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Review

Application of Active Packaging Films for Extending the Shelf Life of Red Meats: A Review

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Abstract: Meat is known for its high perishability and short shelf life if not properly packaged or stored. Packaging materials play a crucial role in preserving food quality, and there is a growing demand from consumers, industry professionals, and researchers for natural packaging materials that incorporate health-beneficial extracts. Additionally, there is an increasing emphasis on avoiding non-biodegradable plastics in order to reduce environmental pollution. Currently used polymers in food packaging typically feature properties such as oxygen barriers, moisture resistance, and oxidation inhibition, helping to prevent undesirable aromas, flavors, and colors in food. Packaging not only serves as a container for transportation but also prevents physical damage, maintains quality, and ensures food safety. In the pursuit of more sustainable solutions, various compounds are being explored for food packaging, including those derived from proteins, lipids, waxes, and polysaccharides. These materials can be combined with bioactive compounds, such as natural plant extracts, which provide antioxidant, antimicrobial, anti-inflammatory, and anticancer benefits. Different techniques, such as electrohydrodynamic processes and casting methods, are employed in the preparation of these packaging materials. This review highlights the applications and properties of polymers used in meat packaging and promotes the use of biodegradable materials as a viable solution to reduce environmental pollution.

Keywords: biosensors in meat; extended life; enhanced packaging; protective films

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1. Introduction

Currently, there is a growing emphasis on consuming safe food products that use natural additives and biodegradable packaging materials. In this context, the investigation of natural resources for packaging materials and the incorporation of bioactive compounds with health benefits are crucial. Polymers and packaging films can serve as barriers to various environmental factors such as oxygen, humidity, temperature, and light [1].

Additionally, they can provide properties such as being a water-vapor barrier. The material requirements depend on the type of food being protected, as the degradation mechanisms of fruits and vegetables differ from those of meat, fish, or cheese [2].

Red meat comes from the muscles of mammals, characterized by its red color due to the presence of myoglobin. It includes meats such as beef, pork, and lamb, and is valued for its distinct flavor and texture. Its color can range from bright red to dark brown, depending on factors like oxygenation and exposure to air. Red meat is rich in proteins, iron, zinc, and

B vitamins, making it a key component in many diets. However, due to its high protein and fat content, red meat is highly perishable and susceptible to microbial contamination and oxidation, requiring proper packaging to maintain its safety and quality. With the global increase in meat consumption, its production is anticipated to rise substantially, with projections estimating around 453 million tons by 2030. This growth in production also drives an increase in packaging needs [3]. Therefore, materials that offer maximum protection against deteriorative or pathogenic microorganisms, prevent oxygen contact, and provide effective moisture protection are essential [4].

The ongoing challenge for researchers and industry professionals is to mitigate the environmental impact of plastic waste. Consequently, there are concerted efforts to innovate packaging solutions derived from natural sources that can effectively preserve highly perishable foods such as meat and extend their shelf life [5]. Natural biopolymers used for packaging can come from sources such as proteins; polysaccharides like cellulose, starch, and pectins; and lipids such as waxes. These hydrocolloids help to modify moisture or gas barriers and improve mechanical properties [6].

The methodologies employed to fabricate high-quality packaging materials vary based on the specific requirements of the food product. Techniques such as electrospinning and electrospraying, as well as traditional methods like casting, are utilized to achieve the desired protective properties and mechanical performance [7].

Through these methods, it is possible to incorporate natural plant extracts, including essential oils and dyes, which are important for their bioactive compounds, providing antioxidant or antimicrobial properties that can help preserve foods such as fresh meat and prevent undesirable colors [8]. These hydrocolloids enhance packaging by improving moisture and gas barriers while also boosting mechanical properties [9].

High-quality packaging production involves various techniques tailored to specific food protection needs. Advanced methods, such as electrospinning and electrospraying, create uniform films with superior barrier-creating properties [10]. Simpler techniques like casting are also employed, often incorporating natural extracts like essential oils and dyes to provide additional bioactive benefits. These compounds offer antioxidant and antimicrobial properties, crucial for preserving fresh meat and preventing undesirable color changes [11]. In [12–14], Previous researchers have carried out works that discuss meat packaging in general, addressing microbiological aspects, as well as focusing on cultured meat. However, in this work a review has been carried out addressing each biopolymer, both on its own and within a mixture, as to its use with red meat.

This study addresses the need for sustainable food packaging by developing innovative biopolymers that combine advanced barrier-creating properties with bioactive compounds for enhanced meat preservation. It also explores advanced manufacturing techniques, like electrospinning with natural extracts, to create effective, biodegradable films. These innovations aim to improve meat quality, extend shelf life, and reduce environmental impact.

2. Current Status of Red Meats—An Overview

In 2018, global meat consumption was 346.14 million tons, and it is expected to increase in the future. As meat consumption increases, the use of packaging materials is expected to rise along with it. Petrochemical packaging materials, which are widely used in the meat processing industry, take a long time to regenerate and biodegrade, thus negatively affecting the environment. Therefore, the need arises to develop ecological packaging materials for meat processing, which are easily degradable and recyclable [15].

Today, consumers demand fresher and more natural products with high nutritional value [16]. However, in certain foods the shelf life can be drastically reduced if chemical additives are not added. The meat industry is a clear example of the production of perishable products with different amounts of fat and a high content of unsaturated fatty acids. Taking this into account, it is easy to understand that lipid oxidation could be considered as the main cause of quality deterioration in meat and meat products. Reactions during lipid oxidation are responsible for the formation of undesirable odors and undesirable flavors, in addition to changes in texture and color, because myoglobin oxidation causes discoloration; these factors influence consumer choice and acceptance. However, organoleptic changes are not the only important consideration during the development of lipid oxidation; the formation of toxic compounds such as aldehydes and the loss of nutritional value must also be considered [17].

The spoilage of meat and meat products generates large economic losses (up to 40% of production) in the meat industry [18]. In this context, the first step is to improve our knowledge about the reactions that lead to meat deterioration in order to design and select the appropriate packaging to minimize quality losses [19]. One of the most widely used methods to prevent lipid oxidation is the reduction of the amount of oxygen in contact with the meat by vacuum- or nitrogen-packaging the products [20]. Active packaging containing synthetic antioxidants can protect meat against lipid oxidation. However, consumer demand for natural products has resulted in the trend of the growing use of natural antioxidants as substitutes for artificial ones [21]. Due to this, it has been proposed to use plant extracts and essential oils as a replacement for synthetic additives. This is a case of agro-industrial by-products becoming an economical and practical source of antioxidant compounds. It is important to mention that the use of essential oils has a particular disadvantage, in that most of them have a strong odor, so it is very important to determine the concentration of essential oil to use without modifying the organoleptic characteristics of the meat [22]. For this reason, researchers and the industry are constantly searching for the best packaging for meat, as well as the optimal incorporation of bioactive compounds that would help to reduce undesirable reactions.

3. Blends of Polysaccharides and Protein Biopolymers

Among the most commonly used biopolymers for packaging materials are proteins and polysaccharides, as they contain similar chain networks. However, they exhibit limitations in the final properties of the films, which is why they are often used in blends [23]. Table 1 presents various studies on the packaging applied to meat with the incorporation of bioactive compounds. Works such as 19, 29, and 44 employ blends of biopolymers, such as gelatin-CMC, whey protein isolate/cellulose, and gelatin/chitosan, respectively, in raw beef, lamb, and turkey meat. These studies report that using these blends has led to improvements in the mechanical properties of the packaging films. Additionally, the blends have been effective in delaying lipid oxidation, thereby extending the shelf life of each sample.

Table 1. Biopolymers with incorporated bioactive compounds applied as meat packaging.

Biopolymer	Bioactive Ingredient	Application	Meat Preservation (Days)	Reference
PEO/Casein	Tymol/β-cyclodextrin	Beef	7	[24]
Carboxymethyl cellulose-gelatin	Shallot wastes	Raw beef	7	[25]
Gelatina-CMC	Chitin nanofiber and *trachyspermum ammi* essential oil	Raw beef	12	[26]
Zein/Wax	Gallic acid	Chilled veal meat chunks	11	[27]
Whey protein	*Origanum virens* essential	Meat products	15, 20	[28]
Carrageenan	Olive leaf extract	Lamb meat	3	[29]
Chitosan	Propolis extract and *Zataria multiflora boiss oil*	Chicken breast meat	16	[30]

Table 1. *Cont.*

Biopolymer	Bioactive Ingredient	Application	Meat Preservation (Days)	Reference
Chitosan-starch	Pomegranate peel extract and *Thymus kotschyanus essential oil*	Beef	16	[31]
Acrylic—Hydrophobically modified state	Eugenol	Beef	14	[32]
Chitosan	Satureja plant essential oil	Lamb meat	20	[33]
Chitosan/Montmorrillonite	Rosemary and ginger essential oil	Poultry meat	15	[34]
Starch	Red cabbage extract and sweet whey	Meat	4	[35]
Whey protein isolate/Cellulose	Nanofiber/TiO_2 Nanoparticle/Rosemary essential oil	Lamb meat	15	[36]
Potato starch/Apple peel pectin/ZrO_2	Nanoparticles/Microencapsulated *Zataria multiflora* essential oil	Quail meat	12	[37]
PLA	Propolis ethanolic extract Cellulose nanoparticle and *ziziphora clinopodioides* essential oil	Minced beef	11	[38]
Chitosanmontmorillonite bionanocomposites	Rosemary essential oil	Poultry meat	15	[39]
Curdlan/Polyvinyl alcohol	Thyme essential oil	Chilled meat	9	[40]
Pectin—Fish gelatin	Olive antioxidants hydroxytyrosol	Beef meat	7	[41]
Chitosan/PEO	Pomegranate peel extract	Meat	7	[42]
Alginate	Pineapple peel	Beef	5	[43]
Chitosan	Nanofibers	Meat	7	[44]
Chitosan	ε-Polylysine	Beef fillet	12	[45]
Chitosan	Lauric acid	Beef steaks	21	[46]
Starch	Sappan and Cinnamon herbal extracts	Meat	3	[47]
Methylcellulose/Chitosan	Anthocyanins	Meat	3	[48]
Gelatin	Henna (*L. inermis*) Extract	Beef meat	8	[49]
Gelatin	Tomato	Pork meat	13	[50]
Gelatin/Chitosan	Ferulago Angulate essential oil	Turkey meat	15	[51]
Pullulan/Chitosan	ZnO nanoparticles and Propolis	Meat	8	[52]

4. Biopolymers Used in the Manufacture of Food Packaging

4.1. Protein

In 2020, the production of plastics increased considerably, reaching 368 million tons. However, they are petroleum-based products, which are not easy to break down. For this reason, contamination is observed more and more since there is no control of these residues. Due to this problem, alternative solutions have been sought, such as containers made from different biopolymers. These materials can be obtained from polysaccharides, proteins, plants, lipids, or from some animal source, and even from microorganism-based materials (Figure 1) [53].

Regarding the protein containers, it is important to mention, in this section, the milk protein, which contains casein and whey protein. Milk proteins can form flexible and transparent films without a discernible taste [54].

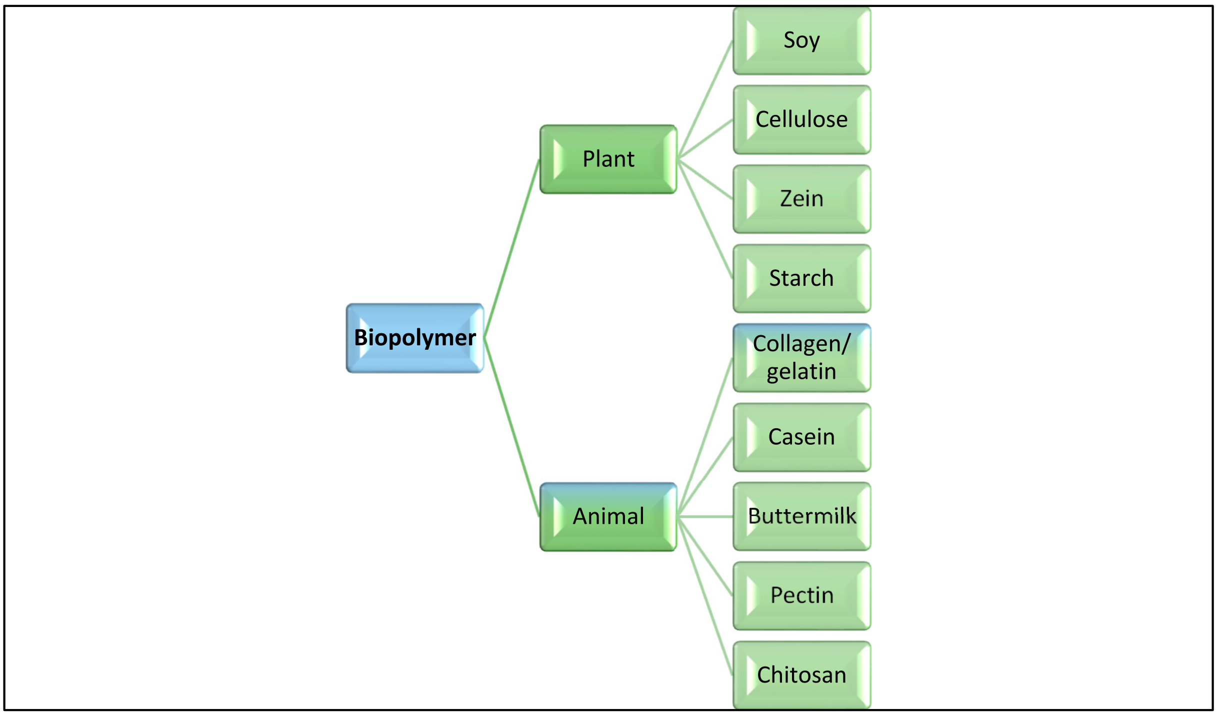

Figure 1. Classification of biopolymers used for food packaging.

4.1.1. Casein

Using casein, it is possible to form edible films from aqueous caseinate solutions. The procedure used to obtain this type of film consists of the casein solution first being washed, before the alkali is dissolved to increase its pH value to 7, and then, finally, the material is dried. If it is necessary to form calcium caseinate, it is possible to use $Ca(OH)_2$, since calcium cations are of great help in promoting the cross-linking of the interactions between proteins. Among the desirable characteristics of this film, it has been found that it provides an efficient barrier to water; however, it tends to be more rigid [55]. On the other hand, if it is required to obtain sodium caseinate films, it is possible to use NaOH, increasing the pH value; this type of film tends to have beneficial optical and tensile properties [54]. In [24], a container was developed based on antimicrobial PEO/casein nanofibers loaded with thymol/β-cyclodextrin for the preservation of beef, and inhibition of microorganism growth was observed during 7 days of storage.

4.1.2. Whey Protein

Whey proteins are composed of several components, including α-lactalbumin, β-lactoglobulin, immunoglobulins, bovine serum albumin, and peptone proteases. They also act as carriers for food additives, antioxidants, colorants, and antimicrobial agents. The most common form of whey protein used for creating edible films is whey protein isolate, which contains 90% protein [56]. The process of making these films begins with the obtaining of a concentrated protein solution that is heated to denature the proteins. The solution is then cooled to remove trapped gases and form the packaging material. Whey protein-based edible films are effective oxygen-barriers at low-to-moderate relative humidity but have poor resistance to water vapor. Whey protein exhibits excellent functional properties and film-forming capabilities, providing high levels of transparency and flexibility, and good barrier-creating properties against oils and gases in conditions which are relatively low-humidity. However, one significant drawback is in their poor water barrier-creating properties, which can be improved by incorporating essential oils and lipids [57]. Understanding the interactions between different biopolymers during coating formation is essential for the development of packaging materials with the desired characteristics. For this purpose, whey protein isolate-based films plasticized with glycerol have been developed showing that bergamot and lemon essential oils act as active components in bioplastic films. Some studies have highlighted the excellent antimicrobial potential and significant oxygen and water-vapor permeability of films containing essential oils [58].

Whey protein concentrate, which contains 25–80% protein, has also been used in the past to make edible films. However, it may contain impurities like lactose, which can improve water-vapor permeability but may compromise mechanical properties [59]. Calcium caseinate and whey protein concentrate are generally less strong than whey protein isolate. Whey protein isolate can replace up to 50% of calcium caseinate without reducing puncture strength in the production of edible films. Although whey provides a good barrier against CO_2, it is fragile. To enhance its mechanical properties, a plasticizer like glycerol can be added [60]. New whey-based films have been developed; for instance, a whey film with seaweed extract was created for poultry meat, showing improvements in thickness, tensile strength, and elasticity, while also inhibiting lipid oxidation during 25 days of storage [61].

4.1.3. Zein

Zein is the main storage protein of corn, being a renewable and biodegradable biopolymer used for medicines, packaging, cosmetics, textiles, and other applications. Due to the amino acids that zein contains, such as proline, leucine, and alanine, it has a high solubility in ethanol solutions. In addition, films with a good gas-barrier can be obtained. The films obtained from zein are suitable for use in fruits and vegetables [62]. However, it is important to mention that zein films are poor in terms of mechanical properties; therefore, it is advisable to add plasticizers to improve them [63]. In [64], a zein film was made for minced sheep meat packaging with the incorporation of eucalyptus extract, obtaining antioxidant and antimicrobial properties to a significant degree, and retarding lipid oxidation.

4.1.4. Collagen and Gelatin

Collagen is obtained from the skins and bones of mammals or fish. For decades, collagen-based edible films have been used in meat products to retain moisture and give products a uniform characteristic. In animals, the collagen and gelatin content constitute approximately 20–25% of the total body mass. Its structure consists of three cross-linked α chains; the denatured collagen derivative is called gelatin, and is composed of many polypeptides and proteins [65]. Collagen is mainly made up of the amino acids methionine, hydroxyproline/proline, and glycine. Collagen-based films can be obtained through an extrusion process and have wide application, but in the production of gelatin-based films, it is preferable that a wet process is used, forming a film-forming solution. Collagen films exhibit good mechanical properties; for example, hydrolyzed collagen films have been reported to have excellent tensile strength. However, among their disadvantages is the fact that they present comparatively poor mechanical and barrier-creating properties [66].

Gelatin is produced by hydrolysis of collagen. Collagen films can be realized as an edible skin, giving beneficial properties when cooking food. Collagen, present mainly in animal skins, muscles, bones, and connective tissues, can be treated in acidic or alkaline solutions, followed by additional heating up to 40 °C [67]. Gelatin in its natural state is pure, dry, transparent, without taste, brittle, odorless, and solid, in addition to having a yellowish coloration. Gelatin-derived edible film is generally made by dissolving gelatin in hot water and drying the material in an oven. When the protein content is increased, gelatin-based edible films have a higher film thickness and better mechanical properties; however, this may result in decreased water-vapor permeability [68]. In [69], a gelatin-based container for pork meat with tomato extract was developed which conferred antioxidant properties, controlling the pH and water activity of the meat, as well as its lipid oxidation.

4.1.5. Soy Protein

Soy protein is a plant-derived protein obtained from soybeans. It is available in several forms, including soy flour, which contains 56% protein and 34% carbohydrates; soy concentrate, which has 65% protein and 18% carbohydrates; and soy protein isolate, with 90% protein and 2% carbohydrates [70]. Soy protein isolate is frequently used to make soy protein films because other forms of soy protein have non-protein components that hinder film formation. Edible soy protein films are typically produced using either the yuba-film method or the baked-film method. The yuba-film method involves boiling soy milk in a shallow pan to create surface films, which are then air-dried. The baked-film method entails spreading soy protein isolate in pans and baking it at 100 °C for 1 h [41]. Soy protein films are generally softer, more flexible, and clearer than films made from other plant proteins. They offer superior gas-barrier properties, with oxygen permeability being at least 260 times lower than those of films made from low-density polyethylene, starch, and pectin, so long as the film remains dry. Soy proteins are also used to create bioplastic films for packaging, which are smoother and more transparent, flexible, and cost-effective, compared to other protein-based bioplastics [71]. These films also provide good oxygen-barrier properties in low-humidity conditions. However, their main drawbacks are lower mechanical strength, heat stability, and allergenicity compared to low-density polyethylene [72].

4.2. Polysaccharides

Polysaccharides can be found widely in nature, and are non-toxic materials providing selective permeability to carbon dioxide and oxygen. Among the most prominent polysaccharides are chitosan, pectin, gums, starch, cellulose, alginate, and carrageenan, which are capable of conferring good gas-barrier properties, particularly against oxygen, due to their ordered network of hydrogen bonds, although most of these saccharides are sensitive to moisture due to their hydrophilic structure [73]. These properties make polysaccharides one of the materials most often used as a sustainable material in the formulation of edible coatings and films in foods [74]. One of the advantages of these films is that they can prevent dehydration, oxidative rancidity, and surface browning in foods. This is because polysaccharide-based films have high starch and amylose content levels, which makes the films flexible and stretchable. However, among their disadvantages is that they do not act as a water barrier; this due to their hydrophilic properties in nature [75]. Because coatings consisting primarily of polysaccharides have exhibited poor water-vapor barrier characteristics, these coatings present an important factor affecting marketers' decisions when there is a focus on retarding moisture loss. Other characteristics of polysaccharide coatings are that they are oil-free and colorless, which makes them low in calories and permits them to be applied to improve the shelf life of meat, seafood, vegetable, and fruit products by considerably decreasing dehydration, oxidative rancidity, and surface browning [76].

4.2.1. Starch

Starch is widely recognized as the most prevalent plant-derived polysaccharide used in bioplastic films, owing to its cost-effectiveness, abundance, and excellent film-forming properties. As a natural biopolymer synthesized from renewable resources, starch has garnered increasing attention in the area of film production [77]. Its low cost, availability, and complete biodegradability have spurred interest in developing starch-based films. Starch, a natural polysaccharide, can produce translucent or transparent colorless and biodegradable films without a discernible taste [56].

Various techniques are employed to modify starch in order to enhance a film's properties. Electrospinning and reactive extrusion, for instance, produce nanofibers with high surface area and increased porosity, facilitating the creation of biodegradable films with specific properties favorable for encapsulating and releasing bioactive compounds. Conversely, 3D printing modifies starch to improve its printability and mechanical properties. In this context, adding stearic acid to starch can adjust its rheological and structural properties, making it easier to form complex structures [78].

Nanotechnology also plays a significant role in the improvement of film properties. It can enhance mechanical strength and moisture barrier performance by making targeted modifications to the film's characteristics. Enzymatic modification, particularly with βamylase, alters the gelatinization and retrogradation properties of starch, reducing viscosity and enthalpy, which helps to stabilize starch films [79].

Chemical modification through acidic hydrolysis is another technique that changes the thermal properties of starch, reducing viscosity and improving the resulting film's properties. Cold plasma treatment, which involves high-voltage dielectric discharge, modifies starch's solubility, hydration, and thermal behavior. This process facilitates the incorporation of reactive functional groups into starch, enhancing the film's properties [9,80].

Dielectric discharge plasma modification, like cold plasma treatment, improves starch solubility, water absorption capacity, and gelation properties, as well as the mechanical strength and flexibility of the film. These techniques are environmentally friendly as they do not involve toxic solvents [81].

Starch typically appears in granular form, with granules being capable of absorbing water due to free hydroxyl groups. Although starch films generally exhibit poor barrier-creating properties, research indicates that incorporating various nanoparticles can enhance their resistance to water vapor and gas permeability. Additionally, integrating other materials into these films can improve their resistance to water vapor and oxygen permeation [82]. Furthermore, some antimicrobial agents are compatible with starch, allowing the development of films that can deactivate a wide range of pathogenic bacteria [83].

4.2.2. Cellulose

Cellulose is the most abundant compound on earth. To break the cellulose chains, it is necessary to alter it through a chemical dissolution process, in which cellulose derivatives are formed from d-glucose units linked by β-1,4 glycoside bonds. Lignocellulosic wood fibers are constituted of approximately 40–50% cellulose and 25–30% hemicelluloses by weight. Therefore, substances derived from cellulose are used in materials for edible films because the former are biodegradable, without taste, and odorless [84]. Some authors have reported that methylcellulose is one of the derivatives most widely used to obtain films, followed by carboxymethylcellulose, and, finally, hydroxypropylmethylcellulose. These film-forming materials show good mechanical and barrier-creating properties [85]. The films obtained from cellulose usually have a high surface gloss, excellent transparency, and good toughness and tensile strength. In particular, carboxymethylcellulose was reported to exhibit excellent film-forming capabilities relative to a water-soluble polymer and thermal gelatinization. In addition, these films are interesting because bioactive compounds can be incorporated into them to introduce antioxidant and antimicrobial properties [86]. In [87], a container for meat and meat products was made with carboxylated cellulose and beetroot extract converted into sodium alginate, providing antioxidant activity and pH responsiveness, in addition to thermal stability, while also presenting a barrier to UV light.

On the other hand, there are also hemicelluloses, which are amorphous and multifaceted heterogeneous polysaccharides that are structurally less ordered, comprising hydrophilic wood-based polysaccharides with minimal thermal resistance. Hemicellulose-based films are brittle; however, the addition of plasticizers could improve their flexibility, toughness, and low oxygen permeability. These films have an interesting role in packaging applications due to their low oxygen permeability [88]. The hemicelluloses can be soft, two examples being galactomannan and mannose, or of hard wood, such as glucoconoxylan, and can be mixed to make packaging materials presenting greater flexibility and oxygen permeability; in addition, by adding a polymer, water absorption resistance can be increased [89].

4.2.3. Chitosan

Chitosan is a linear polysaccardium which can be obtained from fishery products and is used to make films for food packaging. It is a biodegradable, biocompatible, non-toxic compound [90]. When used as a food container, chitosan does not provide the best barrier against gases and water vapor; this is due to its hydrophilic groups. Therefore, it is important that when making a chitosan film, it can be mixed with some other biopolymer [91].

For example, some protein such as casein, an extract, or even an essential oil might be used, improving its mechanical, antioxidant, and even antimicrobial properties [90]. Different chitosan films have been developed for storing meat; for example, [92] obtained a chitosan and starch film with a green tea extract, observing an improvement in its properties against UV light, with a significant response seen as well in the water- and vapor-barrier properties; in addition, the microbial growth in the packaged meat was reduced.

4.3. Factors Affecting Packaging Films

The properties of packaging films used for meat provide features such as the water-vapor barrier, gas permeability, transparency, UV protection, water solubility, antimicrobial properties, antioxidants, and mechanical properties. Each of these characteristics is crucial for their application in the context of food packaging [93].

The water-vapor barrier is important for foods, like meat, that require protection against moisture. The film must be able to resist water-vapor penetration [94]. Some polysaccharides, such as cellulose and carboxymethylcellulose, can provide hydrophilic properties that allow water-vapor permeation, limiting their effectiveness in packaging for foods that need a stronger moisture barrier [95]. On the other hand, chitosan can provide a stronger water-vapor barrier due to its semicrystalline structure and the presence of amino groups capable of forming cross-linked bonds [96]. As for proteins like casein and gelatin, which also have hydrophilic properties, their use would result in films with limited water-vapor barriers. However, improvements can be made through chemical modifications or by blending with hydrophobic materials, such as fatty acids, which would increase the water-vapor barrier [97].

Film transparency is an important property when used for foods like meat, as they are presented fresh, and the appearance of the food is important to consumers. Compounds such as starch, pectin, and agar have been used because they provide higher transparency. Similarly, whey protein and zein are also used to provide this property [98].

UV protection is another property fundamental to the prevention of the nutrient degradation and discoloration of meat, which is sensitive to light. In this context, polysaccharides are used less frequently because they do not provide sufficient UV protection [99]. However, modifications can be made by adding bioactive compounds such as flavonoids. Zein is used to provide this type of protection, and the addition of bioactive compounds like green tea or tocopherol will further enhance the protective benefits [100].

Films can exhibit water solubility, which can be favorable when applied to meat, especially if an edible or biodegradable film is desired that can easily disintegrate in an aqueous environment [15]. In this case, starch and pectin are water-soluble, making them suitable if a soluble film is desired. It is possible to adjust this property through cross-linking or by combining biopolymers, and thereby adapting to the desired decomposition rate [101].

Among the most important properties are the mechanical properties, among which tensile strength, elasticity, and rigidity determine the material's durability during transportation, storage, and handling [102]. Chitosan is one of the biopolymers with the highest tensile strength and rigidity, although it may have less flexibility. To improve flexibility, plasticizers like glycerol can be added [103]. On the other hand, whey proteins and casein can also provide good tensile strength, and their elasticity can be improved by adding plasticizers [104].

The gas barrier, such as that for oxygen and carbon dioxide, is important for meat, especially when modified-atmosphere packaging is required [105]. Starch and cellulose films are known for their low oxygen permeability due to their dense and semicrystalline structure, making them suitable for foods that require protection against oxidation [106].

By adding antimicrobial and antioxidant compounds, it is possible to develop packaging that extends the shelf life of meat. Chitosan is known for its antimicrobial properties due to its positive charge, which interacts with the negatively charged membranes of bacteria, thereby inhibiting the growth of microorganisms. Proteins like casein can also incorporate essential oils or extracts, providing an additional layer of protection against microbial spoilage [107].

5. Natural Compounds Used in Active Packaging Films

5.1. Extracts

Plant, root, stem, leaf, flower, and fruit extracts are used in the food and pharmaceutical industry because they are a significant source of antioxidant compounds such as polyphenols and flavonoids; in addition, they provide anti-inflammatory and antimicrobial properties [108]. Natural extracts are incorporated into materials for food packaging; this is because the packaging improves plasticizing properties and crystallinity properties. Green tea extracts are widely used, as green tea contains compounds such as catechins, epicatechins, epigallocatechins, and gallic acid [109]. Another extract of interest is basil, being an herb that contains antioxidant compounds such as linalool, chlorogenic acid, and chavicol. From natural extracts it is also possible to extract essential oils; in one case, apricot kernel oil has been incorporated into food packaging materials, having oils such as linoleic acid, stearic acid, and palmitic acid, which, when incorporated into the packaging material, have shown a high level of antioxidant activity and a high level of antimicrobial activity, especially against *E. coli* grand negative, as well as against the bacterium B. subtilis gram positive [110]. The amaranth leaf contains phenolic compounds such as betacyanins, presenting antioxidant and antimicrobial activity, and, in addition, it may produce color changes, depending on the state of the food [111]. In [112], a container for minced pork was developed using rosemary oleoresin extract and green tea extract; it presented a high antioxidant capacity.

5.2. Phenolic Compounds

Plant phenolic compounds, also known as polyphenols, are defined as substances featuring one or more aromatic rings with hydroxyl groups; they originate from the secondary metabolism of plants. They are predominantly found in various plant-based foods, including fruits, vegetables, seeds, cereals, berries, wine, tea, olive oil, and aromatic plants [113]. Phenolic compounds can be broadly classified into two main groups: flavonoids and non-flavonoid polyphenols. Non-flavonoid phenolic acids are commonly found in foods, while flavonoids, a key class of polyphenols, are categorized into subclasses based on the oxidation state of their heterocyclic ring. These subclasses include anthocyanins, flavonols, flavans, flavanols, flavones, and isoflavones. Many of these compounds are known for their antioxidant properties [114].

The antioxidant mechanisms of phenolic compounds can vary depending on their specific structural and compositional features. Research has identified antioxidant activities in phenolic compounds from a wide range of natural sources. Recent studies have focused on exploring antioxidants in agricultural by-products, ethnic and traditional products, herbal teas, hydrolysis products, and edible fruits and leaves that have yet to be thoroughly examined [115]. Due to their molecular weight and structure, phenolic compounds can exhibit significant variability. They contain hydroxyl groups that form hydrogen bonds, making them compatible with polymers, and enabling the production of films with increased volume [116]. Additionally, intramolecular interactions can lead to chain cross-linking, enhancing the properties of the films [117]. In Figure 2, a graphical representation of the extraction sources of bioactive compounds and the properties that can benefit foods can be observed.

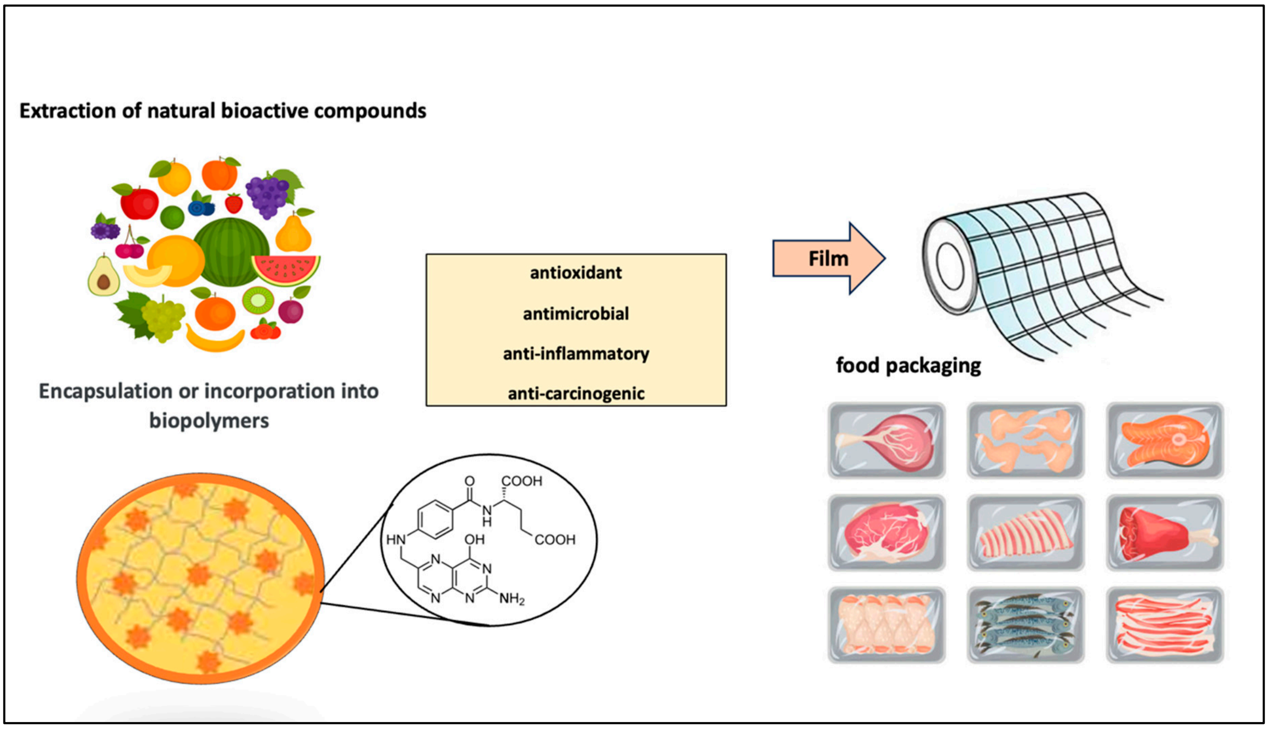

Figure 2. Extraction sources of bioactive compounds and properties.

6. Functional Properties of Active Packaging

Active packaging not only contains and protects the product but also incorporates active compounds that come into contact with the food, offering added benefits such as the extension of shelf life. In this context, the functional properties of active packaging can vary depending on the mechanisms or technologies applied. One example is antimicrobial activity, which involves the release or absorption of substances like organic acids, enzymes, or natural extracts to control contamination and prevent microorganism-related illnesses. Similarly, antioxidant activity can protect the nutritional and sensory quality of meat by releasing compounds that prevent oxidation [118].

Active packaging can also enhance flavor and aroma, improving the sensory properties for consumers. Additionally, it can regulate carbon dioxide (CO_2) levels. In the case of modified-atmosphere packaging, active packaging manages the balance of gases like CO_2 by absorbing excess gas to prevent package swelling or releasing it to maintain product freshness.

Thus, the functional properties of active packaging for meat aim to prevent oxidation, control spoilage, and regulate moisture to ensure optimal freshness. This helps extend shelf life while maintaining the safety and quality of the meat [119].

7. Other Compounds Used in Active Packaging Films

The incorporation of nanoparticles into biopolymers is likely to improve the mechanical or resistance properties of the film, as well as the barrier-creating properties or the antimicrobial and antioxidant activity. Among the most used nanoparticles are zinc oxide and silver [120]. However, currently, nanoparticles made from natural biopolymers such as gelatin have shown significant properties in terms of antioxidant activity [121]. Additionally, the solvents used in the production of packaging materials can impact the final properties of the material, influencing solubility, ideal material formation, and functionality. This is a crucial part when planning the application of each form of packaging for the appropriate food, as it can affect mechanical or barrier-creating properties. On the other hand, secondary biopolymers would also improve resistance properties, such as water resistance, mechanical strength, or bioactivity, influencing the functionality of the film [122].

8. Others

8.1. Lipids

Lipids are molecules that can be obtained from natural sources, whether of animal or plant origin. Among the functional groups of lipids, there are phospholipids, phosphatides, mono-, di-, and tri-glycerides, terpenes, cerebrosides, fatty alcohol, and fatty acids [123]. The main constituents are triglycerides. Depending on its structure, the fat and oil will vary, so its shape can be determined from the balance of solid and oil, depending on the ambient temperature. Lipid-based films can prolong the shelf life of foods when used as coatings or films, while additionally providing shine and reducing moisture loss [124]. In packaging, lipids and waxes can also improve the cohesion and flexibility of films; the main compounds utilized are beeswax and paraffin wax, resins, fatty acids, and mineral and vegetable oils [123].

8.2. Waxes

Specifically, these waxes are obtained from plants and animals and fulfill the function of protecting tissues. Waxes are formed by alcohol and esters of long-chain acids, which is why they have a high molecular weight. Waxes are often used as edible films to reduce moisture permeability, in both plant- and meat-based foods [125]. In [57], a film based on zein wax with gallic acid was produced for meat, and was observed to reduce the growth of microorganisms, prolonging shelf life, in addition to providing antioxidant capacity.

9. Techniques for Obtaining Active Packaging Films

9.1. Casting

One of the most used methods is the solvent casting method, which employs a solution using water or ethanol. In the laboratory version, the polymer is mixed with the bioactive compound, the solution is heated, and the pH is adjusted; the solution is then poured directly in a Petri dish, drying until solid (Figure 3). This is a fast, easy, and productive method, and the technique is widely used in the food industry for the manufacture of packaging. Among the most used materials is polypropylene, PET, obtaining composite films or mixtures with bioactive compounds or natural polymers [126]. In [127], the authors made a chitosan film which was prepared using the casting technique; essential oil of *Cinnamodendron dinisii* was incorporated into the film for meat preservation, and the essential oil was encapsulated in zein, presenting high antioxidant activity and antimicrobial activity. In addition, spoilage reactions were stabilized, and meat color was maintained.

9.2. Electrohydrodynamic Processes

Among the most innovative techniques used to develop materials or films as food packaging are the electrospray and electrospinning processes, which are techniques that focus on nanotechnology, and are employed to obtain nanomaterials by means of non-thermal processing. The technique of this process consists of causing a polymer solution to be expelled from a source with the help of high voltage; the process is carried out at room temperature. Using this technique, it is possible to obtain nanoparticles and nanofibers (Figure 3) with uniform sizes that can be directly applied to food or incorporated into a film. In this case, the nanofibers are described as long filaments with a large surface volume; they are considered suitable for material applications in food since, among their properties, they present elasticity, high porosity, and mechanical resistance; this will, however, depend on the polymer used [128]. On the other hand, the electrospray process is suitable for obtaining micro- or nanoparticles; once the solution is shot, instant solvent evaporation occurs, obtaining the dry material found in the collector. Among the most important parameters for the two techniques are the viscosity, the voltage, the feeding speed of the solution, and the distance between the tip and the collector; these are important for the control of the morphology of the material to be obtained [129]. In addition, these techniques present a novel advantage, since beneficial health compounds are incorporated, as the material is protected from external agents, allowing a controlled release into food, and avoiding undesirable reactions [130].

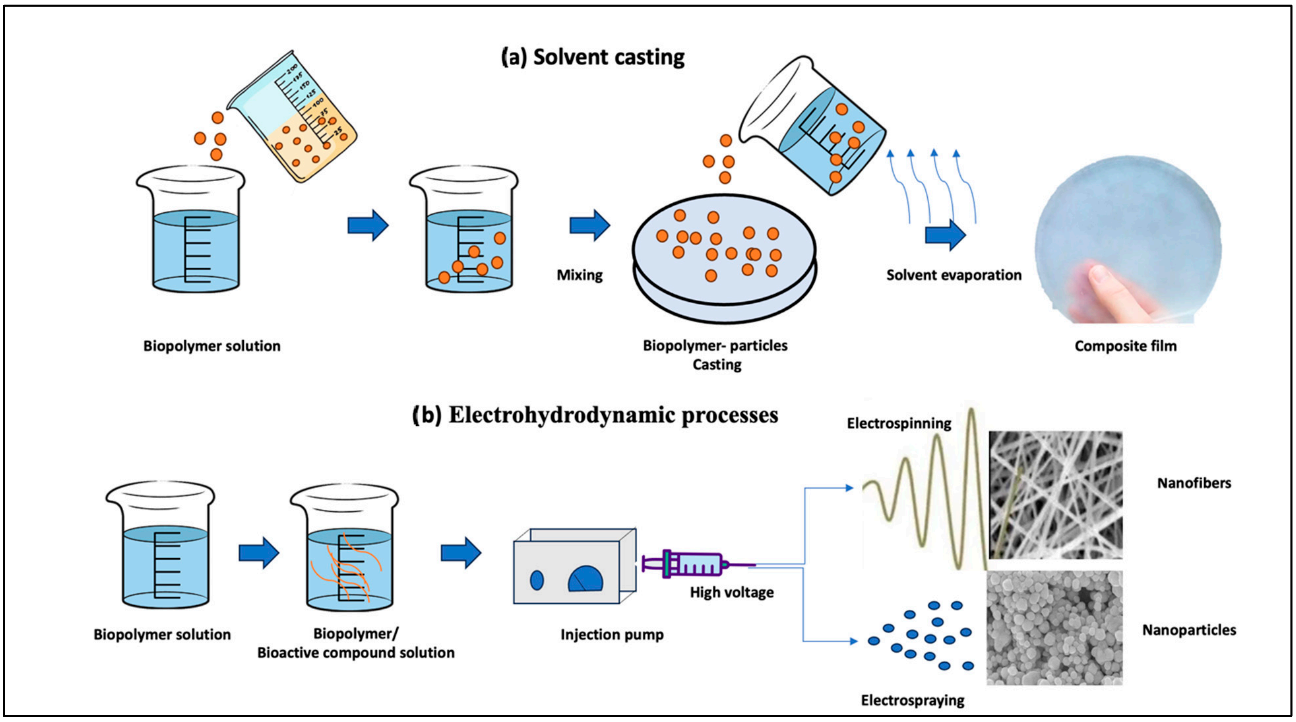

Figure 3. Techniques for obtaining active packaging films: (**a**) casting and (**b**) electrohydrodynamic processes.

10. Applications

10.1. Antimicrobial Packaging Films

Antimicrobial packaging is important for the industry because foods are highly perishable, and contain high levels of nutrients favorable for the development of microorganisms; the industry therefore seeks to develop packaging that can inhibit growth, and preserve safe and healthy food [131]. It is important to emphasize the specific spoilage-related microorganisms, bacteria, yeasts, and molds, as well as pathogenic microorganisms such as *Almonella* spp., *Staphylococcus aureus*, *Listeria monocytogenes*, *Clostridium perfringens*, *Clostridium botulinum*, and *Escherichia coli* O157:H7, these being the ones of greatest interest. With this type of packaging, researchers seek to prolong the useful life of food [132]. According to the literature, different antimicrobial packages can be obtained. The first to be mentioned are those that have an antimicrobial substance incorporated into a pad that can release antimicrobial compounds. The second option is to directly add the antimicrobial compound to the packaging film (Figure 4), while maintaining the bioactive compound, protected by techniques such as those involving solvents and electrohydrodynamics, and preserving its antimicrobial activity. Among the agents tested as antimicrobials is ethanol. Carbon dioxide, essential oils, and plant extracts are also involved [133]. In [134], a film based on soy protein, polylactic acid, and polybutylene adipate was obtained, with the additional incorporation of tea polyphenols, and a microbiological analysis of 10 days was performed, in which an inhibition of microorganisms such as *E.coli* and *Staphylococcus aureus* was observed at 4 °C; in addition, the textural properties were maintained.

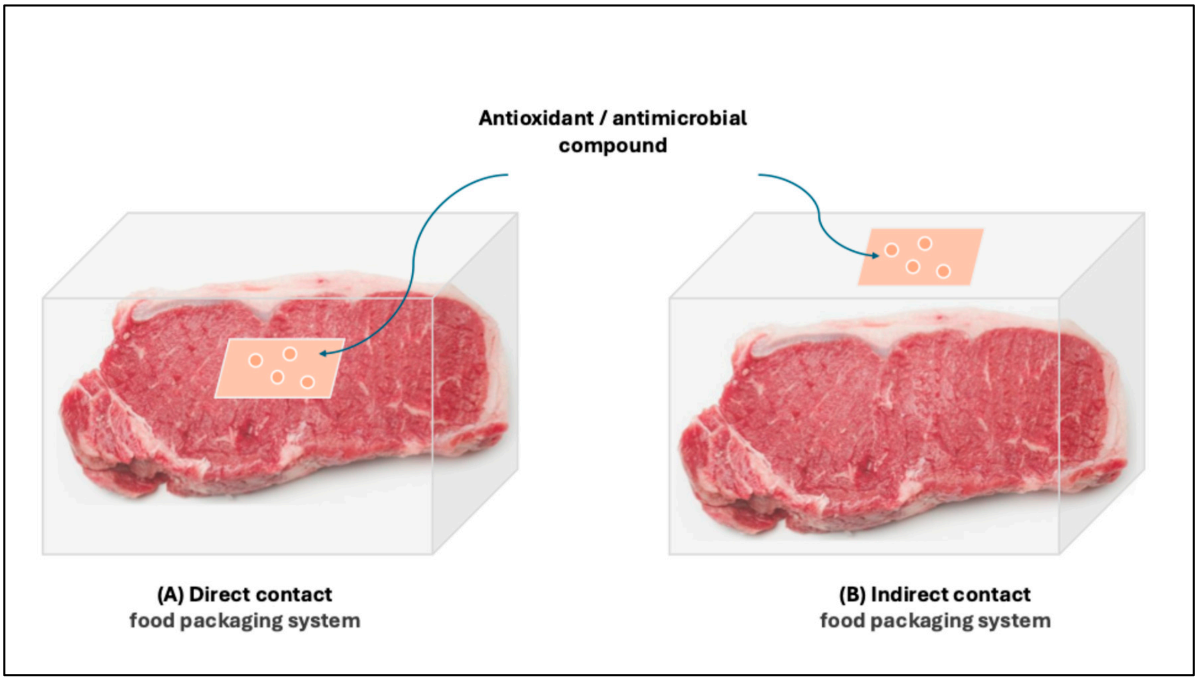

Figure 4. Illustration of antioxidant and antimicrobial packaging systems: (**A**) direct contact and (**B**) indirect contact.

10.2. Antioxidant Packaging Films

Antioxidant packaging promises to prolong the useful life of food, releasing compounds on the surface of the food, a process which can be continued for a long time. The antioxidant compounds used in packaging can be classified as synthetic, with butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT) being the main examples of this type; on the other hand, there are examples of products of natural origin such as polyphenols associated with tea and phytic acid [132]. In addition, it is important to consider how the compound will be applied, whether incorporated into a film or onto the feed directly (Figure 4). In the first case, when combining the antioxidant with the film, the substance is dissolved using an appropriate solvent; this can be performed using either the casting or the extrusion techniques. On the other hand, physical methods can be used to effectuate the adhesion of the compound, utilizing it as a coating to the food [135]. In [136], an antioxidant active packaging was developed using pure essential oils for meat samples, while also evaluating the aroma and heat-sealing properties. The oils used were linseed oil, ginger, grapeseed oil, and rose oil, used in an LDPE container. While noting that linseed oil was the one with the highest antioxidant activity, it was suggested that the containers be protective in order to prevent oxidation of the oils.

10.3. Active Absorbent Pads

The absorbent pads commonly used when packaging meat are placed at the bottom of the food, in order to reduce the loss of water and exudates during storage [137]. There are also innovative active pads, in which a bioactive compound is placed to slow the degradation of meat. There are studies establishing that by using this type of pad, microorganisms such as Pseudomonas and brocothrix thermosphacta have been decreased, with positive effects found on the color of the meat, in addition to decreased values of total volatile basic nitrogen and lipid oxidation [138]. In [139], an active absorbent pad for fresh beef was developed, with regard to which it was observed that microbial growth was delayed for *L. monocytogenes* and *Salmonella* spp., with low values of total volatile basic nitrogen (TVBN) also being observed. On the other hand, [140] developed a pH-sensitive absorbent pad, made from polyvinyl alcohol/agarose and anthocyanins, which indicated in real time the deterioration of meat by its color change, in addition to extending shelf life for an additional 24 h. In [141], an absorbent pad with levulinic acid and sodium dodecyl sulfate was developed, with the use of which powerful inhibitions against *Pseudomonas*, *Acinetobacter*, and *photobacterium* were observed; these are the genera that predominate in beef. In [142], the authors obtained an absorbent pad that increased shelf life by 50%, inhibiting microorganisms such as Escherichia coli, Staphylococcus aureus, and Listeria monocytogenes, and which can be washed and reused at least 10 times.

10.4. Traceability Devices

Generally, barcodes provide information on the traceability of the product. It is important to prepare digital schemes that contain the stages of an order, with the control of critical points, improving the communications to the consumer regarding the status of the product. In Europe, it is feasible to obtain information about the slaughtered animal, such as date of birth, sex, transportation, etc., by simply tracing the barcode [143].

10.5. Biosensors

A biosensor is a compact analyzer that can detect, record, and transmit information about the biochemical reactions that meat presents. This type of sensor usually consists of a bioreceptor which will indicate the target analytes and a transducer which will convert the biochemical signals into electrical responses that can be measured [144]. A bioreceptor can be in the form of an organic or biological compound, be it an antigen, enzyme, microbe, hormone, or even a nucleic acid. In the case of the transducer, it can measure electrochemically, optically, or acoustically. A biosensor can give us information about contaminants and pathogen detection, in addition to information about the meat quality parameters [145].

10.6. Time and Temperature Indicators

The most important factor to ensure when packaging food is the temperature, as well as monitoring the growth of microorganisms. Therefore, time and temperature indicators are useful because they can provide information as to whether the food is in an inappropriate range. These are usually placed as labels on the packaging [146].

10.7. Freshness Indicators

Freshness indicators can provide information about the quality of the packaged product, with respect to microbial growth and chemical change [147]. The most common forms of this information are observed changes in the concentrations of organic acids such as n-butyrate, L-lactic acid, D-lactate, and oil acid; these are potential metabolites, and they provide information about the freshness of the meat. They are measurable by observations of microbial growth. One of the most efficient tests is the pH test, in which the color change indicates the presence of these microbial metabolites [148]. In Table 2, some types and applications of sensors in meat are shown, and in Figure 5, a representation of the signals that can be observed through a biosensor in meat can be seen.

Table 2. Types of biosensors in meat.

Biosensor	Bioactive Ingredient	Application and Effect	Reference
Colorimetric	Anthocyanyns	Fresh pork: The biosensor changes color from pink to orange when the critical amount of total volatile basic nitrogen is detected.	[149]
Colorimetric	Anthocyanyns	Chicken: color change when detecting microbial growth, pH changes, and increases in nitrogenous substances.	[150]
pH sensitivity	Anthocyanyns and Curcumin	Fresh pork: maintains and detects the freshness of the meat.	[151]

Table 2. *Cont.*

Biosensor	Bioactive Ingredient	Application and Effect	Reference
Colorimetric	Anthocyanins	Pork freshness: it changes color from pink to brown, detecting the freshness of the meat.	[152]
Colorimetric fluorescent	Single-atom iron nanozyme	Meat: detection of volatile amines.	[153]
Colorimetric	Anthocyanyns, chlorophyll, beta-carotene	Chicken: color changes from yellow, red, and green to weaker colors.	[154]
Compound detection	Gold nanoparticles, graphene oxide, chitosan	Raw beef: detection of L glutamate.	[155]
Electrochemical	Iron (III) phthalocyanine, gold nanoparticles	Meat products: nitrite detection.	[156]
Electrochemical	Poly(L-aspartic acid)	Meat freshness: xanthine detection.	[157]
Synthetic	Repressor–operator pair (PuuR-puuO)	Beef: detecting putrescene.	[158]
Dielectrophoresis-based microwire	Antibodies, bovine serum	Beef: rapid detection of *Escherichia coli* K-12.	[126]

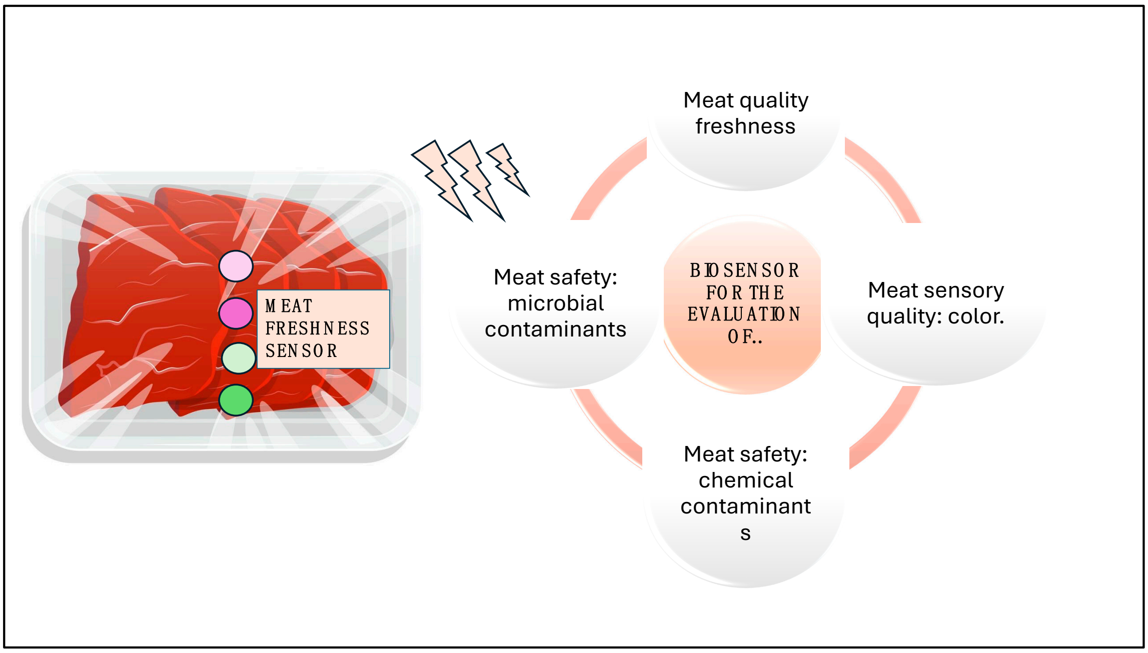

Figure 5. Signals that can be observed through a biosensor in meat.

11. Active Packaging Properties and Applications

Nanotechnology is an innovative force in the active packaging industry, as it provides advanced solutions used to improve the quality and sustainability of food packaging. This allows for significant improvements in packaging properties, such as optimizing barriers against gases, moisture, and light; extending shelf life; and importantly, reducing waste [159]. Figure 6 illustrates how these innovations impact technology in the properties and applications of active packaging.

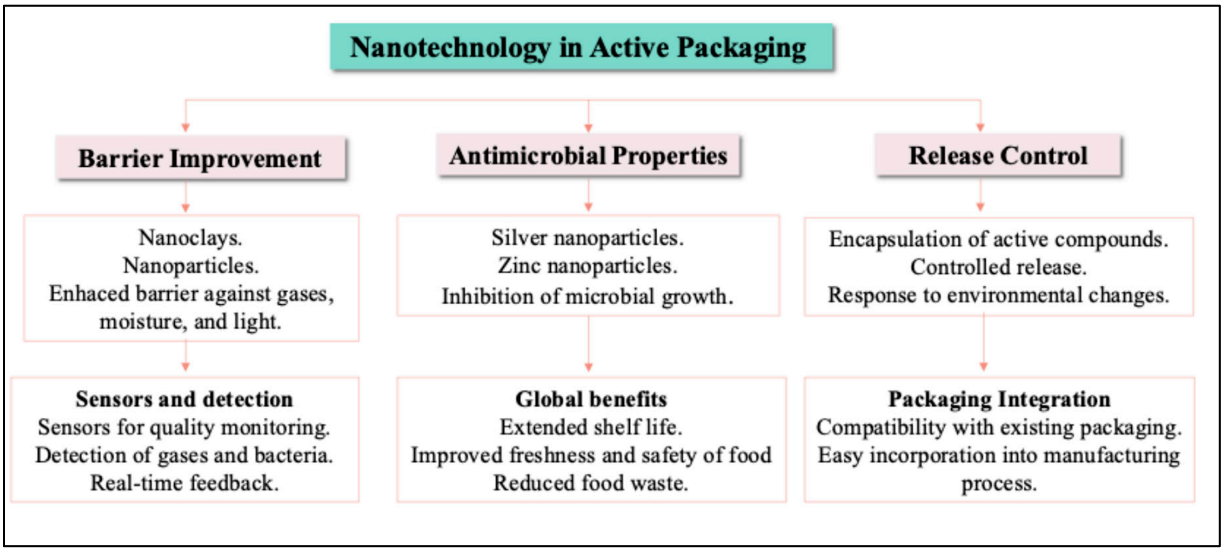

Figure 6. Impact of Nanotechnology on Active Packaging Properties and Applications.

12. Challenges and Limitations of Red Meat Packaging

Red meat, being a protein-rich food with high moisture content, is highly susceptible to deterioration and microbial growth. Therefore, it is crucial to address the specific needs of the product by enhancing packaging materials with effective barriers against moisture, oxygen, and light [160]. However, researchers face a challenge in attempting to improve upon or surpass the protection offered by conventional plastics, particularly in terms of mechanical resistance. They must ensure that the material withstand the conditions encountered during handling and transportation while maintaining the integrity of the meat. Physical damage to the meat could lead to a decrease in quality for the consumer [161].

Another important consideration is the cost of the biopolymers used. Therefore, there is a focus on implementing natural biopolymers that are abundant in nature, or are by-products, to ensure their effective utilization [161].

Safety Aspects in Red Meat Packaging

It is crucial to address chemical safety in meat packaging, with particular attention to ensuring that packaging materials are free from chemicals that could migrate into the meat, thereby posing a greater risk to consumer health [160]. The development of new natural biopolymer-based packaging must adhere to current regulations. Additionally, the environmental impact must be considered, ensuring that biopolymers do not release harmful substances into the environment, thus avoiding detrimental effects. Furthermore, consumer education plays a vital role in the success of these new technologies. Consumers must be well-informed about the benefits and limitations of these materials, as well as the way packaging is labeled to enhance their understanding of emerging technologies [162].

13. Coatings and Compliance: A Global Overview

In [163], the authors conducted a study discussing the current state of sustainable packaging regulations, mainly focusing on how these regulations have rapidly evolved worldwide, aiming to reduce the environmental impact of plastic waste. Jurisdictions like India, the European Union, and China have implemented restrictions on the use of these plastics, creating an incentive to use recyclable, biodegradable, and compostable materials. These regulations aim to promote a circular economy and hold producers accountable for the life cycle of their products. It is important to note that each country varies in its implementation of these regulations. Below, some key points about the coatings and regulations implemented in each country are presented.

In India, several plastics have been banned, with regulations that include the Food Safety and Standards Amendment regulations of 2022, resulting in greater extended producer responsibility under the Plastic Waste Management Rules. In the European Union, a directive has been applied that bans various plastic items, in addition to regulations such as Regulation (EC) No. 1935/2004, Regulation No. 10/2011, and the Packaging and Packaging Waste Directive (94/62/EC). In China, plastic bags have been banned in some regions, and a national ban on non-degradable bags, straws, and plastic utensils is proposed for 2025. The country also follows the Solid Waste Pollution Prevention and Control Law (2005) and more specific regulations such as the National Food Safety Standard for Food Contact Plastic Materials and Article.

In Japan, there is no national restriction, but the country has enacted a Food Sanitation Act and a Containers and Packaging Recycling Law (2000). Likewise, in the United States, there is no national ban, but several states have proposed their own regulations according to the federal Food, Drug, and Cosmetic Act without federal EPR regulations. In South Korea, plastic bags have been banned in stores, with additional proposed bans for 2027. The country has also enacted the Standards for Recycling Law Materials for Food Containers under the Resource Recycling Act. In the United Kingdom, bans have been implemented since 2020 on straws, cotton swabs, and stirrers, following the Producer Responsibility Obligations, Regulations, and Packaging Waste Regulations. Finally, in Australia, plastic bags have been banned, and by 2025, straws, stirrers, and plastic utensils will also be banned, given the regulations of the National Environment Protection Measure and the Australian Packaging Covenant Organization.

Each of these countries also has regulations on recycled plastics in food packaging. For example, in India, 50% recycled content is allowed in packaging. In the European Union, the regulation depends on the material and application of the packaging, following certification from accredited laboratories, as is also the case in the United Kingdom. Therefore, in the future, an increase in biodegradable materials and greater interest in recycling technologies is expected to promote a more circular economy, in which EPRs would become more common. Currently, these regulations have shown a positive impact, mainly in waste reduction, while aiming to improve management through increasingly strict regulations in each country.

14. Conclusions

Food packaging materials must provide and enhance essential properties such as water and gas barriers and lipid oxidation inhibition, while also offering additional health benefits through bioactive compounds. Current research focuses on a wide variety of natural extracts that can boost antioxidant and antimicrobial activities, as well as compounds capable of changing color in response to pH variations. It is crucial to delve deeper into the study of the diffusion mechanisms of these bioactive compounds in order to optimize their effectiveness in packaging materials.

The technologies used to produce packaging materials impact their applications, as the mechanical properties and efficiency of the material can vary depending on the technique employed. In the specific case of meat, whether refrigerated or processed, packaging materials have proven versatile, adapting to various needs and applications.

The development of packaging materials continues to evolve, along with the incorporation of different natural extracts that enhance packaging functionality. Active and intelligent packaging options will continue to play a crucial role in preserving meat quality and safety, promoting sustainable and effective solutions in the food industry.

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