

Review

Green Coating Polymers in Meat Preservation

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Abstract: Edible coatings, including green polymers are used frequently in the food industry to improve and preserve the quality of foods. Green polymers are defined as biodegradable polymers from biomass resources or synthetic routes and microbial origin that are formed by mono- or multilayer structures. They are used to improve the technological properties without compromising the food quality, even with the purpose of inhibiting lipid oxidation or reducing metmyoglobin formation in fresh meat, thereby contributing to the final sensory attributes of the food and meat products. Green polymers can also serve as nutrient-delivery carriers in meat and meat products. This review focuses on various types of bio-based biodegradable polymers and their preparation techniques and applications in meat preservation as a part of active and smart packaging. It also outlines the impact of biodegradable polymer films or coatings reinforced with fillers, either natural or synthesized, via the green route in enhancing the physicochemical, mechanical, antimicrobial, and antioxidant properties for extending shelf-life. The interaction of the package with meat contact surfaces and the advanced polymer composite sensors for meat toxicity detection are further considered and discussed. In addition, this review addresses the research gaps and challenges of the current packaging systems, including coatings where green polymers are used. Coatings from renewable resources are seen as an emerging technology that is worthy of further investigation toward sustainable packaging of food and meat products.

Keywords: edible coatings; biodegradable packaging; bioactive compounds; sustainability; smart packaging; meat packaging

1. Introduction

Muscle foods and their products are highly nutritious; therefore, they are beneficial for human health and wellbeing. While the protein content of muscle foods provides high biological value, amino acids (especially essential amino acids) also complement the proteins [1,2] present in cereals and vegetables. Because muscle foods are susceptible to chemical deterioration and microbiological contaminations, not only do they pertain to health risks but also they might cause economic loss and wastage. Pertinent loss can also be observed where sanitation in handling practices failed to meet the safety standards.

The high risk of foodborne pathogens results in some problems not only in the poor health of the local population but also in the entire food-supply chain where meat and meat products are exported. To reduce the contamination rate and extend the shelf-life of food products, edible films fabricated by spraying, spreading, and dipping can be used for packaging of food products. The films can be also formed as a thin layer of material that is directly applied onto the food surface, hence considered coatings [3].

Edible films are formed from filmogenic suspensions, which are technically developed by solvent casting on an inert surface, followed by drying and furthermore applied onto the food-contact surface. Films can form pouches, wraps, capsules, bags, or casings through further processing. Coatings and films are different in terms of their thickness. Historically and since the early 12th century, wax as the coating material was commonly used in South-east Asian countries, such as China, whereas Japan developed the first soya milk-based coating materials, and the European and some Mediterranean countries in earlier decades used lard or animal fats for brushing food-contact surfaces [4,5]. In the 19th century, the United States filed patents on animal protein, gelatin-based coating materials.

Edible films and coatings are materials that help maintain the quality of meat products during their storage and are able to extend the shelf-life of foods by acting as good water barriers, preventing dehydration, and as oxygen barriers, hence reducing lipid oxidation [6,7]. Minimally processed ready-to-eat meat and meat products are also an excellent nutrient source of pathogens, such as *Salmonella typhimurium*, *Listeria monocytogenes*, *Escherichia coli*, and *Bacillus subtilis*. [8]. Therefore, edible films or coatings not only inhibit the microbiological spoilage and invasion of these pathogenic microorganisms in meat products, but also increase shelf-life without using chemical preservatives during the storage period [9,10]. Indeed, antioxidants can be added to the film formulation, leading to better preservation of meat products, as a high amount of the antioxidant is available on the surface of the meat [11]. Therefore, the demand for manufacturing green-engineered polymers for edible films or biopackages due to consumers' health concerns has increased. Industries have been also focusing on the reduction of global waste and seeking for cost-effective production pathways for better economic strategies in the synthesis of biopolymers or biodegradable-grafted polymers [4].

In this context, the key issue is sustainable packaging development from renewable sources and by-products as added value. Various reports mentioned several types of edible films and coatings or green-engineered polymer matrices reinforced with antimicrobial agents, which retain the desirable eating qualities of meat, such as juiciness, nutritive components, and freshness of muscle foods, including beef, pork, lamb, poultry, and frozen meat [12]. Several studies also highlighted that oxidation resulting in discoloration and dryness of texturized meat products can be prevented by such coatings and edible films [8]. These thin layer of materials, unlike their enhanced barrier properties, even retard the loss of aroma of the food materials, thereby maintaining the sensory attributes of the products. Thus, this review focuses on various types of green-engineering techniques to synthesize such biopolymer-based edible films and coatings [13]. The improvement of biopolymer matrices for better physicochemical properties by grafting with the help of nanoscience and technology has been in progress [14,15]. In the current review, we further consider the role of such green polymers in muscle foods from different species. The research gaps are further addressed where an eco-design strategy is suggested for future advanced packaging materials of muscle foods in the food industry for better meat quality and consumer acceptability.

2. Green Coating Polymers as Potential Matrices for Meat Preservation

In this review, green (coating) polymers are defined as biodegradable polymer matrices that can be categorized into three main groups. The first one corresponds to those obtained from biomass and renewable resources, such as biopolymers extracted from biomass or waste, including polysaccharides (starch, chitosan) and proteins (dairy and soy proteins or gelatin). The second group corresponds to synthetic polymers obtained

from bioderived monomers, such as polylactic acid (PLA), or from synthetic monomers, such as polycaprolactone (PCL) or poly(vinyl alcohol) (PVA). The third group consists of polymers obtained through microbial biosynthesis with the extraction of cultures, such as polyhydroxyalkanoates (PHA) and polyhydroxy butyrate (PHB) [16,17], known also as natural biodegradable polyesters. On the other hand, edible films can be defined as a thin layer of edible material, which may be applied as a wrapping or between food components to extend its shelf-life, while maintaining appropriate organoleptic quality, and can be consumed as a part of the product.

Green polymers are excellent materials that imitate the conventional polymers and have a wide range of applications in food and meat packaging in the form of trays, films, wrappers, and edible coatings [18]. These are environment-friendly polyesters that degrade within a year or two, whereas petroleum-based packages take many years [19]. They have desirable thermo-mechanical properties and can be molded into given shapes by various techniques [20]. The replacement or substitution of non-degradable plastics with green polymers is the stirring interest in the polymer scientists' community, which addresses some health and environmental concerns [21].

Technically, green polymer composites are synthesized by combining different materials so as to enhance thermo-mechanical and gas barrier properties against oxygen, carbon dioxide, and water vapor [22]. In fact, blending polymers reduces the cost of large-scale production [23]. These polymer composites can be manufactured by various techniques, such as solution casting [24], or combining two techniques such as extrusion process and solution casting in the forms of edible coatings [25]. Functionalities of films are tailored by advanced technologies, such as nanomaterials in the form of nanofillers, such as nanotubes or nanowhiskers [26]. The industry manufacturing the polypackages has emerged to reinforce natural fibers, such as flax, hemp, banana, pineapple, sisal, kenaf, and coir, as fillers for better-composting properties [27–29]. Therefore, polymers can be produced from renewable sources or synthetic materials via the biosynthesis route [6].

Several myths and controversial arguments exist between green and petroleum-based polymers [30]. Certain argue that oil-based petrochemicals contribute to environmental hazards, whereas polymers derived from organisms are safer as they are considered eco-friendly [31]. Currently, it has been noticed that petroleum-based polymers can also find an enormous place to accommodate themselves as a starting point for the synthesis of sustainable packages with similar properties of polyethylene (PE) [32]. The techniques aiming to alter their properties, likely microstructure and composition, need to fit the specifications of requirements. For example, these materials have proved to be alternative sources to traditional polymers for food packaging applications [33].

Green polymers are generally recognized as safe (GRAS) since no harmful chemical by-products are obtained during the manufacturing processes [34]. The main categories of green polymers are synthetic and bio-based that are synthesized totally or partially from macronutrients, polyblends of synthetic polymers, and microbial polymers. However, it is worthy to note that there is a contradiction between biodegradable and bio-based material packages [35]. Bio-based packages relate to sources of materials, whereas biodegradable ones relate to the compostable nature of the polymers depending on the chemical structure.

2.1. *Polymers Isolated from Biomass*

Polymers isolated from biomass are generally categorized into polysaccharide- and protein- and lipid-based natural polymers to produce coatings and edible films surrounding the surface of the food (meat) product [36].

2.1.1. Polysaccharides

Polysaccharides contain one or more sugar moieties either as homo- or hetero-polysaccharides. Polysaccharides with linear chains are homo-polysaccharides, whereas polymers with branched chains are hetero-polysaccharides. They can have other functional groups in their chemical structures. In this section, various categories of polysaccharides

are described, based mainly on those that were recently reported as good sources of food/meat packages.

Starch: Among the polysaccharides and biodegradable materials, starch is a well-known and important candidate material used for several purposes [36], but most importantly, for replacement of petroleum-derived synthetic polymers due to its low cost, availability, and excellent and total degradability after usage. Food crops (e.g., wheat, rice, corn) and vegetables (e.g., potatoes) are the most abundant sources for production of starch [37]. The cost effectiveness of starch has made it more popular for the acceptance in synthesizing biodegradable packages. Starch also has a high glass transition temperature (T_g) resulting in thermostable packages. Under controlled temperature, pressure, humidity, shear, and moisture, thermoplastic starch can be produced through the extrusion technique [25]. Currently, intensive effort is being made to address the challenges for better mechanical and moisture barrier properties. For example, three different edible coatings comparing enhanced thermo-mechanical and antimicrobial properties were developed [38]. The authors showed that turmeric starch blended with gelatin when coated on fresh frankfurter sausages exhibited significant resistance against microbial activity over a storage period of 30 days and moderate mechanical strength (5 MPa). The meat quality parameters including pH, color, and texture profile all remained proportionate compared to the control samples. It is worthy to note that the gelatin films exhibited greater mechanical strength compared to the turmeric starch film coats [38]. In addition to this example, starch nanocrystals have been also explored for application as fillers in the polymer matrix for better functionalities [39]. In fact, the interest in starch nanocrystals is recent and among the first studies, we can cite the work by Dufresne et al. [40] who prepared, analogous to the preparation of cellulose nanocrystals, nanosized crystalline starch particles through a controlled acid hydrolysis of starch. Currently, starch nanocrystals and starch nanoparticles can be prepared through top-down and bottom-up approaches following three main methods: (i) acid or enzymatic hydrolysis, (ii) regeneration via self-assembly after dissolution or complexation, and (iii) physical disintegration [41]. The well-known method that is acid hydrolysis involves the hydrolysis of the amorphous fraction of the starch granules and leads to starch nanocrystals with a high crystallinity and a platelet-like shape. Unfortunately, this procedure is difficult for practical applications due to its long treatment period, low yield, and use of strong acid. To overcome these drawbacks, novel approaches relying on physical disintegration seemed to be of interest due to the promising results in terms of increased yield, the rapidity of production, and the absence of tedious recovery and purification steps. Accordingly, high-pressure homogenization, nanoprecipitation, ultrasonication, reactive extrusion, and gamma irradiation among other methodologies have been used as alternatives to acid hydrolysis [41]. Bacterial cellulose nanocrystals (BCNs) also known to be chemically pure as they are free of hemicellulose, pectin, and lignin, were further explored [42]. For example, nisin-BCNs were used as a reinforcing agent in active food packaging for long-term storage of food [42]. Nanoscale dimensions and high surface-area-to-volume ratio of cellulose nanocrystals render them among the promising biodegradable nanofillers for reinforcement of a polymer matrix [43].

Other compostable polyesters, also known as bio-derived materials, such as PLA, polybutylene succinate (PBS), and polycaprolactone (PCL), were also blended with starch to form starch-based plastics [44–46]. These blends were reported to increase thermo-mechanical properties [47], leading to positive outcomes where biodegradability is important, such as agro product packages and food packages [48]. Important to note that research studies are still going on to observe the biodegradation rate in soil and aquatic environments. From a food-contact interaction point of view and biodegradability, these packaging materials have also stirred interest in the research community during the past few years [49]. Among the bio-derived materials, PLA (discussed below in Section 2.2) has received a special attention as one of the most attractive short-use packaging materials due to its good transparency, compostability, high rigidity and modulus at room temperature, and lack of ecotoxicity [50,51]. Very briefly and in the objective of enhancing the long-

period stability and reduced toxicity of active packaging systems, several strategies were proposed, among which two biodegradable covalent immobilized antibacterial packaging films for fresh beef preservation were investigated [52]. A PLA film was prepared by extrusion casting and the surface of the film was modified with a plasma treatment to generate carboxylic acid groups, then an antibacterial agent nisin or ϵ -poly-lysine (ϵ -PL) was covalently attached to the modified film surface. The results showed that covalent immobilized antibacterial packaging films had positive impacts on the shelf-life and quality of fresh beef. The total viable count of the control sample and ϵ -PL-g-PLA film/nisin-g-PLA film exceeded 7 log CFU/g on the 11 days and 15 days of cold storage, respectively [52].

Cellulose: Cellulose is a sustainable, abundant biopolymer derived from a variety of living species, such as plants, animals, bacteria, and some amoebas. An attractive source of cellulose for industrial uses is agricultural waste, as this use does not jeopardize food supplies and improves the rural economy [53]. As stated above for starch, cellulose nanocrystals (CNC) are also a promising material, which have been widely used by industry, including structural plastics, pharmaceuticals, cosmetics, smart coatings, and solar energy collection, with many more uses still being assessed [54,55]. The extraction process of cellulose is very expensive; however, enzyme hydrolysis from biomass using genetically modified organisms is performed cost effectively [56]. Chemical modification followed by purification of cellulose improves its starch binding, which also possesses strong hydrogen-bonding-enhancing packaging properties [57]. Bacterial cellulose (BC) have been widely used for active packaging, including meat shelf-life studies. For example, Pirsá et al. [58] proposed an intelligent and smart packaging using BC modified with zinc nanocomposites for chicken breast storage. Chemical polymerization allowed the authors to develop films to investigate the effect of storage time and temperature for chicken thigh preservation. The results showed a substantial reduction in mesophilic and psychrophilic bacteria and an effect on final pH (reduced/maintained stable). More attention was further gained in preparation techniques of bacterial nanocellulose (BNC) in active packaging. Ultrasound-assisted coating was also used to facilitate the release of postbiotics from the films [59]. Thus, anti-*Listeria* active packaging films containing BNC with sakacin (postbiotics of *Lactobacillus sakei*) were fabricated. These films were wrapped onto beef patties before the examination of microbial content. It resulted that the film with BNC gave a similar result of total viable count, whereas postbiotics incorporated films resulted in 2.3 CFU/g reduction in count after 9 days storage at 8 °C.

Pectin: Pectin is one of the main constituents of the cell wall of a plant that provides integrity and rigidity in shape and is the most complex structure [60]. It is a poly-1- α -galacturonic acid consisting of different degrees of methylation in a carboxylic group or amidated polygalacturonic acids. The gelling properties of pectin extensively depend on the degree of esterification [61]. For example, studies used pectin fish gelatin blend films induced with two naturally occurring antioxidants of olive oil (hydroxytyrosol and 3,4-dihydroxyphenyl glycol) [11]. The findings reported a significant reduction of lipid oxidation in stored beef. Another study by Xiong et al. [62] confirmed such conclusions and showed an evidence that pectin edible coating loaded with nanoemulsions of oregano essential oil and resveratrol is a potential strategy for meat preservation. The results showed that coatings enhanced shelf-life of pork where the color remained unchanged, pH was minimized, and lipid-protein oxidation was significantly delayed. The mechanisms behind this strategy can be related to the synergetic effects of the oregano essential oil and resveratrol. In fact, oregano essential oil is among the most powerful antioxidant essential oils that has been well documented to extend the shelf-life of fresh meat by controlling both protein and lipid oxidation [63]. Furthermore, it has the ability to inhibit microbial growth, along with that of resveratrol, a potent antioxidant, with a better impact on meat oxidation than other well-known polyphenols, such as carnosine, quercetin, and rutin [62,64].

Alginate: Alginate, is a naturally occurring indigestible polysaccharide synthesized by brown-green algae, such as *Macrocystis pyrifera*, *Ascophyllum nodosum*, *Eclonia maxima*, *Sargassum* sp., etc. [65]. Some bacterial strains, such as *Azetobacter* sp., also synthesize

alginates in the form of exopolysaccharides. The chemical structure of alginate consists of unbranched linear binary copolymers of β -mannuronic acid (M) and α -L-guluronic acid (G) bonded by one to four glycosidic bonds. It has been reported that the cross-linking nature of M and G blocks of alginate with polyvalent cations are very important in forming polymers with low solubility [66]. A recent study by Lourenço et al. [67] has developed alginate-based edible films containing active pineapple peel compounds. These films were applied on beef steaks under storage of 4 °C during 5 days. The bioactive films with encapsulated hydroalcoholic extract of pineapple significantly reduced *Pseudomonas* spp. after 2 days of storage and retarded lipid oxidation, hence maintaining the desirable cherry-red color of beef. Similar antibacterial activity against *Pseudomonas* spp. in chicken breast was also observed earlier when wrapped with sodium alginate films infused with ϕ IBB-PF7A bacteriophage [68]. Further, the authors concluded that phage incorporation onto sodium-alginate-based films constitutes a simple and an efficient approach of preserving the antimicrobial activity of phages in a dried and insoluble format.

Chitosan: Chitosan is a well-known film-forming biodegradable polymer obtained from an exoskeleton source of marine invertebrates (crustacean shells) that are abundant, cheap, and easily degradable polymers [69,70]. In addition, chitosan is non-toxic and eco-friendly in nature [71], with high insolubility in water but soluble in acidic pH, and is also known as biocompatible. Chitosan-based edible coatings were already proven as an effective active packaging material for meat preservation during storage, especially as their preservative efficiency was further enhanced when fabricated with other natural antimicrobials and antioxidants, such as cinnamon oil, gallic acid, and polylysine [72–76]. Montaña-Sánchez et al. [77] investigated the anti-lipid oxidation properties of green edible coating from chitosan in the presence of bioactive green tea leaf extract. The authors extracted bioactive compounds using maceration. Polyphenols from tea leaf powder were extracted with water at 80 °C as solvent (1:40, *w/v*) for 20 min. The sample was later centrifuged to collect the supernatant before filtering the solution and its concentration under reduced pressure by rotary evaporation and further freeze dried. Chitosan was dissolved in glacial acetic acid, and the green tea extract was further added by homogenization. Findings of this study showed that the coating served as an excellent antioxidant material against lipid peroxidation in pork chops [77]. Those findings were confirmed in another similar study that used bamboo vinegar blended with chitosan to develop an active edible coating of pork chops [78]. Moreover, Quesada et al. [79] used chitosan films modified with thyme oil (1,8-cineole chemotype) in a ready-to-eat pork product and obtained better microbial resistance to the development of aerobic mesophilic and lactic acid bacteria. Overall, the authors concluded that the presence of a chitosan essential oil layer avoided water condensation, whereas the packages containing only chitosan had evident water droplets. The most significant sensory effects in this study were found for odor, with pork odor intensity decreased with increased essential oil concentration, as a result of a masking process produced by thyme odor. Another recent work highlighted the potential application of a developed chitosan/lauric acid edible coating for the preservation of fresh beef steaks under refrigerated storage and aerobic packaging conditions [76]. Overall and in most studies, chitosan showed an excellent antimicrobial activity against a broad spectrum of bacteria and fungi [80] due to its electrostatic interaction with negatively charged microbial cell membranes [81]. In addition to the microbial effect, the study by Hoa et al. [76] reported two major findings. First, the incorporation of lauric acid preserved beef samples from discoloration for 21 days of storage. Second, the coating with chitosan alone or chitosan/lauric acid did not affect the volatile flavor profiles of cooked meat; especially showed inhibitory effects against the formation of bacterial spoilage-derived volatile compounds (e.g., 2,3-butanedione, butylamine, urea, butane, and acetoin) associated with meat off-flavors. Therefore, a coating of chitosan containing 1–3 mM lauric acid could be a promising strategy (next generation of preservatives against bacterial growth in meat and meat products) in the preservation of fresh beef to improve sensory quality and safety under aerobic packaging conditions.

Pullulan: Among the broad range of biopolymers, pullulan, a non-ionic exopolysaccharide obtained from the fermentation medium of the fungus-like yeast *Aureobasidium pullulans* (originally called *Pullularia pullulans*), due to its unique film and coating forming properties, has been investigated in the last 10 years in the area of food packaging. Unfortunately, its high price restricts its use to laboratory-scale or pilot-scale applications. On the other hand, the amorphous structure of pullulan with high flexibility has the capacity to form thin layers, electrospun nanofibers, nanoparticles, flexible coatings, stand-alone films, and three-dimensional objects. These distinct features of biodegradable pullulan resembling synthetic petroleum-based polymers (e.g., poly(vinyl alcohol) (PVOH) and nylon-PA 6,6) do not exist in other polysaccharides [82]. Recent developments of implementation of pullulan include the creation of biopolymer nanocoating layer that is deposited directly in the form of liquid solution onto the surface of plastics, namely polyethylene terephthalate (PET). These nanocoatings create exceptional barriers against oxygen [83–85]. Among the few examples that used pullulan, we cite the recent study by Hassan et al. [86] who developed and evaluated a pullulan-based active packaging film matrix incorporated with nisin, thymol, and lauric arginate with the aim of reducing foodborne disease strain growth in muscle foods. The comparative study revealed that pullulan incorporated with lauric arginate in the ratio of 0.5, 1.0, and 2.5% maintained proper thermo-mechanical properties compared to those using only nisin- or thymol-incorporated film matrices. The authors observed significant reduction in the growth of *Salmonella* spp., *Listeria monocytogenes*, and *Staphylococcus aureus* in raw beef, turkey, and chicken breast wrapped in pullulan films incorporated lauric arginate after 28 days of cold storage. With the objective of increasing the functionalities of pullulan, nanoparticles are reinforced for biopackaging applications. Accordingly, lysozyme nanofibers were exploited as antibacterial- and antioxidant-reinforcing additives to produce homogeneous, transparent, and glossy nanocomposite films composed of pullulan and lysozyme nanofibers [87]. The authors showed promising use of pullulan and lysozyme nanofiber nanocomposites as eco-friendly edible films for active packaging.

2.1.2. Proteins

The main proteins used in biodegradable edible films are usually animal (e.g., casein, creatine, gelatin, collagen) or vegetable proteins (e.g., soy proteins, gluten, zein). A protein is a clean polymer that can be utilized as lamination or edible coating due to its strong functionalities [88]. Protein-based films are known to exhibit a high water vapor permeability. Limited resistance of proteins to water vapor permeation is provided by the content of hydrophilic groups in proteins, as well as hydrophilic plasticizers. Such films are unfortunately brittle due to extensive intermolecular forces involving protein chain-to-chain interaction [89]. An alternative to reduce the brittleness of the film is to add food plasticizers during the formulation. In fact, plasticizers are a good strategy to reduce intermolecular forces along the protein polymer chains, with a resulting increase in the mobility of polymer chains and greater flexibility of the films. Apart from improving the mechanical properties of the film, synthetic plasticizers increase permeability, which could negatively impact the quality of packaged food.

To date, protein-based biopackages are not hugely explored at the industrial level, and limited information exists on plant proteins (i.e., soy protein, wheat gluten, corn zein) as edible films in meat and poultry applications [90]. Plant-based, such as soy, protein isolate films can be modified with oleic and stearic acids for better moisture properties. Kim et al. [91] investigated yuba, a thin layer produced on the surface of soymilk, for use as a natural and biodegradable edible film with properties of environmental sustainability. In their study, yuba films were coated by the authors with active agents (oregano essential oil, grapefruit seed extract, and their mixture) to improve the microbiological and oxidative stability and the feasibility of preserving beef patties. It was observed that all coated yuba films increased antioxidant stability mainly when incorporated only with grapefruit seed extract oil. A strong inhibition zone against *Listeria monocytogenes* was also observed in

grapefruit seed extract oil-infused films. The mixture and oregano oil-infused films on their part exhibited significant resistance against *E. coli*. In the case of lipid peroxidation, films incorporated with grapefruit seed extract oil showed better results compared to the other compositions when beef patties were wrapped. The color of the beef patties, which was red, turned to dark purplish red during storage. Another recent report proposed an active food packaging from cassava starch and whey protein blend films [92]. Another work confirmed the efficiency of whey protein isolate-based edible films incorporated with natural antioxidant extracts (phytochemicals from *Laurus nobilis* L. and *Salvia officinalis*) on the oxidative stability of cooked meatballs during frozen storage at $-18\text{ }^{\circ}\text{C}$ for 60 days [93].

Caseins also seemed of interest for use as soluble hydrocolloids with emulsification properties [94]. Casein films further have good barrier properties [95], but they have a shrinking tendency during the drying process of prepared films, making them brittle. There are several challenging factors for such films as they show high water-sensitivity, absorption, and release of water that affect their mechanical properties [96]. To overcome such problems, modifications of polymer matrices by cross-linking can be adapted for better performance of casein based packaging materials [28]. Another possible method to reduce the intermolecular forces along the protein polymer chains is to decrease the molecular weight of the polymer using enzymatic hydrolysis, with a resulting increase in polymer chain end groups and polymer free volume. This strategy might decrease the amount of the added plasticizer in films, hence minimizing the permeability of the films while achieving the desirable film flexibility [89,97].

2.1.3. Lipids

Lipids, such as glycerides, waxes, oleic, and stearic acids, are used for better moisture barrier properties, i.e., improving hydrophobicity of films [90] as discussed previously for enveloped chitosan/lauric acid edible coating for the preservation of fresh beef steaks under refrigerated storage and aerobic packaging conditions [76]. The functional properties, such as crystal structure, chain length, and oxidation state, are all taken into account while processing lipid-based coatings for packaging applications. For example, Trevisani et al. [98] reported the exceptional preservative properties of beeswax coating for traditional Italian salami. The results indicated that beeswax coating can be used as a synthetic polymer alternative for prolonged aging, while retaining both the texture softness and flavor, and inhibiting lipid peroxidation.

2.2. Chemically Synthesized Polymers from Bio-Based Monomers

Practical substitution of polymers with monomers synthesized from renewable sources is still a dilemma, and the expense of the synthesis technique is a burgeoning concern as well where sustainability and economic viability can be an issue. The substitution of conventional polymers by preparing their monomer units from bio-based sources is an implemented approach. For instance, the most abundantly synthesized, monomer-based polymer, already mentioned, is PLA. The production of PLA requires a small amount of energy compared to oil-based polymers, being a biopolymer chemically produced from renewable resources, especially from sugar and starch or cellulose [50]. Moreover, PLA has barrier properties comparable to those of PET [99]. The traditional synthesis of PLA is performed with hydrogen cyanide and acetaldehyde. Natural sources, such as fungi or bacteria, also produce lactic acid by anaerobic fermentation [100]. Recently, agro waste has been proposed as a new resource of PLA synthesis [101]. Ring opening and condensation are the two most acceptable techniques for PLA synthesis [102]. Both low and high molecular weight of PLA can be prepared, but low molecular weight PLA are not used commercially as they are more amorphous in nature and not suitable for food-packaging applications. An optically pure form of PLA is obtained from microbial fermentation using *Lactobacillus* sp. [103]. The combination of various isomers results in good packaging applications at a specified ratio. In fact, the transparency, stiffness, barrier properties, processability, and printing accountability make PLA a successful packaging material,

though several research gaps are being addressed to overcome its thermal degradation properties [104]. Blending PLA with other polymers and nanofillers as stated previously could improve some of PLA's shortcomings (slow crystallinity rate, low melt strength, high brittleness, low toughness, low service temperature, biodegradability). Polymer blends play an important role in the modern polymer industry, not only for the development of new materials, but also for the reduction of costs [48]. PLA-based films can be used in a wide spectrum, as food-safety issues are no longer a concern to address. PLA can be judged as an easily degradable polymer in the compost and soil, where it is hydrolyzed into oligomers, monomers, and dimers, which are further degraded into CO₂ and H₂O by microorganisms. Packaging materials based on PLA are therefore considered safe materials, both in terms of food contact, as well as for the environment [105]. However, despite being an efficient packaging material, there are certain drawbacks related to moisture, CO₂, and oxygen barrier properties; therefore, acidic food packages are still under reconsideration [106].

2.3. Polymers from Genetically Engineered Microorganisms

Various organisms, such as *Bacillus* sp., *Alcaligenes* sp., and *Azotobacterium* sp. have been used to produce renewable materials for various applications. PHA, PHB, and BC are the main polymers produced from microbial sources [107,108]. Feed and type of bacteria are the most important factors for the production of biopolymers. PHA is a rigid, rubber-like polymer of which yield depends on the type of bacteria; whereas PHB is semi-crystalline, which is also recognized as biodegradable PHA [109]. PHB is formed by the condensation of two main copolymers, i.e., poly(hydroxy-co-valerate) and poly(hydroxyl co-hexanoate). PHA and PHB are effective moisture barrier materials; hence, they can be used in forming blends where gaps need to be addressed [110]. These are the best alternatives to conventional polymers, such as polyvinylchloride (PVC) and polypropylene (PP) [111]. Bacterial cellulose is expensive due to its low yield [112]. Therefore, despite good mechanical properties and purity (in nature), their production at large scale is always challenging. Table 1 gives an outline of biodegradable films, film preparation techniques, and their use in preserving various meat products.

Table 1. A few examples of biodegradable films' compositions, their preparation techniques, and applications in preserving various meat products.

Types of Films	Additive	Technique	Meat Types	References
Chitosan	Green leaf extract	Homogenization followed by dipping	Pork chops	[77]
Chitosan	Liquid smoke	Magnetic stirring followed by dipping	Beef	[113]
Corn starch	<i>Zataria multiflora</i> root extract essential oil	Nanoemulsion followed by dipping	Chicken breast	[114]
Chitosan	N/A	Solution casting	Chilled meat	[115]
LLDPE-coated chitosan gel matrix	Composite of allyl isothiocyanate β cyclodextrin	Deposition coating layer on plastic films	Beef	[116]
LLDPE and cassava composite	Sappan and cinnamon extract	Blow extrusion	Beef	[117]

LLDPE: Linear low-density polyethylene.

3. Brief Overview on the Preparation Techniques of Green Coating and Film Polymers

To obtain satisfactory film-forming solutions for active packaging of meat products, the conditions of preparation techniques, as well as storage under controlled temperature, as reported previously, should be established. Likewise, Garavito et al. [118] evaluated guar gum and isolated soya protein to prepare edible coatings, and the blended films were

infused with oregano oil and nisin as antimicrobial agents to use for the preservation of chicken breast fillets. The authors used plasticizer sorbitol and glycerol, and they observed that 0.4% (w/v) of guar gum and 1% (w/v) of plasticizer resulted in glossy, transparent, bright films. The increase of the plasticizer to 4% (w/v) led to brittle and opaque films. It seems then that the presence of higher amounts of isolated soya protein contributed to the opacity and higher yellow index of the films. On another hand, a combination of 1% nisin and 0.05% oregano oil seemed to be the most acceptable condition for antimicrobial resistance activity against *Pseudomonas* spp. Therefore, the formulation with 0.4% guar gum and 1% plasticizer was selected for further validation under storage conditions.

The use of natural preservative liquid smoke, which consists of phenols and diluted acids, such as acetic acid, was also found very promising [119]. Chitosan in alkaline pH is mostly preferred to dissolve in organic and inorganic solvents [120]. However, the techniques of dissolving chitosan may be substituted using liquid smoke that might result in cost-effective films for meat preservation. Accordingly, a recent study by Desvita et al. [113] developed liquid smoke from rice hulls using pyrolysis at 340 °C followed by distillation at 190 °C. The edible coating was prepared using 3–5% liquid smoke and 0.5–1.5% chitosan under magnetic stirring at 50 °C for 90 min until a homogenous film-forming solution was obtained. Later on, meatballs were prepared and dipped in the solution and stored before shelf-life studies. The meatballs dipped in 1.5% chitosan concentration gave an excellent antimicrobial inhibition zone for 54 h. Figure 1 gives an outline of this dipping technique using pork chops.

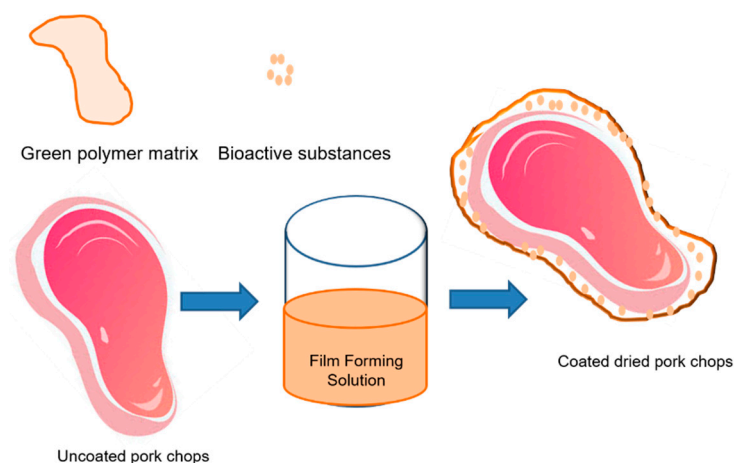


Figure 1. Schematic drawing for exemplifying the dipping technique of pork chops.

The most common film preparation technique for biopolymers is solution casting [121]. The main limitation of this procedure is the long drying duration. To overcome this limit, the temperature is often increased for fast film formation, because the degree of reorganization of crystallinity affects the mechanical properties [122]. However, several contradictions between heating time and mechanical properties of films do exist. In fact, chitosan films have lower water vapor solubility and poor mechanical strength with temperature and time alterations for casting technique [123]. The longer drying times might lead to brittle films. Accordingly, Liu et al. [115] investigated the effect of drying temperature of chitosan films on their microstructural, mechanical, and barrier characteristics. Technical guidance was then given by these authors as to how select, based on drying temperature (45–85 °C) of chitosan films, the appropriate conditions to achieve the desirable storage of wrapped meat and consequently prevent excessive drip loss [115]. The authors dissolved chitosan in an acetic solution and added plasticizer glycerol at room temperature. The solution was then casted on petri plates, peeled, and further soaked in caustic soda followed by a deionized water rinsing step. The films were finally dried at various temperatures ranging from 45 to 85 °C. It resulted that the films prepared at the lowest temperature enhanced

water-holding capacity and tenderness of meat and increased the shelf-life compared to the film at higher drying temperatures.

Coupled techniques of agitation and sonication can be also used to disperse nanoparticles, such as nanocellulose, in a chitosan matrix [15,124]. Chitosan nanocellulose composites films were found to be resistant against both Gram-negative and Gram-positive bacteria and inhibited lactic acid bacteria production in ground meat. Solution-casted gelatin films loaded with curcumin nanoemulsions were recently reported to exhibit high antioxidant activity and significant antimicrobial activity against *Salmonella typhimurium* and *E. coli* when used as chicken meat packaging material [125].

Molecular-imprinted technology is another innovative way that gained success in drug-delivery applications [126], where molecular-imprinted polymers (MIPs) are used for target specificity and sustained release [126]. Although MIPs have not been yet evaluated for active food packaging, several authors proposed to develop packaging materials for meat products with imprinted hydrogels loaded with natural antioxidants. For example, Huang et al. [116] investigated the kinetic release of active packaging material from allyl isothiocyanate (AITC) MIPs and chitosan for beef preservation. The authors prepared the MIP by ultrasonication of β -cyclodextrin, 2,4-toluene diisocyanate (TDC), and AITC in a reaction system at 45 °C for 24 h. Then, a degasification was performed before the saturation of the mixture with nitrogen for 30 min. TDC was added at a corresponding amount at 65 °C for 24 h. A precipitate was obtained by vacuum filtration that was then washed with acetone for few times at 50 °C. This MIP was reinforced in chitosan gel matrices by ultrasonication and deposited on low-density polyethylene (LDPE) films by blade-coating technique before wrapping the beef samples. This work showed that meat deterioration can be postponed by AITC-MIP active packaging film compared with LDPE packaging film.

Plastic film extrusion is another well-applied process in the packaging industry [127]. For most thin films, the film extrusion process takes place by blow or cast extrusion. Recent trends of biopolymer-based extruded films in the form of casings have taken a quantum leap where collagen, alginate, thermoplasticized starch, and chitosan composites are commonly used. As mentioned earlier, starch is an abundantly available biopolymer used in food packaging applications [128]. The hydrophilic nature of starch plastics restricts its usage, therefore, a blend of thermoplastic starch (TPS) and conventional polymers, such as linear low-density polyethylene (LLDPE), not only reduces the costs but also produces eco-friendly packages [129]. TPS composites were investigated for preserving minced meat for a long duration [117]. A comparative study was performed between thermoplasticized starch and acetylated starch separately by blending with LLDPE, followed by blown extrusion technique [130]. The TPS polymer composite films exhibited enhanced oxygen barrier and mechanical properties yet higher water vapor permeability with increased film solubility due to pore formation, and the release of green tea as an antioxidant act a crucial efficiently in preserving the freshness of meat. Thus, the TPS-polymer extruded film with increased green tea release is more effective to prolong shelf-life of meat by reducing metmyoglobin, hence retaining the red color of meat with limited microbial growth. Marcos et al. [131] proposed co-extruded alginate as an alternative to collagen casing for dry fermented sausage. The authors did not observe any effect on the organoleptic properties among casing types, whereas dry kinetics seemed to be faster for alginate coating.

4. More Specific Applications of Green Coating Polymers in Meat Preservation

As stated above, the most abundant biopolymers are polysaccharides, proteins, and lipids, which are commonly used for the synthesis of both rigid and brittle materials for packaging applications [132]. Their challenging issue is sensitivity to moisture, which can be addressed using biodegradable synthetic polymers over times. In this section, the special role of blends of such biopolymers with biodegradable synthetic polymers in meat preservation is discussed by highlighting some of the recent studies and many other

aspects that are summarized in Table 2 to support each of the materials and macromolecules we cited in the sections so far.

Table 2. A non-exhaustive list of examples using green polymers and additives and their overall role or effect in meat preservation.

Green Polymers	Additive	Overall Effect/Role	Meat Types	References
Alginate	Curcumin	Improvement in mechanical, barrier, antioxidant properties	Pork	[133]
Thermoplastic starch (TPS)	Sappan and cinnamon	Controlled oxygen permeability, inhibition of the formation of metmyoglobin due to lipid oxidation, antimicrobial effect	Beef	[117]
TPS, acetylated starch (AS), native starch (NS)	Green tea extract	Promotion of the formation of oxymyoglobin, retardation of lipid oxidation and free radical formation, reduction of the total viable count	Bacon	[130]
Gelatin, alginate	N/A	Color preservation	Pastirma	[134]
Alginate	Basil extract	Antioxidant	Beef sausage	[135]
Gelatin	Chitosan	Antioxidant, color preservation	Beef	[136]
Carboxymethyl cellulose	Epigallocatechin	Antioxidant	Pork	[137]
Sodium caseinate	Ginger extract essential oil nanocapsules	Antioxidant, color preservation	Chicken breast fillets	[138]
Gelatin	Zinc nanoparticles	Antimicrobial	Chicken fillets	[139]
<i>Lepidium perfoliatum</i> seed mucilage	Chicory extract oil	Antimicrobial	Beef slices	[140]
<i>Plantago major</i> seed mucilage	Citrus lemon seed oil	Antimicrobial	Buffalo meat	[141]
Alginate	Propionic acid, thyme oil	Antimicrobial	Chicken	[142]
Alginate	Thyme and garlic oil	Antimicrobial	Lamb	[143]
Carageenan	Oregano oil	Antimicrobial	Chicken patty	[144]
Maize starch guar gum and xanthan composite	Oregano oil	Enhanced vitamin and mineral content, antimicrobial	Osmotically treated pork slices	[145]
Starch and D-glucose	AgNP	Antimicrobial	Chicken sausage	[146]
Chitosan, polyethelene oxide	Pomegranate peel extract	Antimicrobial	Meat	[147]
Chitosan	Nanocellulose	Antimicrobial	Ground meat	[124]
Turmeric starch	Gelatin	Antimicrobial	Frankfurter sausages	[38]
Polylactic acid	Nisin	Antimicrobial	Fresh beef	[52]
Bacterial cellulose	Zinc nanocomposite	Antimicrobial	Chicken breast	[58]
Bacterio nanocellulose	Sakacin	Antimicrobial	Beef patties	[59]
Pectin fish gelatin blend	Olive oil	Significant reduction of lipid oxidation and increased meat preservation	Stored beef	[11]
Pectin	Oregano oil and resveratrol	Antioxidant and antimicrobial	Pork loin	[62]

Table 2. Cont.

Green Polymers	Additive	Overall Effect/Role	Meat Types	References
Alginate	Pineapple peel bioactive hydralcoholic acid	Antimicrobial	Beef steaks	[67]
Chitosan	Bamboo vinegar	Antioxidant	Pork chops	[78]
Chitosan	Thyme oil	Antimicrobial	Ready-to-eat pork	[79]
Pullulan	Nisin, thymol, lauric arginate	Antimicrobial	Raw beef, turkey, chicken	[86]
Yuba	Oregano essential oil, grapefruit seed extract, and their mixture	Antimicrobial	Beef patties	[91]
Whey protein	Phytochemicals from <i>Laurus nobilis</i> L. and <i>Salvia officinalis</i>	Antioxidant	Cooked meatballs	[93]
Acetylated starch	Green tea extract	Color protective, antioxidant	Bacon	[148]
Soya protein isolate/guar gum blend	Nisin	Antimicrobial	Chicken breast fillets	[118]
Gelatin/polyvinyl alcohol composites	Amaranthus leaf extract	Color protective, antioxidant	Chicken	[149]
Methylcellulose/chitosan nanofibers	Barberry anthocyanin	Freshness indicator	Meat	[150]
Qodume Shirazi seed mucilage	Lavender essential oil	Antimicrobial	Ostrich meat	[151]
Gelatin	Curcumin nanoemulsions	Antimicrobial	Chicken	[125]

4.1. Enhancement of Mechanical Properties and Barrier Properties in Active Polymer Packages

There is an increased demand in the scientific community for developing biodegradable packaging materials that can reduce the negative impacts identified in conventional polymer packages. Although edible films can have desired intrinsic oxygen barrier [62], tailored moisture [152], and mechanical properties [135], interest to provide additional functionalities by incorporating bioactive antimicrobial agents, such as curcumin, was reported in several studies [153,154]. Bojorges et al. [133] prepared alginate films incorporated with turmeric (*Curcuma longa* L.) by solution casting. To the best of our knowledge, this is one of the unique studies where mechanical, barrier, and antioxidant analyses were performed with turmeric edible films. It was observed that the transparency was improved in the turmeric-incorporated films, while water vapor permeability was relatively low. This may be due to the long carbon chain of benzene ring hydrophobicity of curcumin. The oxygen-permeability rate directly correlated with the shelf-life of meat that was also found very low. This can be explained by the interactions of bonds between curcumin and alginate matrix where the film might form hydrogen bonds within the carboxyl groups. This phenomenon could have a cross-linking effect, leading to decreased oxygen permeability. Based on the overall findings of the study by Bojorges and co-workers, it was concluded that the curcuminoids (phenols) in the film reduced lipid oxidation, thereby extending the shelf-life and improving the acceptance of pork when wrapped.

As previously stated and exemplified for the different macromolecules, several bioactive compounds can be introduced into packaging materials to improve their functionalities [155]. However, due to several limiting factors and processability issues, complete replaceable biopolymer packages cannot be industrialized. Instead low-cost, non-toxic linear density polymers are blended to make eco-friendly packages for the food industry [156]. For example, starch matrix can be tailored to achieve longer shelf-life requirements or be

processed by extrusion. Panrong et al. [130] produced TPS composites by adding acetylated starch and native starch composites films and observed mechanical, barrier, and antimicrobial properties. The composites were further reinforced with green tea extracts as antioxidant agents. The results revealed that if native starch was increased and tensile strength was decreased, non-homogeneity of film structure was also increased. If the degree of substitution increased, tensile strength also decreased. If the starch content was increased as in the acetylated starch, then both tensile strength and elongation break were slightly increased. Moreover, the acetylated starch decreased the turmeric-incorporated films due to its hydrophobic bonds compared to TPS and native starch. Bacon packed in LLDPE showed continuous color loss, whereas acetylated starch-based films incorporated with green tea extract contributed to the redness of meat during storage [148]. Indeed, meat color is an important quality aspect for positive purchase decisions by consumers and overall acceptability of meat products [157–159]. The mechanism of meat-color loss may be due to the release of antioxidants from the film material, promoting formation of oxymyoglobin and retarding lipid oxidation and free-radical formations, thereby lowering the total viable count of bacteria.

4.2. Protection against Lipid Peroxidation and Discoloration

The redox-activities involved in the discoloration of fresh meat and processed meat products affect the oxidative stability of the lipid fraction of the product, as iron redox cycling among other mechanisms seems to initiate peroxidation and formation of low-molecular weight compounds responsible for off-flavors and rancidity. Pastirma is a widely produced dry-cured meat product worldwide [5,160]. During the processing of the product, the use of curing agents, such as nitrite, to preserve color and flavor for consumer acceptance is performed. The process of curing affects the sensory attributes, textural properties, and the final color of the product on prolonged storage due to lipid oxidation in the meat and metmyoglobin formation [161]. Accordingly, a recent study addressed such problems by technically producing edible film coating from alginate and gelatin [134]. The authors used polysaccharides as cost-effective and non-toxic products to help the retention of water content, to delay the oxygenation and respiration rate, and to preserve the desirable color by enhancing the thermal and barrier properties. This combination also resulted in the prevention of free-radical scavenging activities. The authors obtained a gelatinized solution of alginate at 80 °C and gelatinized solution of gelatin at 60 °C under magnetic stirring. The two solutions were further cooled before application on pastirma. The use of alginate and gelatin coated-pastirma revealed lower thiobarbituric acid reactive substances (TBARS) values which was within the acceptable limit (0.67 and 0.86 mg/kg) until the end of storage, however, the TBARS values of traditionally coated pastirma reached 1.33 by the end of storage. The findings further revealed a reduction in lightness (L^*) and significant increase in redness (a^*) and yellowness (b^*) values. Gelatin-coated pastirma exhibited a significant reduction in L^* and increase in a^* , whereas no significant change was observed for b^* values. Another study used alginate edible coating enriched with *Ocimum* sp. (commonly known as basil) extract [135]. The beef steaks were submerged in the coating solution and further color studies were performed. The coating consisting of 1–2% basil extracts gave greater a^* and b^* in stored meat during the aging process up to 14 days. The phenolic content increased in the coated samples, thereby reducing lipid peroxidation.

Another study by Ruan et al. [137] documented few analytical data on the discoloration of fresh pork. The authors developed an edible coating with carboxymethyl cellulose incorporated with epigallocatechin gallate (an antioxidant). The redness (a^* values) of the coated meat decreased at a delayed rate due to the release of the antioxidant converting myoglobin into metmyoglobin, whereas uncoated meat started deterioration on the second day of the experiment.

The main strategy so far adapted for meat preservation is also a combination of biodegradable or non-degradable polymers with synthetic antioxidants [90]. Recent research trends have focused on the extraction of natural antioxidants due to the rising health

concerns among consumers regarding chemical preservatives [162]. Therefore, studies have focused on antioxidant extracts from plant sources (e.g., green tea or essential oil) [163–165] and many other sources [166]. This approach may have a challenge in terms of product loss, i.e., chemical sensitivity characteristics once the extract is out of the plant matrices may have a significant role. To overcome this problem, some authors developed, for example, a process where spray-drying microencapsulation technique and lyophilization were coupled to obtain microparticles of antioxidant capsules from pineapple peel [67]. The minced beef was wrapped and analyzed for physicochemical, color, and microbial parameters. The results indicated that hue angle measured on the initial day of wrapping gave the same values after removing the wrap on the day 5. The stability in color was due to the antioxidant activity of pineapple peel extract microcapsules that indicated a sign of freshness. The color tone decreased significantly after the films were removed.

A variety of antimicrobial edible active packaging are developed by inserting essential oils (EOs) in polymer matrices to preserve meat and meat products [167]. The immiscible nature of EOs in the aqueous matrix makes them form particles that scatter the visible light. Their volatile nature also allows them to escape from the films. This peculiarity was exploited by researchers to improve the functionality of EO-reinforced films using advanced technologies [168]. For instance, nanoemulsions consisting of lipid nanodroplets proved their efficacy in improving transparency and increasing surface area where a low quantity of EOs is required, hence allowing effective inhibitory effect on microbial contamination and scavenging free radicals. In this context, a study by Noori et al. [138] investigated the nanoemulsions from ginger EOs prepared by ultrasonication that were then incorporated in edible sodium caseinate films and coated on chicken breast fillets. It seemed that the conventional ginger EOs exhibited limited antimicrobial activity on pathogenic bacteria; whereas, when they were included in the nanoemulsion system, its inhibition zone increased against the pathogens [138]. This is further highlighted in Figure 2, which gives an illustration of the efficacy of nanoemulsions of ginger EOs.

4.3. Antimicrobial Activity

Coatings and edible films not only add physical beauty to products but also provide enhanced barrier properties and antimicrobial efficacy, thereby extending the shelf-life several times [6–8] as exemplified. The biopolymer-based composites can also be formed from blending conventional polymers. Gelatin has impeccable food-packaging qualities [169]; however, there are several restrictions in the wide use of this material due to moderate mechanical strength and greater hydrophilicity leading to poor moisture-barrier properties [170]. From the recent studies, gelatin zinc nanoparticle composites were developed by solution casting and the *S. aureus* and *E. coli* inhibitory effects were studied along with other physicochemical analyses [139]. It seemed that the coated chicken breasts had less microbial contamination, as low as 4.2 log after 8 h of treatment, whereas uncoated ones gave a high level of 4.6 log. The inhibitory activity may be due to the production of reactive oxygen species (ROS) by zinc nanoparticles that are toxic on microorganisms.

Currently, biopreservation using natural antimicrobial agents is being widely explored due to health concerns [171]. Bacteriocins from lactic acid bacteria are one of the most promising antimicrobial agents that have been used so far in meat-packaging industries [172]. There are several classes of bacteriocins; some of the commonly used are nisin [173], pediocin, and enterocin [174], which are mostly used for meat preservation. Reports showed that nisin, when incorporated in soya protein isolate-guar gum-blended films, exhibited an excellent inhibition zone against the formation of *Pseudomonas* spp. spores in wrapped chicken fillets [118].

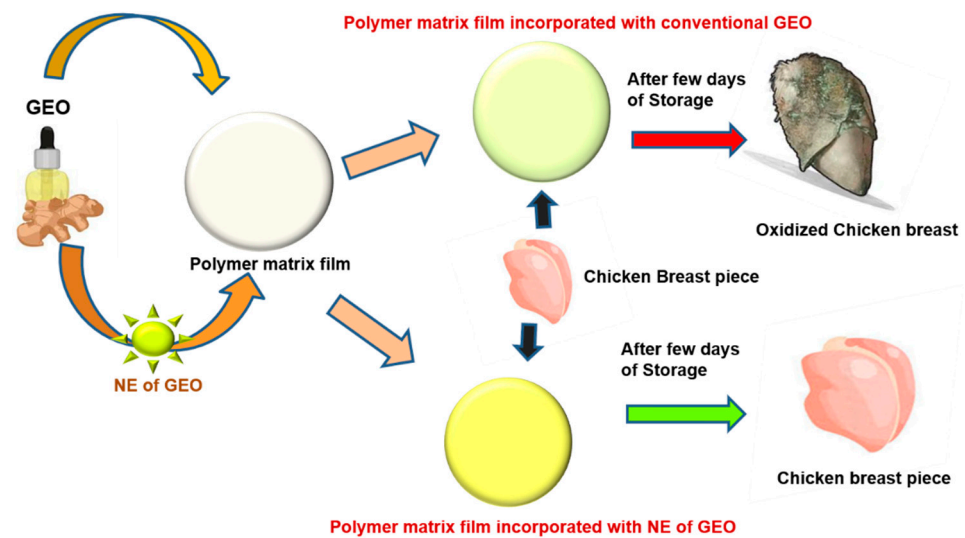


Figure 2. Difference in chicken breast after removal of biodegradable polymer film incorporated with conventional emulsion of ginger oil extract (GEO) and nanoemulsions (NE) of GEO after storage for 5 days.

Meat-processing industries are also showing greater interest in natural-origin edible coatings for packaging applications of meat to preserve their products against microbial contamination, hence improving shelf-life [175,176]. For example, some studies incorporated chicory extract oil (CEO) into *Lepidium perfoliatum* seed mucilage to prepare CEO-loaded edible films for beef slices [140]. It was observed that a low level of a *L. perfoliatum* seed mucilage edible coating incorporated with CEO oil is enough to suppress the growth and kill Gram-positive bacteria (*S. aureus*, *B. cereus*, and *L. innocua*), compared to Gram-negative bacteria (*S. typhae*, *E. coli*, and *P. aeruginosa*). Thus, the results revealed that beef slices coated with CEO-loaded *L. perfoliatum* seed mucilage edible coating had a significant inhibitory effect on lipid oxidation and microbial growth. The bioactive-loaded edible coating also decreased weight and texture losses during display and improved beef acceptability. Therefore, edible coatings rich in natural compounds with efficient antimicrobial and antioxidant effects could be used in animal meat products to improve their shelf-life. In the same context, another group investigated the effect of edible coating from Qodume Shirazi seed mucilage edible films containing lavender EOs during storage of ostrich meat [151]. The results revealed that coatings containing different amounts of lavender oil (0–2.5%) inhibited the microbial growth during storage. In addition, the juiciness was retained and the toughness of the meat samples was significantly reduced. A similar observation was noted by Noshad et al. [141] while analyzing the antibacterial efficacy of an edible package from *Plantago major* seed mucilage film incorporated with *Citrus lemon* EOs used to wrap buffalo meat under refrigeration conditions. The edible coating that contained limonene and carene was able to significantly reduce lipid oxidation and microbial growth in buffalo meat during a storage period of 10 days at 4 °C in comparison with the controls.

Several studies have already been performed to detect the efficacy of EOs as antimicrobial agents extending the shelf-life of meat products coated with edible films [177]. Propionic acid among others is known to inhibit pathogens in the meat industry. It has already been used as an antimicrobial agent in pork and sheep meat preservation [178]. Its antimicrobial efficacy when incorporated with thyme oil in alginate film and coated on chicken breast fillet was described [142]. *E. coli* and *Salmonella* sp. growth was observed after 7 days of storage; whereas in uncoated samples, it was detected after 5 days. Similar reports on minced lamb were reported by Guerrero et al. [143] using alginate edible coatings incorporated with thyme and garlic EOs. The results exhibited excellent color stability in lamb meat cuts even during prolonged storage. A combination of thyme with oregano EOs was also incorporated in carrageenan edible films, and the antimicrobial inhibitory

property was confirmed in wrapped chicken patties [144]. The shelf-life of chicken patties extended significantly during 30 days of storage.

Researchers continuously focus on extending the shelf-life of meat as oxygen promotes deterioration by inducing the formation of ROS [161]. In this context, a recent study observed that sensory acceptability, color parameters, and total viable count on osmotically treated pork chops under controlled atmospheric conditions were improved using a solution-cast edible film of maize starch and guar xanthan gum composites incorporated with oregano EOs [145]. The osmotic dehydration technique also enhanced the color of the meat and delayed oxidation even after 60 days of storage.

The addition of various bioactive substances to edible coatings and their antimicrobial effects mentioned above are not the only that are of great interest, but the green route synthesis of various nanoparticles as preservatives in edible films have also been investigated [179]. For example, biosynthetic silver nanoparticles (AgNPs) and their release kinetics from biodegradable packages were explored [15,146]. The study by Marchiore et al. [146] showed that AgNP-coated chicken sausages showed different lipid oxidation compared to uncoated samples. This can be due to several mechanisms, but one of the postulated reasons may be related to the release of AgNPs and their interaction with muscle proteins. The controlled release of antimicrobial agents at the site of microbial contamination is a new paradigm of preservation strategies [180]. Indeed, encapsulated natural antimicrobials in electrospun nanofibers from PE oxide, pomegranate peel extract, and chitosan blend due to high surface area and enhanced mechanical and physical properties have been adapted to develop active packaging [15,147]. This type of active packaging might inhibit, for instance, the proliferation of *E. coli* present on the meat surface.

5. Brief Overview of the Role of Functional Polymers in Smart Packaging

Smart packaging is not directly involved in extending the shelf-life of meat and meat products like active packaging, but it presents a series of warning and freshness indicators [181]. For example, it helps the consumers to decide about the acceptance of food products in terms of freshness and quality [182]. Indicators, sensors, and data carriers are the three main categories of smart packaging [183]. Indicators indicate environmental, surrounding medium change, time temperature, or comfort indicators [184]. Sensors are the devices that quantify matter or energy and transduce signals that identify the presence of toxin or any contaminating particle in the food package [185]. Data carriers are those that cannot quantify or qualify the preservative, but they identify, automate, and help to store and transmit data, such as barcode labels and radio-frequency identification (RFID) tags [186]. Freshness or microbiological sensors depict the changes of the environmental medium by pH changes represented by modifications in the color [187]. Several groups are trying to introduce pH-sensitive polymer matrices for meat or chicken packaging [188]. Recently, natural dyes have been widely used to detect floor degradation as per consumer demand and health concerns [189]. For example, starch and anthocyanin composites were proposed where any changes in the color can indicate the freshness of meat [150]. The recent study by Kanatt [149] proposed gelatin-polyvinyl alcohol composites impregnated with *Amaranthus* leaf extract as an indicator to detect chicken meat freshness. The color changes in films were observed from red to yellow as a consequence of pH change and high microbial count. Temperature time indicator-based smart packaging was developed to determine pork products' quality based on color changes over a cumulative period. Other authors developed agar coating composed of sodium alginate microcapsules, iodine, amylose, and glucosamine to control the freshness of chilled pork [190]. Metal nanoparticles in situ layer within biopolymer matrices were also proposed as temperature time for sensor activities [191]. During the past few years, several groups have tried to develop cellulose-embedded, food-grade material to detect aging, juiciness, or ripening of food material by a color change from green to red indicating a better acceptance rate among consumers.

6. Conclusions and Future Perspectives

With the ever-increasing demand of minimally processed food products, innovative smart and active packaging is evolving in this era. Recently, biopolymers and their composites in the form of edible coatings, wraps, and pouch sachets have become prevalent in the packaging sector as alternatives to conventional polymers due to their ecological and non-toxic nature. The industrialization of such packages is still hindered due to limitations related to their mechanical properties, barrier properties, and high process costs. To overcome these issues and improve the physicochemical characteristics of these biopolymers, researchers introduced new methods for high-performance packaging and redesigned polymer structures by employing nanotechnological routes [15]. Alternative low-cost natural polymer from animal skin camel gelatin [192] or fruit peel wastes of orange peel pectin [193] sources are also being explored.

Despite ample studies on their performances, the industrialization of several films and coatings still needs careful attention for further research to devise effective techniques addressing the issues. For example, although PLA is a very popular biodegradable polymer widely used in biopackaging applications, it suffers from its low thermal stability. Polyglycolic acid (PGA) is very interesting but highly expensive; therefore, researchers are performing extensive research to find an alternate source for its cost-effective extraction from renewable waste sources, such as sugar or bagasse waste industries. Natural antimicrobial agents, such as bacteriocins, have a wide variety of which only a few, such as nisin, pediocin, and enterocin, are used, whereas exploration of other classes, such as sakacin A from *L. sakei* [194], need to be explored for active packaging. Another recent and emerging way to advance active packaging is to use probiotics bacteria.

The application of nanotechnology is also considered a potential alternative in addressing the existing problem of biodegradable biopolymer films and coatings [15]. Several studies were conducted where implementation of nanoparticles as fillers or nanocapsules enhanced sensory attributes, as well as the nutritional and safety qualities of food (meat) products [15]. Direct use of nanofillers is still limited due to the lack of food-safety regulation and policy or lack of toxic studies in connection with nanofillers in food-contact materials. Researchers should be more involved in carrying forward their observations to address the interacting mechanisms of nanoparticles with food-contact surfaces, including meat products. Studies are limited in the current literature in regards to natural dye implementation as indicators in active and smart packaging for freshness detection of muscle foods. Thus, more studies are needed. It is also important to emphasize that no studies to date were conducted in animal models for toxicity detection that is the fate of coated products when ingested. Mitigation studies where release kinetics of nanoparticles from coatings or retention of those particles after washing or after cooking should be also addressed. Detailed synergistic studies on bioactive composites, preparation techniques, reinforcement of nanomaterials, their interactions with food materials, sensory attributes, consumer acceptance, and retail storage should be undertaken before wide application of biopolymers or green coating polymer composites in meat preservation.

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