging materials must be designed in a way to retain these active components and provides the prolonged/controlled release of the components [32].

Plasticized and cross-linked films

Plasticized and cross-linked films are of great importance as crosslinking and plasticization of the film components significantly impact the mechanical, thermal, and crystalline properties. Plasticizer generally increases the free volume by augmenting the polymer chain mobility whereas cross-linkers restrict the chain mobility and thereby decrease the free volume. Plasticizers improve film flexibility and resilience whereas cross-linkers reduce film flexibility [33, 34]. Thus, proper selection of a type and amount of plasticizer or cross-linker can result in films with desirable thermal, mechanical, and barrier properties. Different range of films and their specific application has been presented in Table 1.

Challenges

Recently biopolymeric films received a lot of attention however these films also face the following challenges when it comes to their production from laboratory to large scale.

Inadequate mechanical strength

Synthetic films like LDPE (Low-density polyethylene) are commonly used in plastic pouches, bags, wraps, and films due to their high flexibility and resistance against moisture, tearing, and chemicals [52]. LDPE-based packaging films mostly end up in landfills after single use as they are not commonly recycled due to their flexible nature, low strength, and low cost [53]. Recycling monolayer LDPE-based films is very difficult because of their contamination with foreign materials and sorting (as per the type and grading of plastics) related challenges [54]. Thus, such films could be alternatively replaced with biodegradable polymer-based films such as polylactic acid (PLA) and many others. Even a blend of LDPE with biodegradable polymer has been reported to increase the biodegradability of low-density polyethylene (LDPE) [54]. A recent study explained that the degradation of LDPE-chitosan might be triggered by the existence of chitosan as a nutrient source for microbial growth [55]. EAB values of LDPE varies in between 300–500%, though some of the reports confirmed EAB > 1000. However tensile strength of LDPE ranged in between 10–18 Mpa which

Table 1 Different types of films with their specific applications

Application	Composition (polymers)	Component responsible for the application	Application	References
Anti-sprouting films	Carboxymethyl cellulose	coarse emulsions and nanoemulsions of citral	Application suppression of potato tuber sprouting	[4]
Cross-linked films	Different polymers with organic acids	Synthetic cross-linkers: Divalent calcium salts, sodium tripolyphosphate, N,N′-methylene bisacrylamide, ethylene glycol dimethacrylate, poly (ethylene glycol) diacrylates, epichlorohydrin, and glutaraldehyde. Natural: (Gallic, vanillic, cinnamic, caffeic, ferulic, tannic, citric, succinic, salicylic, rosmarinic acids, etc.)	To improve the physical and chemical properties of the film	[35, 36]
Active films		Natural additives (glucosides, polysaccharides, phytosterols, phenolic acids, esters, carotenoids, tannins, alkaloids, anthocyanins, flavonoids, terpenoids, caffeic acid, and other organic acids)	To reduce the surface multiplication of pathogenic microorganisms and prevent food deterioration	[37]
Multilayer films	The hydrophobic zein outer layer, hybrid zein/gelatin middle layer, and the hydrophilic gelatin inner layer	Tea polyphenol	To improve water barrier property	[38]
pH-sensitive films	Corn starch Buckwheat starch	Anthocyanins Natural rose petal extract	Real-time quality assessment for packaged food products, as film color of changed from pink to purple and blue, as a function of the pH	[39]
Composite films (multicomponent films)	Binary/ ternary/multiple biopolymers from, protein, polysaccharides, and lipids	Different active components have been reported	To improve the physical and chemical properties of primary polymer	[40]
Super-hydrophobic films	Chitosan	Tea polyphenol-carnauba wax material	extremely low water-absorbing quality	[40]
Thermal stable films	Polylactic acid	Bionano calcium carbonate	Thermal properties improved after incorporation of nano-$CaCO_3$	[41]
	polysaccharide/gelatin	-	incorporation of gelatin into soybean polysaccharide films increased the thermal stability	[20]
Nano-engineered films	Chitosan	Zinc oxide nanoparticles with pomegranate peel active phenol compounds	For the preservation of pomegranate arils	[42]
Moisture resistant films	Mung bean starch	Sunflower seed oil	Increase in water-resistance properties	[17]
High-performance UV-blocking films	Alginate, Whey Protein	Curcumin	Incorporation of Curcumin enhanced UV-blocking efficiency within the films	[43]
Two-dimensional films	Different polymers	Graphene, transition metal dichalcogenides, hexagonal boron nitride, layered double hydroxides, graphitic carbon nitride, transition metal carbides and nitrides	Improve mechanical, thermal, surface area, and electrocatalytic activity	[7]
Multi-Shaded films	Gelatin and starch	Food grade colorants	To attract the customers	[8]

Table 1 (continued)

Application	Composition (polymers)	Component responsible for the application	Application	References
High-barrier water vapor-resistant films	Hydrophobic polymers such as cellulose derivatives (such as ethyl cellulose), Polylactic acid	Food grade essential/vegetable oils, waxes, fats, gums, suitable plasticizers that are compatible with polymers	To improve the barrier property against water vapors	[44–46]
Carbon dioxide scavenging films	Different polymers such as zein and cellulose derivate	Carbon dioxide absorbers (Activated carbon, Zeolite, $Ca(OH)_2$, Na_2CO_3 can be used. Plasticizer can also improve the gas transmission	To improve the barrier property against carbon dioxide	[47, 48]
Ethylene-absorbing films			to absorb ethylene gas	[49]
Oxygen scavenging films	Starch, cellulose nanocrystals, polyhydroxyalkanoate, whey protein	Starch-highly ordered hydrogen-bonded network structure (increased crystallinity or higher amylopectin content in the sample improves the barrier properties), likewise, other polymers have inherent properties to control oxygen transmission. In addition, food-grade natural/synthetic antioxidants absorb and remove oxygen from the packaging	These films absorb and remove oxygen from the packaging, which helps to slow down the oxidation process	[50, 51]
Superior Ductile	Poly(lactic acid)	Biaxial stretching and constrained annealing to induce oriented nano-sized crystals induced	Sustainable packaging	[51]

is comparable and even less than biodegradable films [52, 56].

It is challenging for natural polymer-based films to beat the elongation at break (EAB) of LDPE and to achieve more flexibility which is a prime requirement of films when they are used as a wrapping material. Thus, approaches like blending natural polymer with LDPE could be an attractive approach to increase the EAB and biodegradability profile of the films [55]. Films without plasticizers are brittle, however, their tensile strength is comparable to synthetic films, they show poor film-forming properties when compared to synthetic films. The addition of an optimum amount of plasticizer improves the EAB values and can ease out the production of multi-layer, nanoengineered, and multilayer films.

Unsatisfactory sealing performance

Due to less weight and low expense, flexible packaging is usually favored over rigid packaging. Films can be used as an excellent sealant to protect the packed product until the consumer opens it for use. The requirement of seal performance for different packaging varies depending on the type of product and users. Seal performance depends on the type of polymer/s involved and its interaction with other additives such as plasticizers, tackifiers, crosslinkers, lubricants, slip agents, fillers, etc. The performance of the seal strength is also dependent on the polymer's inherent properties such as the percentage of crystallization which is again dependent on the molecular weight, molecular weight distribution, and whether the polymer chains are linear or branched. For instance, the variation in crystallinity, impacts the melting temperature of the polymer and thus can cause a shift in heat sealing, seal/hot tack strength, and initiation temperature [57]. These films when used as a sealing application, must be sealed, as the mechanical fix is quite impossible. Most biopolymer-based films cannot be sealed in their natural state [58].

One of the major reasons for the unsatisfactory sealing properties of these biopolymers such as chitosan, starch, and chitosan as they degrade before they melt [59]. The addition of a suitable plasticizer, and blending it with a secondary polymer, multilayer, and nanoengineered approach can improve the film sealability profile.

Scaling up challenges

Films show fluctuation in thickness. Generally, a thickness less than 0.025 mm is considered as edible coating while a thickness greater than 0.050 mm is considered as edible films/sheets [60]. The compatibility of bioplastics with production procedures like blown film extrusion or cast film extrusion must be considered. In case multilayers are considered, their compatibility with coextrusion and lamination procedures where they are used in combination with one more polymer, paper, or foil. This process includes heating and drying procedures which raised a concern for the compatibility of biopolymers with such operations.

Due to the non-compatibility of the biopolymer-based films with several industrial operations such as blowing, and sealing, failure in manufacturing continuous films, challenges in controlling the thickness, high cost, and long drying period, their commercialization is still challenging. Some of the adhesive biopolymers such as cellulose stick firmly to the substrate and are thus difficult to peel from the surface. On the other hand, some films lose the moisture content during the drying procedure resulting in challenges in peeling the films. Thus, to ease out the peeling procedure optimal moisture content must be in the range of 5 and 8% [61]. The suitability of the composite and native biopolymer-based films with other operations such as biaxial orientation (stretching of films using rollers) must also studied [62].

Unsatisfactory water vapor and oxygen barrier property

The most used native hydrophilic biopolymer-based films such as pectin, starch, sodium alginate, gelatin, collagen, chitosan, and many other polysaccharides and proteins have poor water vapor barrier properties because of their hydrophilic nature [62–65]. However, these polymers have moderate to satisfactory oxygen barrier properties [65, 66].

Starch-based films have satisfactory oxygen barrier properties. This is due to a highly structured hydrogen-bonded network formed by amylose and amylopectin. This ordered structure comprises alternate crystalline and non-crystalline regions that control oxygen barrier properties [50]. Thus, the addition of antioxidants, and hydrophobic substances, changing the architecture (from monolayer to multiple layers) can improve the barrier property of the films.

Nanotechnology and 2D materials: safety and regulatory concerns

Several reports showed that the addition of nanoparticles and two-dimensional materials improved the properties of films however their safety profile and toxicological assessment are still unclear. High chance of nanoparticles and two-dimensional materials movement from the coating or films to fruit, as well as the chances involved in human consumption increased in such films [6].

Edible films: are they edible?

Only a few research studies provide in-depth in vitro digestion and in vivo assay-related studies to support that biopolymer-based films are edible, safe, and deprived of any toxic effects. It is important to study the end products produced from these biopolymers (or composite materials) after their degradation in the gastrointestinal tract and their effect on human health [67]. Toxicological studies of the films must be performed to ensure their safety profile before asserting them as edible. It is also important to assess the toxicological profile of films treated with radiations, heat, and chemicals to modify their properties. In recent study, cold plasma treatment was tested to assess whether its treatment resulted in the formation of toxic compounds or not. The findings from this study showed that cold plasma-treated edible film exhibited less toxicity [68].

The toxicity of nano or two-dimensional materials used in the food packaging to human health and to the environment is also a subject of debate [69]. Moreover, cross linkers, plasticizers, surfactants, and other additives used in the films must be assessed for their safety. For an instance geniposidic acid, glutaraldehyde used as crosslinkers have been reported for their inherent toxicity. Thus, utilization of such additives must be restricted [70].

The genotoxicity of the chitosan nanoparticles for use in food packaging films was assessed and it was found that 82 and 111 nm nanoparticles reduced mitotic index values at the highest concentration tested (180 mg/L), demonstrating their toxicity to the cells [71]. Thus, it is important to control the size of nanoparticle, intended to load into the films. Moreover, shape, surface charge, solubility, and degree of agglomeration as well as on surface coating of the nanoparticles must be considered. Moreover, arguments based on the toxic compound formation or other health-related issues have restricted the use of photo polymerization to modify the surface of food packaging polymers [72]. It is also important to assess the inorganic composition of the biopolymers used for food packaging. As natural polymers derive from waste or plant or algal sources may contain traces of toxic metals, such as arsenic, cadmium, lead, and mercury, and other metals such as cobalt or iron. These toxic metals can potentially migrate to food and thus pause a safety concern to the human health. Understating deeply about biopolymer (mainly composite films) interactions with gastric digestive physiology could shed a light on its degradative products formed after their exposure to gastric environment. Hydrolyzed products formed during this process and its further impact over gastrointestinal tract must be assessed. Natural polymers such as chitosan can cause allergic reactions in some people since they are derived from biological sources [73, 74].

Lack of biodegradability studies in different medium

The degradation of biopolymer-based films differs in diverse environments (soil, water, and compost). The biopolymer-based films take considerably less time to degrade than synthetic plastics. As xenobiotic-loaded synthetic polymers have poor water solubility, high molecular weight, and chemical structure, and thus tough to degrade in a natural condition is limited. Limited studies are available to investigate the biodegradability of the biopolymer-based films in different mediums such as natural and compost soil as well as fresh water and seawater. It was found that starch nanocomposite showed a higher degradation rate in compost soil than in planting soil [67]. Another study demonstrated that the deterioration of chitosan-based film showed biodegradation in all tested soils after 14 days [75]. Ahsan et al. highlighted the biodegradation of several biopolymers [76]. Still, a lot of studies must be encouraged to investigate the biodegradability of the native biopolymer-based film with the composite material and their percentage of weight loss in a time-dependent manner. Furthermore, in-depth understanding related to depolymerization, bio assimilation, and mineralization of biopolymers and the involvement of naturally occurring microorganisms, such as bacteria and fungi in biodegradation and studying their mechanism of action in mineralizing materials must be explored in the future [76].

Human factors and biopolymeric films

It is also important to study the feedback from the consumers about the experience of using films and how these edible films interact with end users and different environmental conditions. Films developed by using biopolymers can be further utilized to develop pouches, bags, wrapping material, laminates, etc. to pack the product efficiently. However, its interaction with the packed food, environment and the users must be considered. Post marketing surveillance to collect feedback from the end consumers plays a vital role in determining the how films interact with environment, product, and users. For an instance the following aspects must be considered prior to the development of biopolymer-based films:

- How the developed films would interact with variable environment such as changes in humidity, temperature, and pressure during supply chain?
- How these films would interact with humans while packing and unpacking of targeted food?
- After digestion, what would be the impact of these films over the health of the users?
- What would be the impact of these films on the environment as biopolymers are active medium for some pathogenic microorganisms and their disposal as well

as their significant accumulation in the environment could pause a concern?
- How these films can be further developed into pouches, bags and other packaging materials with efficient design considering the suitability of food product as well as users?

Lacking legal considerations

Legal consideration for films is still unclear. FDA, ISO, and the European Union have notified certain considerations for edible films [77]. As per EU rule, 1935/2004, food contact materials should not transfer harmful components into food [77]. The films for food packaging application must be Generally Recognized as Safe (GRAS) as per the recommendation of the American Food and Drug Administration (FDA) federal agency [60]. Depending upon the type of chemicals present in the food industries, the Food Drug Administration and European Food Safety Authority grouped chemicals into three different classes food coating materials, food contact articles, and food contact substances. Regulations no. 1935/2004 and no. 2023/2006 must be followed for the packaging necessities and food coating materials [78]. Biopolymer which is not GRAS approved can cause toxicity and allergic reactions, and thus cannot be used for edible coatings [78]. The carnauba or bee-wax-based coating materials are approved in India by the Prevention of Food Adulteration Act for coating fruits and vegetables [79].

Lack of studies on the blend of biopolymer and plastic films

Less studies are available combination of synthetic materials with biodegradable materials to improve the physical and chemical properties of the films and study its impact on the processability and compatibility of the materials. A recent study showed that chitosan addition resulted in approximately a hundred times larger biodegradability compared to plastics based on LDPE alone [55, 79].

Conclusion

In conclusion, the persistent use of synthetic polymers in the food packaging industry, despite bans on non-degradable plastic bags, has prompted the exploration of innovative alternatives. Edible films, biodegradable and biocompatible materials, have emerged as a promising solution to address the environmental concerns associated with traditional plastic packaging. This review highlights the diverse forms of films and their applications as advanced food packaging materials. These innovative solutions not only address environmental concerns but also offer enhanced functionality and performance, marking a significant step forward in sustainable and effective food packaging solutions. Additional research is necessary to investigate and address the challenges related to the scaling up of these films with the aim of substituting conventional plastic films.

Acknowledgements
The Authors are thankful to the Natural and Medical Sciences Research Center, University of Nizwa, Oman, for providing literature collection facilities.

Authors' contributions
Yasir Abbas Shah, Saurabh Bhatia and Ahmed Al-Harrasi designed the study and wrote the manuscript. Talha Shireen Khan helped in preparing figures and tables and improving the overall quality of the manuscript. All authors revised the manuscript critically.

Funding
This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Availability of data and materials
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Not applicable.

Competing interests
The authors declare no competing interests.

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Received: 13 February 2024 Accepted: 30 March 2024
Published online: 27 May 2024

References

1. Ahankari, S.S., A.K. Mohanty, and M. Misra, Nanomaterials from Renewable Resources for Emerging Applications. CRC Press. 2023.
2. Siddiqui SA, et al. Migration of microplastics from plastic packaging into foods and its potential threats on human health. Adv Food Nutr Res. 2023;103:313–59.
3. Chen, Q., et al., Screening of Plant Essential Oils as Potato Sprout Suppressants at Low Storage Temperature. Potato Research. 2023. p. 1–14.
4. Arnon-Rips H, et al. Effective suppression of potato tuber sprouting using polysaccharide-based emulsified films for prolonged release of citral. Food Hydrocolloids. 2020;103:105644.
5. Ezati, P., et al., Biopolymer-based UV protection functional films for food packaging. Food Hydrocolloids. 2023. p. 108771.
6. Koirala P, et al. Nano-engineered edible films and coatings for seafood products. Food Packag Shelf Life. 2023;38:101135.
7. Yu Y, et al. Applications of two-dimensional materials in food packaging. Trends Food Sci Technol. 2021;110:443–57.
8. Channa IA, et al. Multi-Shaded Edible Films Based on Gelatin and Starch for the Packaging Applications. Polymers. 2022;14(22):5020.
9. Gascon M. Masking agents for use in foods. In: Modifying flavour in food. Elsevier; 2007. p. 232–42.
10. El-Sayed, S.M. and A.M. Youssef, Potential application of herbs and spices and their effects in functional dairy products. Heliyon, 2019. 5(6).
11. Yang L, Paulson A. Mechanical and water vapour barrier properties of edible gellan films. Food Res Int. 2000;33(7):563–70.

12. Janjarasskul T, Krochta JM. Edible packaging materials. Annu Rev Food Sci Technol. 2010;1:415–48.
13. Kumar A, et al. Trends in edible packaging films and its prospective future in food: a review. Applied Food Research. 2022;2(1):100118.
14. Gaikwad KK, Singh S, Lee YS. Oxygen scavenging films in food packaging. Environ Chem Lett. 2018;16:523–38.
15. Gupta, P., Role of oxygen absorbers in food as packaging material, their characterization and applications. Journal of Food Science and Technology. 2023: p. 1–11.
16. Busolo MA, Lagaron JM. Oxygen scavenging polyolefin nanocomposite films containing an iron modified kaolinite of interest in active food packaging applications. Innov Food Sci Emerg Technol. 2012;16:211–7.
17. Lee J-S, Lee E-S, Han J. Enhancement of the water-resistance properties of an edible film prepared from mung bean starch via the incorporation of sunflower seed oil. Sci Rep. 2020;10(1):13622.
18. Rhim J-W. Physical and mechanical properties of water resistant sodium alginate films. LWT-Food science and technology. 2004;37(3):323–30.
19. Ghasemlou M, et al. Physical, mechanical and barrier properties of corn starch films incorporated with plant essential oils. Carbohyd Polym. 2013;98(1):1117–26.
20. Liu C, et al. Heat sealable soluble soybean polysaccharide/gelatin blend edible films for food packaging applications. Food Packag Shelf Life. 2020;24:100485.
21. Das D, et al. Improvement in properties of edible film through non-thermal treatments and nanocomposite materials: A review. Food Packag Shelf Life. 2022;32:100843.
22. Jeevahan J, Chandrasekaran M. Influence of nanocellulose additive on the film properties of native rice starch-based edible films for food packaging. Recent Pat Nanotechnol. 2019;13(3):222–33.
23. Iversen LJL, et al. The emergence of edible and food-application coatings for food packaging: a review. Molecules. 2022;27(17):5604.
24. Lu Y, et al. Application of gelatin in food packaging: A review. Polymers. 2022;14(3):436.
25. Putranto A, et al. Design and performance evaluation of edible film printing machine based on automatic casting knife. In: IOP Conference Series: Earth and Environmental Science. IOP Publishing; 2021.
26. Cheng Y, et al. Rheology of edible food inks from 2D/3D/4D printing, and its role in future 5D/6D printing. Food Hydrocolloids. 2022;132:107855.
27. Zhang Y, et al. Functional food packaging for reducing residual liquid food: Thermo-resistant edible super-hydrophobic coating from coffee and beeswax. J Colloid Interface Sci. 2019;533:742–9.
28. Liu B-Y, et al. Fabrication of superhydrophobic coatings with edible materials for super-repelling non-Newtonian liquid foods. Chem Eng J. 2019;371:833–41.
29. Huang S, et al. Preparation and dynamic response properties of colorimetric indicator films containing pH-sensitive anthocyanins. Sensors and Actuators Reports. 2021;3:100049.
30. Liang H, et al. Supramolecular design and applications of polyphenol-based architecture: A review. Adv Coll Interface Sci. 2019;272:102019.
31. Wu F, Misra M, Mohanty AK. Challenges and new opportunities on barrier performance of biodegradable polymers for sustainable packaging. Prog Polym Sci. 2021;117:101395.
32. Wang Q, et al. A review of multilayer and composite films and coatings for active biodegradable packaging. NPJ Sci Food. 2022;6(1):p.18.
33. Bhatia S, et al. Gallic Acid Crosslinked Gelatin and Casein Based Composite Films for Food Packaging Applications. Polymers. 2022;14(19):4065.
34. Sothornvit R, Krochta JM. Plasticizers in edible films and coatings. In: Innovations in food packaging. Elsevier; 2005. p. 403–33.
35. Ordoñez R, Atarés L, Chiralt A. Biodegradable active materials containing phenolic acids for food packaging applications. Comprehensive Reviews in Food Science and Food Safety. 2022;21(5):3910–30.
36. Sapuła P, Bialik-Wąs K, Malarz K. Are Natural Compounds a Promising Alternative to Synthetic Cross-Linking Agents in the Preparation of Hydrogels? Pharmaceutics. 2023;15(1):253.
37. Kaur J, et al. Natural additives as active components in edible films and coatings. Food Biosci. 2023;53:102689.
38. Xia C, et al. Multilayer zein/gelatin films with tunable water barrier property and prolonged antioxidant activity. Food Packag Shelf Life. 2019;19:76–85.
39. Prietto L, et al. pH-sensitive films containing anthocyanins extracted from black bean seed coat and red cabbage. Lwt. 2017;80:492–500.
40. Dhumal CV, Sarkar P. Composite edible films and coatings from food-grade biopolymers. J Food Sci Technol. 2018;55:4369–83.
41. Gbadeyan O, Linganiso L, Deenadayalu N. Thermomechanical characterization of bioplastic films produced using a combination of polylactic acid and bionano calcium carbonate. Sci Rep. 2022;12(1):15538.
42. Anean HA, et al. Nano Edible Coatings and Films Combined with Zinc Oxide and Pomegranate Peel Active Phenol Compounds Has Been to Extend the Shelf Life of Minimally Processed Pomegranates. Materials. 2023;16(4):1569.
43. Botalo A, et al. Smart and UV-Resistant Edible Coating and Films Based on Alginate, Whey Protein, and Curcumin. Polymers. 2024;16(4):447.
44. Mohan S, Panneerselvam K. A short review on mechanical and barrier properties of polylactic acid-based films. Materials Today: Proceedings. 2022;56:3241–6.
45. Assis RQ, et al. Biodegradable packaging of cellulose acetate incorporated with norbixin, lycopene or zeaxanthin. Ind Crops Prod. 2020;147:112212.
46. Liyanapathiranage A, et al. Recent Developments in Edible Films and Coatings for Fruits and Vegetables. 2023.
47. Park HJ, Chinnan MS. Gas and water vapor barrier properties of edible films from protein and cellulosic materials. J Food Eng. 1995;25(4):497–507.
48. Lee DS. Carbon dioxide absorbers for food packaging applications. Trends Food Sci Technol. 2016;57:146–55.
49. Mariah MAA, et al. The emergence and impact of ethylene scavengers techniques in delaying the ripening of fruits and vegetables. Membranes. 2022;12(2):117.
50. Singh GP, et al. Effect on the properties of edible starch-based films by the incorporation of additives: A review. Polymers. 2022;14(10):1987.
51. Melendez-Rodriguez B, et al. High-oxygen-barrier multilayer films based on polyhydroxyalkanoates and cellulose nanocrystals. Nanomaterials. 2021;11(6):1443.
52. Ncube LK, et al. Environmental impact of food packaging materials: A review of contemporary development from conventional plastics to polylactic acid based materials. Materials. 2020;13(21):4994.
53. O'Rourke K, et al. Diverted from landfill: reuse of single-use plastic packaging waste. Polymers. 2022;14(24):5485.
54. Koinig G, et al. Lifecycle Assessment for Recycling Processes of Monolayer and Multilayer Films: A Comparison. Polymers. 2022;14(17):3620.
55. Kusumastuti, Y., et al., Effect of chitosan addition on the properties of low-density polyethylene blend as potential bioplastic. Heliyon, 2020. 6(11).
56. Shit, S.C. and P.M. Shah, Corrigendum to "Edible Polymers: Challenges and Opportunities". Journal of Polymers. 2022.
57. Stehling, F.C. and P. Meka, Heat sealing of semicrystalline polymer films. II. Effect of melting distribution on heat-sealing behavior of polyolefins. Journal of Applied Polymer Science. 1994. 51(1): p. 105–119.
58. Kibirkštis E, et al. Study of physical and mechanical properties of partially biodegradable LDPE polymeric films and their application for printing and packaging. Polym Testing. 2022;112:107646.
59. van den Broek LA, et al. Chitosan films and blends for packaging material. Carbohyd Polym. 2015;116:237–42.
60. Paidari S, et al. Edible coating and films as promising packaging: a mini review. Journal of Food Measurement and Characterization. 2021;15(5):4205–14.
61. Tharanathan R. Biodegradable films and composite coatings: past, present and future. Trends Food Sci Technol. 2003;14(3):71–8.
62. Singh S, et al. Orientation of polylactic acid–chitin nanocomposite films via combined calendering and uniaxial drawing: Effect on structure, mechanical, and thermal properties. Nanomaterials. 2021;11(12):3308.
63. Christophliemk H, et al. Oxygen and water vapor transmission rates of starch-poly (vinyl alcohol) barrier coatings for flexible packaging paper. Prog Org Coat. 2017;113:218–24.
64. Olivas GI, Barbosa-Cánovas GV. Alginate–calcium films: Water vapor permeability and mechanical properties as affected by plasticizer and relative humidity. LWT-Food science and technology. 2008;41(2):359–66.
65. Wen H, et al. Enhancement of water barrier and antimicrobial properties of chitosan/gelatin films by hydrophobic deep eutectic solvent. Carbohyd Polym. 2023;303:120435.
66. Ngo TMP, et al. Characteristics and antimicrobial properties of active edible films based on pectin and nanochitosan. Int J Mol Sci. 2020;21(6):2224.

67. Giteru SG, et al. In-vitro degradation and toxicological assessment of pulsed electric fields crosslinked zein-chitosan-poly (vinyl alcohol) biopolymeric films. Food Chem Toxicol. 2020;135:111048.
68. Han SH, et al. Oral toxicity of cold plasma-treated edible films for food coating. J Food Sci. 2016;81(12):T3052–7.
69. Duncan TV. Applications of nanotechnology in food packaging and food safety: barrier materials, antimicrobials and sensors. J Colloid Interface Sci. 2011;363(1):1–24.
70. Mi F-L, et al. Physicochemical, antimicrobial, and cytotoxic characteristics of a chitosan film cross-linked by a naturally occurring cross-linking agent, aglycone geniposidic acid. J Agric Food Chem. 2006;54(9):3290–6.
71. De Lima R, et al. Evaluation of the genotoxicity of chitosan nanoparticles for use in food packaging films. J Food Sci. 2010;75(6):N89–96.
72. Ozdemir M, Floros J. Analysis and modeling of potassium sorbate diffusion through edible whey protein films. J Food Eng. 2001;47(2):149–55.
73. Asuwin Prabu RG, et al., A review on the recent applications of synthetic biopolymers in 3D printing for biomedical applications. Journal of Materials Science: Materials in Medicine. 2023. 34(12): p. 1–22.
74. Peng S, et al. Anaphylaxis induced by intra-articular injection of chitosan: a case report and literature review. Clinical Case Reports. 2022;10(12):e6596.
75. Oberlintner A, et al. Biodegradability study of active chitosan biopolymer films enriched with Quercus polyphenol extract in different soil types. Environ Technol Innov. 2021;21:101318.
76. Ahsan WA, et al. Biodegradation of Different Types of Bioplastics through Composting—A Recent Trend in Green Recycling. Catalysts. 2023;13(2):294.
77. Díaz-Montes E, Castro-Muñoz R. Edible films and coatings as food-quality preservers: An overview. Foods. 2021;10(2):249.
78. Umaraw P, et al. Edible films/coating with tailored properties for active packaging of meat, fish and derived products. Trends Food Sci Technol. 2020;98:10–24.
79. Dhall R. Advances in edible coatings for fresh fruits and vegetables: a review. Crit Rev Food Sci Nutr. 2013;53(5):435–50.

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