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REVIEW ARTICLE

Natural antimicrobial and antioxidant compounds for active food packaging applications

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Abstract
Food needs a step ahead technology to store food fresh and safe for a more extended period. At the same time, ecological awareness and consumers' demand for safe food and quality products have led us to explore emerging food preservation techniques, including active food packaging. Antioxidant and antimicrobial are emerging practices in the active packaging segment. The chemical additives adversely affected the food and were not economical for commercial production. The active packaging with natural additives such as natural antioxidants and antimicrobial agents could bring a sustainable solution to this concern. Plant (herbs, spices), animals, mushrooms, enzymes, and microorganisms are considered the natural active component's reservoirs. The active compounds from natural sources were recently utilized to develop active packaging materials. Here we reviewed various natural sources as an antioxidant and antimicrobial compounds for food packaging application. We present the mechanism of active compounds methods of incorporation of active compounds into packaging. Further, we discussed the food packaging applications and challenges in the utilization of natural antioxidant and antimicrobial compounds for food packaging industries.

Keywords Active packaging · Natural · Antioxidant · Antimicrobial · Sustainability · Extract · Edible · Biopolymer

1 Introduction

Nature has abundant active components as different parts of the plants, animals, or soils. For the food industry, particularly for food preservation and packaging, these extracts have significant utilization as bio-preservative and functional ingredients in the active and intelligent packaging system for food application. Packaging is a critical factor in the food processing sector and is dominated by a synthetic petroleum-derived non-biodegradable polymer. Food packaging is the fastest expanding area in worldwide packaging market [1, 2]. At the global level, many materials such as paper, glass, wood, and plastics are utilized to make packaging material, with more than two-thirds used in food packaging alone. This effect is being generated due to changes in food preparation and consumption habits and the profitable growth of various places and markets worldwide [3].

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At present, the polymer has become an integral part of daily life due to its desired quality parameters and ease in terms of the manufacturing process. According to previous reports, the plastic (Thermoplastics, thermosets, elastomers, adhesives, coatings and sealants, and polypropylene-fibers production was 359 million tonnes in 2019 at the global level. The major contributors are Asia (51%), China (30%), Europe (17%), Middle East & Africa (7%), and others [4]. India is one of the leading countries for plastic manufacturing; in 2019, polyethylene (PE) was the most used plastic, with over 15 million tonnes of films and sheets being produced [5]. The excessive utilization of the synthetic polymer increases the accumulation that causes adverse environmental concerns, including a significant contribution from food packaging application [1]. The rising difficulties in disposing of garbage and the negative impacts on the ecology and public health caused by synthetic polymers have sparked worldwide concern about developing an environmentally suitable alternative material [6]. Biodegradable polymers can be utilized as alternatives in place of synthetic polymer for many industrial applications, including food packaging. Biodegradable plastic, according to the American Society for Testing and Materials (ASTM), is "plastic that dissolves

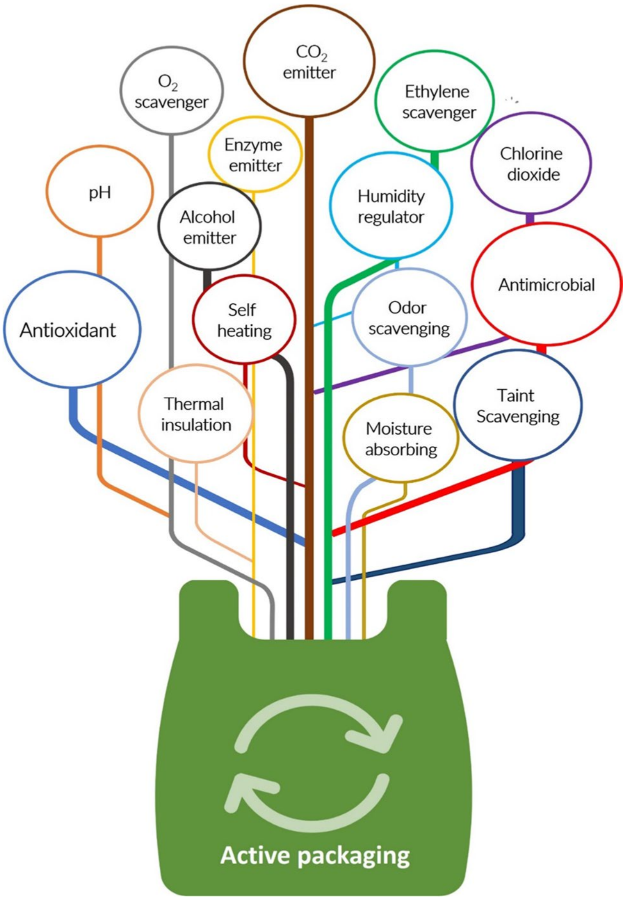


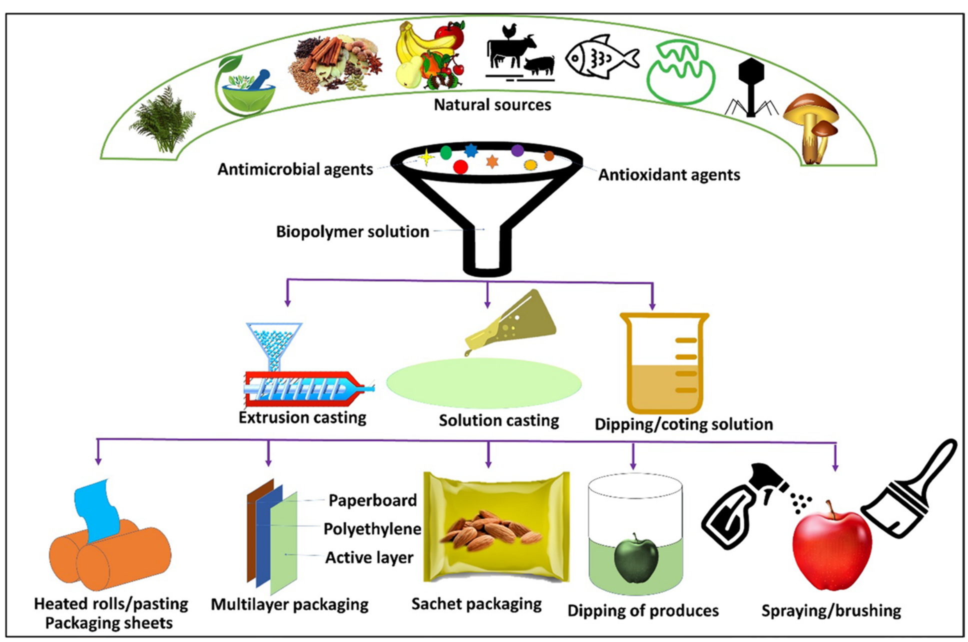
Fig. 1 Classification tree of different types of active packaging systems for food applications which helps in extension of shelf life, monitor freshness, display information on quality, improve safety, and improve convenience

due to the activity of naturally occurring microorganisms such as bacteria, fungi, and algae" [7]. Biopolymers such as proteins, polysaccharides, and lipids are commonly used in the food industry to produce biodegradable and environmentally friendly packaging films [8].

Combining biodegradable polymers with natural extract is one of the most successful ways to create new materials with desired qualities. Furthermore, they have antioxidants, antibacterial, antifungal, and antiviral activities [9]. When compared to films consisting of individual components, packaging films generated by adding plant extract into polymers frequently resulted in modified physicochemical, mechanical, and barrier properties and have been employed for a wide variety of applications in polymers [1]. The active packaging classification can be seen in Fig. 1. Plant extract compounds have been extensively used in the food business to increase the shelf-life of perishable food. The use of active compounds derived from natural sources in food is an intriguing opportunity to put their biological properties to use, as illustrated in Fig. 2. It renders the production potential without chemical additives because the current scenario reduces the chemical intervention to assure consumers safety. Recently, the biodegradable packaging system developed employing natural antioxidant and antimicrobial agents has attracted producers and consumers. Incorporating natural extract from different sources as antioxidants and antimicrobials improves the biopolymers matrix properties.

Furthermore, this improves the oxidative stability of food products and limits the formation of foodborne pathogens [10, 11]. They give further safety measures to food even when cold storage, controlled atmospheric packaging (CAP), or modified atmospheric packaging (MAP) are not available.

Fig. 2 Schematic representation of incorporation of different natural sources of antioxidant and antimicrobial compounds into packaging material via extrusion, solution casting, and dipping/coating methods for food packaging application



Most of these antioxidants and antimicrobials are found in extracts and essential oils derived from various bioresources and have been extensively investigated in earlier studies. Natural antioxidants and antinutritional agents are produced from natural sources. They are biodegradable, biocompatible, and easily decomposable in the environment, making them an effective alternative for developing effective antioxidants and antimicrobial biopolymer matrix synthesis. This article has thoroughly discussed different antioxidant and antimicrobial agents from numerous natural sources, which have been utilized to prepare biodegradable packaging films. Moreover, this review focused on the recently reported studies on the plant, animal, and microorganisms-derived sources of antioxidant and antimicrobial components used in biopolymer-based packaging films. Besides, various impediments and future research opportunities in the coming time towards sustainable food packaging solutions in the industry are outlined.

2 Natural antioxidants and antimicrobial compounds

2.1 Sources of natural antioxidants

The natural extracts have been extensively used to develop, modify and increase the desirable properties of packaging film. The natural additive or extracts obtained from plants, herbs, spices, animals, or microflora were considered resources for active components [12]. The natural antioxidant extract is called phenolic chemicals, often known as polyphenols. They are classified as secondary metabolites of plants engaged in defense from ultra violet (UV) radiation or oxidative chemicals. These antioxidants belong to a large family of chemicals. They can be found in a wide variety of fresh produce, including fruits, vegetables, herbs, spices, and by-products of these foods. Plant phenolics have become increasingly popular in recent years because of their sources and compatibility with the biopolymers in which they are used [13]. Hydrogen atom transfer (HAT), single electron transfer (ET), reducing assays, metal chelation, and other techniques can be used to detect antioxidant levels. These extracts are accompanied to develop a natural or synthetic antioxidant mechanism in the packaging or coating of produce. These active components can migrate to food or absorb antioxidative radicals to improve food quality and shelf-life. Previously, butylated hydroxy toluene, butylated hydroxy anisole, and tert-butylated hydroquinone were used in research to develop active packaging film for the preservation of oxygen sensitive foods [14]. These synthetic antioxidants are poisonous and hazardous to health, and healthy alternatives for antioxidants are being researched in a variety of sources, including plants, herbs, spices, and microflora. These antioxidant chemicals include aqueous and alcoholic extracts, essential oils, and a wide range of phenolic components derived from various waste bioresources [15]. The natural antioxidant from fruits and vegetable sources increased last years due to their availability and economic perspectives. Fruits such as cherry, grapes [16], pomegranates, berries, olive *(Olea europaea L.)* and olive oil [17], lemon, and a wide range of products and vegetables such as spinach, broccoli, and cauliflower along with waste generated from their inedible parts such as peel, seeds or stones, and un-used pulp have been extensively studied in recent years. Table 1 shows the exploited sources in previous studies for developing active packaging film or coating as antioxidant activity [18]. Recent studies have found that eating whole grain products have several health benefits. Nutritious metabolites found in dietary grains with significant antioxidant potential include rice and bran [19]. Tea has long been regarded as a critical commercial product due to its health advantages and strong phytochemical content with antioxidant capabilities. Catechins are the most prevalent and potent components in tea. Tea extract from various sections of the plant, such as the leaves and stems, was used as an essential antioxidant agent in the manufacture of biopolymers for food packaging applications [20]. Antioxidant properties of spices and herbs have discovered long time ago, food preservation with garlic, mint, rosemary extract had already been popular since the ages [21, 22]. The microflora such as algae or yeast as source of antioxidant agents, many studies have been presented this as a potential antioxidant effect of marine algae along with their active compounds [23].

2.2 Antioxidant mechanism of natural compounds

The oxidation in food is initiated with unsaturated fatty acid in the presence of a catalyst, such as iron, copper, enzymes, heat, or light. It is a chain reaction that begins with auto-oxidation and ends with termination; once launched, self-acceleration of the process takes it further. Free radicals are atoms, molecules, or ions with an unpaired electron, which reacts rapidly with another molecule present in them. Free radicals are often consequent from oxygen, nitrogen, and sulfur molecules in the biological system. "These free radicals are subdivided into different groups such as reactive oxygen species (ROS), reactive sulfur species (RSS), and reactive nitrogen species (RNS)" [24]. These free radicals cause a nucleic acid breakdown, protein degradation, and a double bond in unsaturated fatty acids. Conjugated dienes, hydroperoxide, aldehyde, and ketone are formed and exert rancid aroma and flavors before combination with other functional groups to impair the Physico-chemical properties of foods [25]. Inhibiting lipid oxidation with the antioxidant agent or active packaging can potentially preserve foods with high unsaturated fatty acids from possible quality deterioration and extend the shelf life. The antioxidant

Table 1 The studies reported on natural extract incorporated into the packaging material for antioxidant biopolymer food packaging application

Antioxidant agent	Natural source	Polymer Matrix	Observations	Reference
Pineapple peel extract	Pineapple waste	Polyvinyl alcohol and corn starch	Improved antioxidant activity of the developed film as compared to control film	[148]
Coconut shell extract	Coconut waste	Polyvinyl alcohol and corn starch	Developed film with active agent showed antioxidant activity and delayed the oxidation reaction of packed soybean oil in the sachet	[149]
Licorice residue extract	Licorice residues	Soy protein isolate	The developed film exhibited improved mechanical and barrier properties with high antioxidant activity, which is applicable for high-fat content products	[150]
Pecan nut shell extract	Pecan nut shell	Whey proteins	The natural extract improved film resistance and barrier properties	[151]
Mango leaf extract	Mango leaf	Chitosan films	The developed film is thicker, denser, and hydrophilic with antioxidant activity. The film showed good application for cashew nut packaging with 56% higher oxidation resistance compared to control film	[152]
Betalain-rich red beet	Red beet	Ethylene–vinyl alcohol	UV barrier property and antioxidant activity improved	[153]
Yellow onion peel extract	Yellow onion	Gloiopeltis furcate	Yellow onion peel extract improved the flexibility and DPPH and ABTS radical scavenging activity of the developed film	[154]
Olive leaf extract	Olive leaf	Carrageenan	Improved antioxidant activity of the developed film	[58]
Black soybean seed coat extract	Soybean seed coat	chitosan	15% of black soybean seed coat extract showed the best performance among other compositions	[155]
Ginkgo biloba extract	Ginkgo biloba leaves	Gelatin	UV barrier property increased, and antioxidant improved	[156]
Fennel essential oil and peppermint essential oil	Funnel and peppermint plant	chitosan	Increased thickness, density with low moisture, and water solubility of the developed film	[157]
Green tea extract	Green tea leaves	Polylactic acid	Water vapor barrier and mechanical properties improved, and packed salmon in the film exhibited reduced lipid oxidation for 60 days	[158]
Germinated fenugreek seeds	Fenugreek seeds	Semi-refined κ-carrageenan	The extract improved the antioxidant activity, film applied in chicken breast packaging showed improved shelf life	[159]
Polyphenol-rich purple rice extract / black rice extract	Black rice extract	Chitosan	Light barrier and antioxidant activity increased due to extract incorporation into the film	[160]
Anthocyanin-rich purple corn extract	Corn	Chitosan	pH sensitivity increased	[160]
Moringa leaf extract	Moringa leaves	Papaya puree and Pectin	Improved antioxidant activity and shelf life of minimally processed pear increased	[161]
Camu camu extract	Camu camu	Teff starch	Tensile strength reduced while elongation at break increased from 26 to 72%	[162]

Table 1 (continued)

Antioxidant agent	Natural source	Polymer Matrix	Observations	Reference
Haskap berries Extract	Haskap berries	Fish Gelatin	Haskap berries extract improved the film's water barrier, light barrier, and tensile strength	[163]
kiwifruit peel extract	Kiwi fruit	Water melon rind pectin	The extract improved tensile strength and young's modulus with elongation at break. Chicken thigh packed in kiwifruit peel extract had lower peroxidase and thiobarbituric acid reactive substances than control film	[164]
Red pitaya peel extract	Red ptaya	Starch/polyvinyl alcohol	The extract improved the microstructure of the film with high antioxidant activity	[165]
Red apple pomace extract		Chitosan-based	The improved mechanical property, the salmon fillet freshness maintained for a longer time	[166]
Pomegranate rind	Pomegranate rind	Polycaprolactone/starch	It enhanced the rigidity of film and the release rate of polyphenol	[167]
Mulberry extract	Mulberry	κ-carrageenan	It is improved in thickness, tensile strength, thermal stability, antioxidant activity, and pH-sensitive property of the κ-carrageenan film	[168]
Grape fruit seed extract	Grape fruit	Polyvinyl alcohol	Extract improved UV-barrier (up to 95%) and mechanical property of the film	[169]
Persicaria minor extract	Persicaria minor	Semi refined carrageenan	Improved antioxidant activity due to persicaria minor extract	[170]
Pu-erh Tea extract	Tea leaves	furcellaran and gelatin	Tensile strength increased from 9.62 to 24.14 or 13.59 MPa after extract incorporation, antioxidant activity improved	[171]
Chive root extract	Chive root	Chitosan	Optical and mechanical properties improved	[172]
Bitter orange peel extract	Orange peel	Novel bioactive fiber/ Ethylene cellulose	The film exhibited good tensile strength and increased water contact angle	[173]
Litchi shell extract	Litchi shell waste	Guar gum/carboxymethylcellulose/Halloysite nanotube	With 20% of litchi shell extract, the antioxidant activity of film increased up to 91.52%. Roasted peanuts packed in the developed exhibited delayed oxidation reaction as compared to control film	[174]

packaging systems' effectiveness depends upon the release rate of active compounds and the oxidation mechanism of particular food constituents. If the release rate of active agents is uncontrolled, the effectiveness evaluation of antioxidant mechanism can be difficult. The antioxidant packaging films or coating has three parts: packaging matrix, active components, and the food material. The significant migration activity of active components is diffusion in the polymer matrix, releasing from packaging material to food surface, and distribution between molecular level inside food constituents. The selection of a suitable packaging matrix to incorporate the active agents depends upon the molecular structure, polarity, and releasing property of the packaging system. Active compounds diffuse through the polymer to the food surface and promote numerous chemical and biological reactions inside the food. With the myriad of synthetic and natural antioxidant compounds, it is difficult to explain a single molecular mechanism to account for their antioxidant activity [26].

The primary pathway to lipid peroxidation involves a chain of self-catalytic free radicals' reactions from initiation to propagation to termination as shown in Eq. (1) to (5), where R refers to the lipid alkyl group [27, 28].

$$\textbf{Initiation}: RH \rightarrow R^* + H^* ----------- \quad (1)$$

$$\textbf{Propagation}: R^* + O_2 \rightarrow ROO^* ---------- \quad (2)$$

$$ROO^* + RH \rightarrow ROOH + R^* ------ \quad (3)$$

$$\textbf{Termination}: ROO^* + R^* \rightarrow ROOR -------- \quad (4)$$

$$R^* + R^* \rightarrow RR ----------- \quad (5)$$

External factors such as moisture, light, oxygen, inherent free radicals, and metal ions influence the initial radicalization of peroxidase, fatty acids, and glycerol, as shown in Eq. (1). Then autoxidation occurs at the propagation stage, as in Eqs. (2) and (3), with lipid radical oxidation or peroxide radicalization of high lipid foods. Further, at the termination stage, the lipid-free radicals may recombine with peroxide radicals as in Eq. (4) or with themselves as in Eq. (5) [29]. The antioxidant prevents undesirable lipid oxidation; chemical compounds containing polyphenols and phenolic derivatives or organic sulfides are the antioxidants most frequently used. They turn in to serve as radical scavengers, which prevents photo or thermal degradation of many organics and polymeric materials [30]. Chemical reaction Eq. (6) to (12) explains antioxidation reaction with free radicals, where AH refers to antioxidant molecules.

Radical/AO

$$ROO^* + AH \rightarrow ROOH + A^* ------ \quad (6)$$

$$R^* + AH \rightarrow RH + A^* ---------- \quad (7)$$

$$RO^* + AH \rightarrow ROH + A^* -------- \quad (8)$$

$$ROO^* + A^* \rightarrow ROOA ---------- \quad (9)$$

$$RO^* + A^* \rightarrow ROA ----------- \quad (10)$$

$$A^* + A^* \rightarrow A - A ----------- \quad (11)$$

From all the above equations, the antioxidant mechanism involves scavenging reactive oxygen and nitrogen-free radical species, hence decreasing the free radicals in Eqs. (6) to (8) and antioxidant combination shown in Eqs. (9) and (10). Antioxidant activity is inhibited by these reactions, which degrade lipid peroxidase into non-radical products and chelate metal ions [31]. Active packaging is an innovative way to prevent oxidation without adding any antioxidant additive directly to food. The incorporation of active components in the packaging matrix (synthetic or natural) and its release to the contained food in a controlled manner is depicted in Fig. 3 illustrates the antioxidant mechanism of packaging material.

2.3 Sources of natural antimicrobials

Consumers' preferences change over periods, becoming more conscious about the safety parameters and nutritional content. Over the last decades, food quality and safety concerns have arisen due to the increased foodborne outbreak caused by pathogenic organisms. Therefore, it needs to seek alternative methods of food preservation rather than chemical and artificial antimicrobial methods. Much fresh produce contains natural components with antimicrobial activity [32]. Consumer demands have increased recently for premium quality food with high nutrients. The need to use natural preservation systems or preservatives to remove or destroy the pathogenic organisms is a major requirement at present, where the synthetic preservative has dominated now. For these reasons, preservatives from natural sources such as plants, animals, and microflora have come into trend now [12]. The active material in the packaging can play a vital role in extending the shelf life of foods when applied to the biopolymer matrix. The antimicrobial agents from natural sources are gaining considerable attention; search for combined interaction of two or more factors would be beneficial to control the microbial growth in the food. Spices and herbs are the reservoirs of antimicrobial effects against gram-positive pathogens like *Listeria monocytogenes.* The active compounds from the spices and herbs can extend the storage time considerably with their antimicrobial and antioxidant effects, such as aldehyde, ketone, esters, and

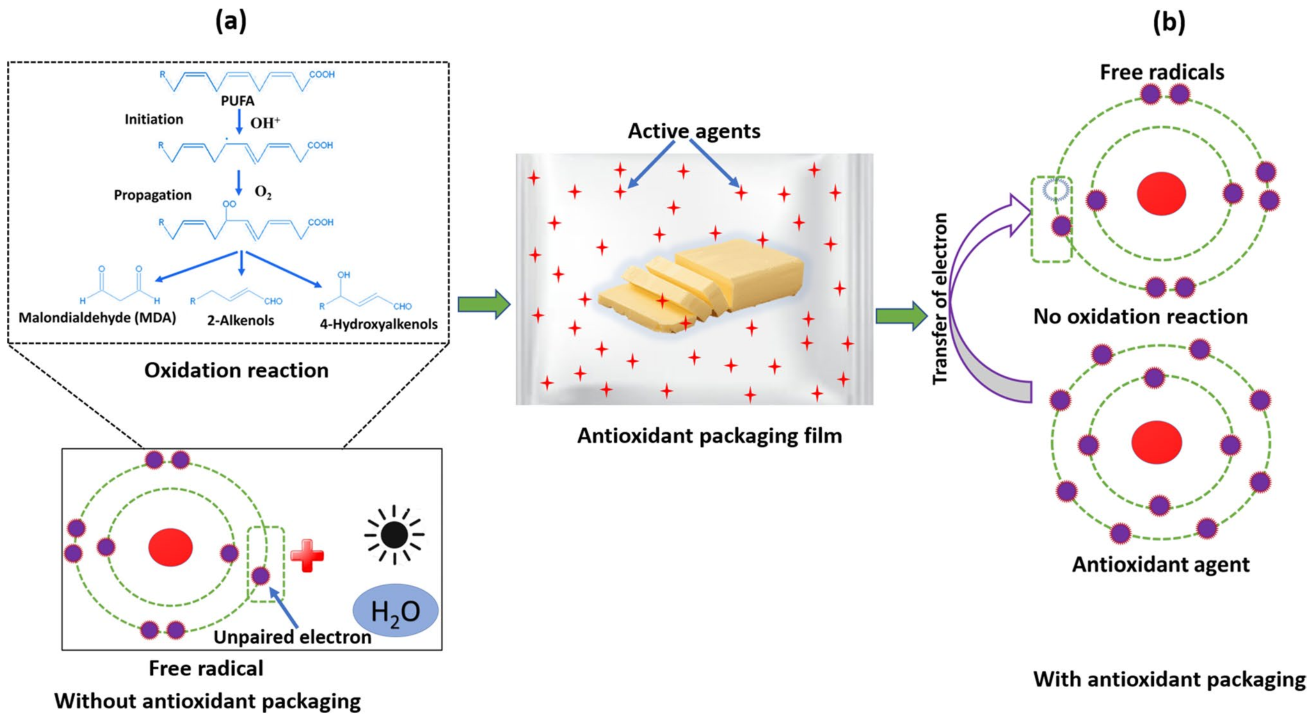


Fig. 3 Representation of oxidation and antioxidant mechanism (a) oxidation mechanism before inclusion of antioxidant compounds into packaging materials and (b) after inclusion of natural antioxidant compounds in packaging material for food applications

hydrocarbon in the onion, garlic, and cinnamon. The first evidence on the preservative effect of spice was found in the 1880s, and they observed the antimicrobial action of cinnamon oil against spores of *Bacillus anthracis* [32]. The antimicrobial action of major herbs and spices found against the bacteria, molds, and yeast was found considerably [33]. The extract of bell pepper hydrosols, rosemary, and bay leaves exhibited the antimicrobial effect against the vegetative cells of pathogenic organisms [34, 35]. Spices and herbs were categorized according to their effectiveness as strong (cinnamon, clove, and mustard), medium (coriander, cumin, thyme), and weak (ginger, black pepper) [36]. Ethanol and hexane extracts of different plants and herbs have shown potential antimicrobial action against *Listeria innocua, S. aureus*, and *P. fluorescence* [37]. Extraction of the active components through aqueous solvent extraction has lower antimicrobial activity against bacteria such as *Bacillus fastidious*, *S. choleraesuis, K. pneumoniae*, and *P. aeruginosa* at a different strength. (1:1, 1:5, and 1:20) [38]. Green tea components have an antibacterial effect against *B. cereus* and *L. monocytogenes*, and rosemary shows strong inhibition against *B. cereus* in soy broth solution [39]. Plant extracts with a mixed composition of cinnamon, rosemary, and clove oil exhibited a significant antimicrobial effect in vacuum-packed fresh pork from 1.81 to 2.32 log reduction during the storage period with the control sample [40]. Dried oregano powder and lemon were combined to reduce microbial degradation during 12 days of storage at refrigeration temperature [41]. Table 2 shows the investigated antimicrobial agents to food preservation either directly or with the packaging film or coatings. Food quality and safety are affected by physicochemical and microbiological factors. Food must be protected from microbiological invasion because microbiological factors are responsible for most physicochemical changes in food. The use of food additives from natural origin involves different steps such as extraction, isolation, filtration, stabilization, and incorporation of these antimicrobial agents into the food and/or food packaging film or coating. At the same time, it is expected not to affect adversely the sensory properties, nutrition, and its health promoting elements.

2.4 Antimicrobial mechanism of natural compounds

Microbial proliferation reduces the product's quality and safety. The microbial population accelerates the creation of off-odors, and changes in aroma, color, and texture can also occur. Furthermore, several secondary pathogenic bacteria and toxins can produce severe foodborne outbreaks. Effective preventive measures and intelligent preservation technologies have been implemented to reduce food spoilage and extend food shelf life. Packaging materials, biodegradable, edible films, and coating can be incorporated with natural

Table 2 The summary of natural antimicrobial agents incorporated for the antimicrobial biopolymer food packaging application

Biopolymer Matrix	Antimicrobial agent	Observations	Reference
Polylactic acid	Pediocin	Active agents added polylactic acid (PLA) film reduced the growth of *L. monocytogenes*' growth when raw pork was packed	[175]
Pectin and Polylactic acid	Nisin	Pectin-polylactic acid composite film having nisin as antimicrobial agents reduce the growth of *L. monocytogenes* in growth medium and food products	[176]
Biodegradable bacterial cellulose	Sorbic acid	Antimicrobial film was effective against the growth of Escherichia coli	[177]
Hydroxypropyl methylcellulose	Ethanol, citric acid	Active coating inhibits the growth of *S. Montevideo* and maintains the quality of tomatoes up to 18 days	[178]
Alginate	Nisin	Nisin inhibits the growth of *S. aureus* when alginate-nisin based films are used to pack the sterile beef	[179]
Chitosan	Lactic acid	Chitosan-lactic acid-based films have high antimicrobial activities against the *Bacillus subtilis*	[180]
Zein protein	Sorbic acid	When sweet corn is coated with zein-sorbic acid-based coating, it controls the population of *L. monocytogenes* for 8 days	[181]
Protein-polysaccharide composite	Nisin	Composite films with nisin as an antimicrobial agent inhibit the growth of microorganisms (S*almonella spp.*) on the fresh skin of broiler/chicken	[182]
Carrageenan	Nisin and lysozyme	Carrageenan based biopolymeric films were effective against pathogens and food spoilage bacteria	[183]
Polylactic acid/ polyhydroxy butyrate	Citrus peel extract	Exhibited excellent antimicrobial effect against *S. aureus*	[184]
Chitosan	Procyanidins	Antimicrobial effect against foodborne pathogenic organism	[185]
Pullulan and carboxylated cellulose	Tea polyphenols	Antioxidant, antimicrobial, and UV-barrier properties	[186]
Oxidized cellulose	Nisin	Good antimicrobial activity against *Alicylocacillus acidoterrestris*	[187]
Sodium caseinate	Matricaria recutita essential oil	Potential antimicrobial activity against *Staphylococcus aureus*, and *E. coli*	[188]
Alginate	Clove, cinnamon, and marjoram oil	Showed antimicrobial inhibition against *E. coli, S. aureus*, and *L. monocytogenes*	[189]
Bio-based zein	Cinnamon essential oil	Growth reduction of *E. coli* and *S. aureus*	[190]
Nano-emulsion	Thyme and lemongrass oil	*E. coli* and *Listeria innocua*	[191]
Chitosan/nano clay nanocomposite	Rosemary essential oil	Total reduction 1.2 to 2.1 log CFU/g for fresh poultry meat storage	[192]
Carboxymethyl cellulose/agar biocomposite	Summer savory sensory oil	Showed good antibacterial activity against gram-positive (*B. cereus*) and gram-negative bacteria (*E. coli*)	[193]
Polyvinylalcohol/Polyethylene glycol	Thyme essential oil	Antibacterial effect against *E. coli.* and *S. aureus*	[194]

antimicrobial compounds to inhibit microbial growth. The packaging materials serve as a carrier of antimicrobials to be released effectively into the food to inhibit microbial growth and prolong the shelf life, maintain quality, assure the safety of produces. They can decelerate the release of antimicrobial substances through controlled release strategies. Over the past several years, a wide range of antimicrobials has been incorporated into packaging polymers. Among chemical additives, natural antimicrobials can give bioactive packaging characteristics that could be very attractive for consumers [42]. Antimicrobial packaging systems modify the internal atmosphere of the package by continuous interaction with food constituents over the storage period. Physical, chemical, and biological factors influence the diffusion of antimicrobial chemicals through packaging materials [43]. The antimicrobial action of antimicrobial packaging is based on the lag phase extension and decreased live cell number of target bacteria. Antimicrobial packaging protects against bacterial infection and fungal, yeast, or sporulation on meat, dairy, and fresh fruits and vegetables. Although, the inhibitory effect may vary from species to species according to their unique antimicrobial action mechanism and variation in microorganism's physiology. Understanding the antimicrobial action of these agents can assist in determining antimicrobial efficacy and its inhibitory effects [44, 45]. The exact mechanism of antimicrobial activity is yet to be precise. The natural source compounds possess diverse structures, and the antimicrobial activity against the microorganisms depends on their structural configuration. The phenolic group contains hydroxyl groups in the structural units, which cause inhibitory activity against the microorganisms as they interact with the cell membrane of target bacteria to disrupt membrane structure and cause leakage of cellular components [46]. A specific mechanism of plant-sourced antimicrobial agents is destabilizing the cytoplasmic membrane by -OH groups, which serves as proton exchanger that leads to lower pH gradient across the cytoplasmic membrane and lead to cell death. Another explanation of the antimicrobial action of plant-derived natural antimicrobial agents could be the position of the -OH substitution in the aromatic ring and the length of the saturated chain. The size of the alkyl or alkenyl group also affects the antimicrobial activity of a compound. The alkyl groups associated with the double bond between two carbon atom, which has a high electronegativity, interfere with electron transfer and react with protein and nucleic acid, thus improving antimicrobial activity [47]. The phenolic structure in EOs plays a significant role in antimicrobial action. The active groups in the EOs are critical for their antimicrobial activity, such as -OH group and allylic acid chains enhance the EOs antimicrobial efficacy [48]. Acetate moieties in the EOs also positively correlated to the antioxidant activity of different plant extracts. The antimicrobial action of any active compound does not depend only on the chemical constituents but also on the potential of aqueous solubility or lipophilic potency. These properties involve in the membrane disruption by lipophilic compounds lead to hindrance of electron transport, protein translocation, and other metabolic activity, which ultimately destroy the cell membrane integrity in the death of microorganisms. The natural compound's antimicrobial activity may differ depending on the type of microorganisms, extraction method, culture medium, inoculum size, and determination method [32].

The effectiveness and efficiency depend on the antimicrobial agents' concentration [49]. At lower concentrations, the polyphenols affect enzyme activity associated with energy generation, while it causes protein degradation at higher concentrations. The ability of an antimicrobial compound to modify cell permeability causes interference in cell membrane function (electron transport, food uptake, protein, DNA production, and enzyme activity), ultimately changing the structure and functionality of the cell [12, 50]. Natural antimicrobial agents' activity can be further clarified regarding alkyl substitution into phenol nucleus [48]. The antibacterial action of isothiocyanate is initiated by the oxidative breakdown of disulfide bonds in extracellular enzymes. Thymol and carvacrol have been shown to affect intracellular adenosine triphosphate (ATP) production and plasma membrane disruption in *E. coli O 157:H7* cells [51, 52]. The disruption of numerous enzyme systems, such as energy generation and structural component synthesis, is related to yeast inactivation [53]. The antimicrobial mechanism of antimicrobial packaging is well explained in graphical illustration Fig. 4.

3 Plant extracts as antioxidant and antimicrobial compounds

3.1 Essential oil

Essential oils (EOs) are secondary metabolites with a volatile nature, synthesized from different plants such as herbs spices through various extraction processes. Like many other metabolites, they possess numerous bioactivity that has been utilized for centuries by humankind. EOs are complex molecules that have been used primarily for pharmacological, medicinal, aromatic, and cosmetic purposes. They have been used in food science and nutrition since the ninteenth century due to their high bioactivity as antioxidants, antimicrobials, antifungals, and antivirals [54]. The activity of the EOs depends upon the chemical constituents of spices or herbs, the collection area, and the extraction process and solvents. Previously these compounds have been explored as aroma and flavor ingredients and as a preservative for some foods. The possibility of EOs as an active component in developing a packaging system is promising as it contains natural bioactive compounds, which reduces the food safety risks associated with chemical or artificial additives [55, 56]. At present, EOs application in the development of food packaging film or coating is firmly correlated to their application into the biodegradable or edible film in amalgamation with protein-polysaccharide-lipid multi-composite system [57]. Therefore, incorporating EOs came in trend because this enhances the antioxidant and antimicrobial activity and reduces the developed film's water permeability. These EOs are incorporated as active agents [58]. Essential oils are combined with different edible or biodegradable polymers. Papers and wooden packaging material were traditionally used, but active cardboard trays coated with emulsion

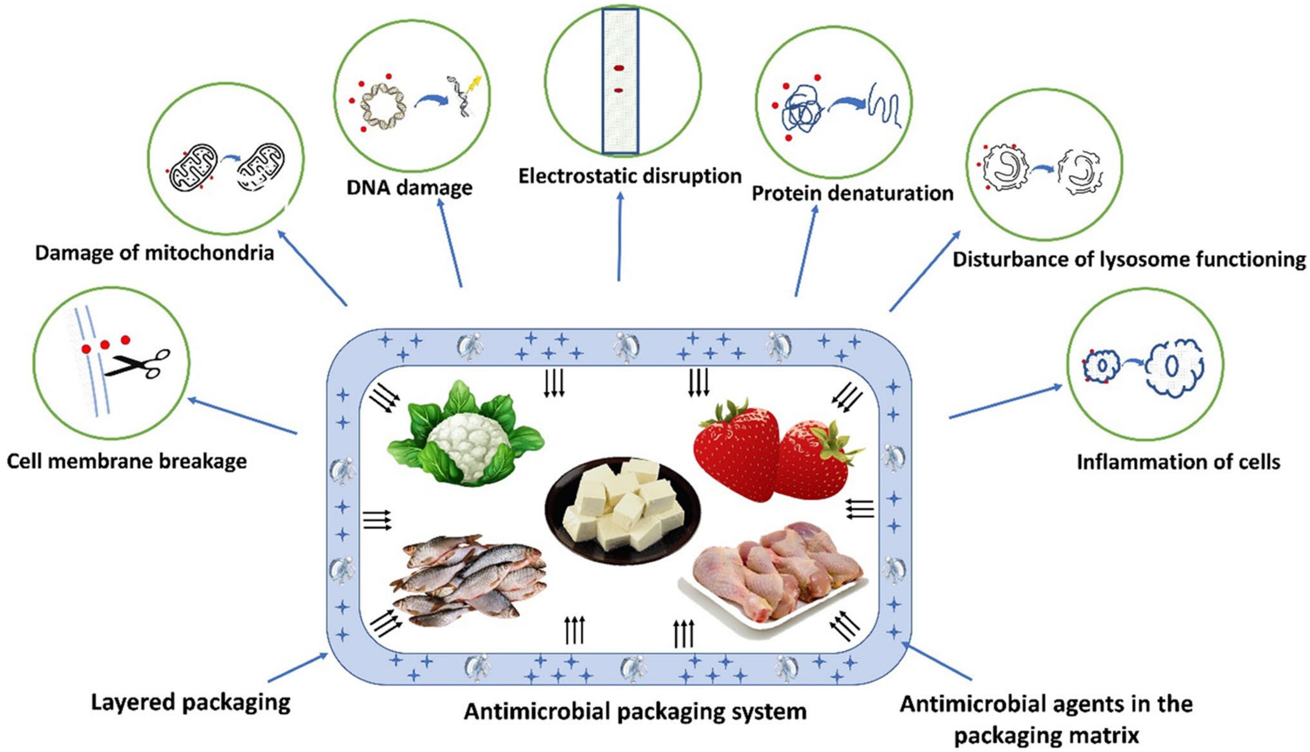


Fig. 4 Schematic illustration of antimicrobial mechanism of packaging material containing natural antimicrobial compounds for food applications

blended with EOs continuously manufactured. These are popular for fruit and vegetable produce with waterproof layers and are considered an alternative to plastic caret material [59]. EOs such as citronella, tea compounds, oregano, cinnamon, clove, peppermint, rosemary, lemongrass, etc., are plant-derived compounds that have potential inhibitory action against a broad range of spoiling microorganisms.

3.2 Polyphenols

Polyphenols are universally found in different plant parts such as peel, leaves, pomace, stem, roots, etc. Their functionality and chemical structure are diverse, which has promoted incorporating into the packaging system. Polyphenols found in plant sources include phenolic acid (hydroxybenzoic acids and hydroxycinnamic acids), flavonoids (flavonols, flavones, flavanols, flavanones, isoflavones, proanthocyanidins), polyphenolic amides, resveratrol, and lignans [60]. Plant extracts are rich in polyphenol content, which are incorporated into the food product to conceal the undesirable color and flavor or promote the desirable quality of food products and nutritional and functional properties. One use is the incorporation of polyphenols into edible films and coatings, such as polysaccharide-protein-lipid-based food packaging solutions [61]. Phenolic compounds are employed as functional agents such as antioxidants and antimicrobial in the biodegradable and edible polymers, exhibiting an excellent opportunity to provide longer storage life. It is applied to direct contact or indirect with the packaging film surface. Polyphenols are a vast range of compounds found in most plant parts, such as leaves, stem, bark, seed, fruit, peel, pulp, and pomace. However, the efficiency determination of polyphenols in food or food packaging needs to be evaluated case by case [62]. There are different ways to incorporate the phenolic compounds into the packaging system, as illustrated in Fig. 1.

3.3 Flavonoids, flavones, and flavonols

Flavonoids or flavones have a similar chemical structure as phenols except for having a carbonyl group. Generally, flavonoids contain three hydroxyl groups and hydroxylated phenolic compounds in some flavones with a C_6-C_3 bond in the aromatic ring [61]. Flavonoids are abundant in nature, such as fruits, flowers, seeds, stems, honey, propolis, vegetables, tea, and wines. Since ancient ages, these compounds have been used as physiologically active substances to treat human diseases. Furthermore, with an exploration of these constituent's properties, the antioxidant, antimicrobial, anti-infective, antiviral, and antifungal activities have been observed [63–65]. Flavonoids are biosynthetic origins like chalcones, flavanones, flavan-3-ols, and flavan-3,4-diols. Their intermediates products in the biosynthetic process are anthocyanidins, proanthocyanins, flavones, and flavanols, which possess the antioxidant and antimicrobial for different applications [66, 67].

3.4 Tannins

Tannins are water-soluble polyphenols from higher herbaceous and woody plants such as leaves, stems, bark, wood, roots, and seeds [68, 69]. They can be classified into two categories such as hydrolyzable, non-hydrolyzable (condense), complex tannins, and phlorotannin [70]. These compounds are normally present diet of animals; nonetheless, only a few of these are consumed by the human diet because the containing of these compounds is limited edible parts of the plants, or they are not consumed at all. Due to this reason, tannins are extracted from wood and bark, normally applied in leather tanning, but now new fields of application have been explored as food sector, among others. Beverages that contain tannins such as green tea and red wines constituents can give remedial support to many diseases [70]. As a result of unique chemical properties, tannins extracts possess astringency and bitterness, which most recognizable mouthfeel for many food products are used to improve food quality by several modes of action and in a wide variety of products. Antimicrobial properties of tannin involved several mechanisms, including metal chelation (iron), interaction with protein and cell membrane for structural decomposition, and enzyme inhibition. Gram positive bacterial cells are more prone to the effect of the tannins; however, it is also effective against gram-positive bacteria, viruses, and parasites [68]. Commercialized tannins of wood extract and castalagin from chestnut had antimicrobial effects against pathogenic bacteria such as E. coli., staphylococcus aureus, Salmonella typhimurium, Vibrio spp. Etc [71, 72]. Tannins are approved as generally recognized as safe (GRAS) category to utilize as food additive compounds approved by the US "Food and Drug Administration (FDA)." Therefore, tannins properties such as antioxidant, antimicrobial/antifungal activity, and UV absorption present their potential for functional food packaging application [73, 74]. Condensed tannins have been successfully applied to Polylactic acid (PLA) film and found that high crystallization, thermal and textural improvement. Polyvinyl alcohol (PVA) with condensed tannins showed high antioxidant activity and UV barrier properties [75, 76]. Tannins have good compatibility with polysaccharides and can be used against bacteria, yeast, fungi [70].

3.5 Quinone

Quinones have an aromatic ring structure with two ketone substitutes and color alteration (browning, darkening) in fruits and vegetables. Coenzyme such as ubiquinone has the primary role in the electron transport system, whereas naphthoquinone (Vit K), a free radical, quinones bind irreversibly with nucleophilic amino acid in protein causing inactivation and loss of functions. Therefore, quinone has a potential antimicrobial effect when the surface adhesion is exposed to cell wall polypeptide and membrane-bound enzymes [77, 78]. Naphthoquinones (plumbagin) have shown inhibition efflux and antimicrobial effect against gram-negative bacteria [79].

3.6 Coumarin

Coumarin is also a phenolic compound constituent of benzene and a-pyrone ring. As of now, more than 1300 coumarins spp. have been identified. Warfarin is the most used oral coagulant, vasodilatory, and anti-inflammatory activity. It shows antimicrobial effects against *C. Albicans* and effective against bacterial infections. Pure coumarin exhibited modest activity against bacteria, yeast, and mold [80]. Antioxidant effect of the coumarin observed in chitosan and fish gelatin with coumarin, the free radical's formation occurs in the film containing compared to the control film [81]. The utilization of coumarin compound in active packaging has not been explored compared to other agents, which gives a promising opportunity to explore and exhibit its active properties.

3.7 Enzymes

Enzymes are proteinaceous material found in all living cells, whether plants or animals. They act as biological catalysts, which promote the biological process in the cells. The first characteristic of enzymes is their catalytic power, as they can accelerate the chemical and biological reaction that occurs in the system. Secondly, the enzymes are specific; for example, they don't contribute to the chemical reaction as substrate but can alter the reaction rate. Moreover, a particular enzyme is required to optimize the reaction process [82]. Enzymes have many applications in almost all science and biotechnology areas, especially in the food industry, such as catalysts, oxygen scavengers, and antimicrobial for different applications. In food packaging, enzymes can play a vital role inbound or entrapping chemical components in films or sachets. Depending upon the mechanism of action, enzymes are entirely immobilized into the packaging materials or released into the food. Immobilization of enzymes shows a safer application in the migration of the active components from packaging matrix to food because enzymes do not leach from package to food [83]. Active food packaging incorporated with one more enzyme provides synergistic action of preserving the food. The key variation will be the enzyme is not altered by the reaction and can continue to function indefinitely. However, temperature and pH are two important factors that can affect the effectiveness of the enzyme in a packaging matrix [84].

4 Active components from microorganisms

4.1 Bacteriocins and nisin

Antimicrobial agents generated from bacterial cells called bacteriocins are getting popularity due to their ability to tolerate high temperatures and acidic environments. These are just metabolic by-products such as antimicrobial peptides generated by bacterial defense systems from the bacterial cell [44]. Bacteriocins can inhibit the growth of microorganisms, especially gram-positive bacteria; they destabilize the cytoplasmic membrane of bacteria when contact with the cell's surface [85]. Bacteriocin from the lactic acid bacteria source has higher acceptance due to its application in fermentation for different dairy and alcoholic based product manufacturing applications. Nisin is produced by *Lactococcus lactic* bacteria, generally present in milk is approved by FDA and GRAS [86]. However, there are investigations available that demonstrate that many other bacteriocins such as lacticins, pediocin, and propionicins have been explored as antimicrobial agents in many food applications [87].

4.2 Pediocin

In an aqueous solution, pediocin has a random coil structure; however, pediocin has a partially helical structure with varied hydrophobicity levels in a nonaqueous solution. It primarily comprises two regions: an N-terminal hydrophilic cationic area and a C-terminal hydrophobic/amphiphilic region [88]. The structure of pediocin is intimately related to its antibacterial function, which involves the generation of spores in the targeted membrane. Results in minor efflux, intracellular chemicals, cytoplasmic ATP depletion, proton motive force dissociation, and, eventually, cell death [89]. Pediocin incorporation on the cellulosic packaging material exhibited antimicrobial action against *Listeria innoucua* and *L. monocytogenes* [90]. Another study where nanocomposite developed with methylcellulose incorporated with pediocin and zinc oxide nanoparticle (nano ZnO) showed stability against *staphylococcus aureus* and *Listeria monocytogenes* with improvement in physicochemical properties of the developed film [91].

4.3 Reuterin

Reuterin is produced using the *Lactobacillus app.*, which is produced in the fatty acid with the help of glycerol. It is effective against several pathogenic and spoilage organisms [42]. It exerts bacteriostatic action towards *L. monocytogenes*, *Campylobacter jejuni*, *S. aureus*, and *E. coli O157:H7* [92]. Pectin utilized as edible coating with the lemon essential oils demonstrated high antimicrobial activity for storing cold-stored strawberries. Compared to control treatment, it reduced viable penicillium spp conidia considerably (more than two logarithmic cycles) [93]. The antimicrobial action of reuterin is not explored thoroughly. Evidence express that aldehyde content in the reuterin could react with the sulfhydryl group of microorganisms' essential biomolecules. Another explanation could be the broad action of the dimeric form of reuterin could inhibit DNA synthesis and eventually kill the microorganisms [94, 95]. There are contradictions between the available investigation and the active ingredients in the packaging film or coating. Some findings showed the adverse effect on the physical appearance of fresh-cut produce such as lettuce. In contrast, other studies suggest that reuterin with an essential oil does not have a physical appearance on the fresh-cut lettuce [96]. However, reuterin might be a potential food preservative and possible antimicrobial application due to its vast action mechanism, high-temperature resistance, water solubility, and wide pH range.

4.4 Bacteriophage

Bacteriophage is found in large amounts on the earth and is widely available in many food commodities. It can be sufficiently used as preservatives for foods to inhibit microbial colonies, control diseases in animals, and disinfection of raw products such as meat, fruits, and vegetables [97]. Investigations revealed bacteriophages against *Salmonella* and *Campylobacter spp*. in chicken and pathogenic *E. coli* in ruminant animals [98, 99]

4.5 Organic acid and salts

The food preservation and processing approaches have been extensively explored by utilizing salts and organic acids. Some organic acids are the most used preservative for many foods such as fruits, vegetables, and processed food such as jam, jelly, and beverages. Acetic, benzoic, citric, fumaric, malic, propionic, and sorbic acid are the commonly utilized organic acid in food preservation [100]. These approaches depend upon the pH-dependent equilibrium between the dissociate and undissociated weak organic acids. The maximum inhibitory action of acids acquired at low pH, when the cell membranes are an uncharged and dissociated form of acids, can diffuse quickly across the cell membrane, which results in cytoplasmic destruction [101]. Weak acids are not specific antimicrobial against the bacterial cell and fungus. Gram-negative bacteria are less susceptible to weak acids due to their outer membrane layer, which protects them from the antimicrobial action of acids. Nowadays, their application as an antimicrobial packaging material is less common due to their deactivation in different packaging development processes such as extrusion, casting, and coating [102].

5 Active components from an animal source

5.1 Chitosan

Chitosan is a linear polysaccharide having the bond of (1, 4)-linked with 2-amino-deoxy-β-D-glucan, a chitin derivative, which is the second most abundantly found polysaccharide in nature after cellulose. Chitosan is non-toxic, biodegradable, and, most important biocompatible to have antimicrobial characteristics [103]. Chitosan is mainly obtained from the food waste of marine products (exoskeleton) of crustacean shells. Chitosan outperforms other biobased packaging films in terms of its ability to contain valuable components such as minerals or vitamins, as well as its antibacterial action. As a result, chitosan has been utilized as a packaging material to improve the integrity of stored containers of various foods [104]. Chitosan acts as an antimicrobial agent due to the positive charge amino acid group, which might interact with the negatively charged pathogenic cell membrane, causing protein and other intracellular elements to leach out [105, 106].

5.2 Lysozyme

Lysozyme is, also known as muramidase or N-acetylmuranic hydrolase, is a small, monomeric protein liked with disulfide linkages among the eight cysteine residues of its polypeptide chain [107]. Lysozymes are natural components found in animals that are effective against microorganisms. They are regarded as GRAS and can be included in the food matrix and application [108]. The antimicrobial effect of the lysozyme against several pathogenic and spoilage bacteria has been experienced in previous investigations with great potential to inhibit gram-positive bacteria like bacillus *stearothermophilus spp., clostridium spp., and micrococcus spp.* Because their cell wall comprises 90% of peptidoglycan, rather than the gram-negative bacteria, which is merely 5–10% of cell wall [109]. Lysozyme is immobilized onto the polymeric material and acts directly from the polymeric packaging film without being released onto the packed food matrix. The antimicrobial effect of developed lysozyme immobilized polyvinyl alcohol (PVOH) film has shown significant inhibition against selective spoilage organisms [110]. In another study where lysozyme from an egg has been incorporated into the PVOH, nylon, and cellulose acetate films and notices the antimicrobial action against the spoilage organisms such as micrococcus spp [111].

5.3 Lactoferrin

Lactoferrin is a natural antimicrobial compound found in milk, applied to control or prevent the growth of spoilage and pathogenic cells in processed foods. This compound has an additional functional activity like antioxidant, anticarcinogenic, and antibiotic, which present the lactoferrin as a multifunctional component [112]. Antibacterial action of lactoferrin against gram-positive and gram-negative bacteria, viruses, and fungi has been well documented. Lactoferrin's function depends on its ability to bind iron ions, which results in iron deficiency, which restricts bacterial development [113]. Lactoferrin is often included in the included antimicrobial for incorporation into the packaging films and coating solution, but only a few investigations are listed previously. The antimicrobial action has an impact due to the presence of Na^+, which shifts the activity from bactericidal to bacteriostatic [44]. To protect the activity of the lactoferrin, microcapsules are incorporated in whey protein isolate biopolymer. The developed film of lactoferrin-based packaging film applied on the surface of bologna slices stored for 28 days and found microbial growth delayed compared to no encapsulated sample [114].

5.4 Lactoperoxidase

Lactoperoxidase (LPS) is another animal-based active component; cow milk and epithelial secretion contain many LPS. Mammalian LPS are unique from the plant LPS in size, amino acid composition, prosthetic groups, and the binding nature of the prosthetic group to the protein [115]. LPS catalyzes the thiocyanate ion (SCN^-) and generates oxidized products such as hypothyocyanates ($OSCN^-$) and hypothiocyanous acid (HOSCN). These oxidized products in the lactoperoxidase system are known to have antimicrobial activity through the oxidation of sulfhydryl (SH) groups of the host–pathogen enzyme and proteins [116, 117]. The active functional activities of the LPS have shown its potential application in food applications.

6 Incorporation methods for active agents in packaging

6.1 Addition of sachets into a food package

Including a sachet in a food item has proved appropriate for volatile antibacterial agents. There will be no direct contact between the food and the compounds; instead, the volatile antimicrobial compounds are discharged into the package headspace, inhibiting germs' growth [118]. Adding a sachet inside the food package is the most successful commercial application of an antimicrobial packaging system. The principle of the carrier or emitting sachet involves the adsorption of the antimicrobial agent into the enclosed packaging environment. The sachet is placed along with the food packed in the packaging bags or container and separated from the outside environment [119]. The antimicrobial agents are enclosed in loose sachets or attached to the interior of the package, as shown in Fig. 2.

6.2 Antimicrobial agents' incorporation into the polymer matrix

Active antimicrobial compounds are incorporated into the packaging matrix by extrusion heating, heat-press, or solution casting methods. It has potential commercial application in pharmaceutical drugs and insecticide delivery, household appliances, textiles, medical appliances. The main setback in this method is antimicrobial activity diminished due to high heat treatment due to methods like extrusion, heat-press, etc. [28]. Enzymes, as antimicrobial agents like lactoferrin, lysozymes, and lactoperoxidase, and some peptides such as magainins, cecropins, natural phenols, etc., have wide application in the packaging, particularly polymer fabrication [120]. Biodegradable and edible films incorporated with nisin or lysozymes inhibit bacterial infection like *E. coli* when blended with the chelating agent such as ethylene diamine tetra acetic acid (EDTA) [121]. Clove essential oil (CEO) loaded with chitosan-ZnO nanoparticles developed film shows antimicrobial activity against *P. aeruginosa, S. aureus,* and *E. coli*. [122], chitosan-thyme essential oil composite films [123], eucalyptus globulus essential oil (EGO) in chitosan composite film as the antimicrobial film showed inhibition of microorganisms [124].

6.3 Coating or adsorption on polymer substrate

The coating of fruits and vegetables with an antimicrobial agent blended with different additives is in early development. Different active agents which act as antimicrobial agents to inhibit the growth of microorganisms are added into waxes or coating material to dip the fresh produce commodity [125]. Antimicrobial active compounds that can not withstand high temperatures used in polymer processing are usually applied as coating the produces. Casting on the edible and biodegradable films used as a carrier for antimicrobial and implied as primary contact layer in the food packaging films [126]. Edible coatings are thin layers of edible materials that could be consumed or removed as per consumers' choice, as shown in Fig. 2. Their biodegradability and edible nature are the two most important benefits, along with the ease of production availability at low cost and sustainability with all the environmental concerns [127]. For example, the essential oregano oil coated on the mango surface to reduces the *Salmonella enterica* and decrease the anthracnose disease [80], nanoemulsion coating with the antimicrobial agent on the kiwi fruit [128], vanillin as active compounds enhances the safety and shelf life of fresh-cut apples [129], gellan coatings were applied on the strawberries and quality improved during storage period [130].

6.4 Immobilization of antimicrobial compounds

Antimicrobial immobilization onto polymers or other materials has already been studied. The immobilization process happens in functional groups on antimicrobials and polymers. Enzymes, peptides, and organic acids could be examples of a functional group for antimicrobial agents to immobilize on the polymers [45, 131]. Polystyrene, acrylic acid, nylon, vinyl acetate, and ionomers are functional groups for polymers [132]. Released antimicrobial activity from the immobilized polymers or films highly depends on the bonding types, which allows slow release of active agents into the food. Both lysozyme and chitinase, which have been covalently immobilized using polymeric films, are efficient against gram-positive bacteria. When the enzyme glucose oxidase is covalently coupled to insoluble support that is compatible with packaging materials, it catalyzes the production of antimicrobial hydrogen peroxide from reaction mixtures of glucose and oxygen [133].

7 Food packaging applications

Antimicrobial and antioxidant agents can be utilized in several food-related applications, including as development of food packaging applications. Earlier, antimicrobial agents were intentionally utilized in food to inhibit microorganisms (molds, bacteria, and yeast) [12]. Antimicrobial agents in packaging accomplish threefold companion in protecting and preserving foods. First, and the most known, is to extend the shelf life by inhibiting the growth of all kinds of microorganisms by direct or indirect contact with the foods. Second, the packaging film or layers are self-sterilizing to reduce potential decontaminants from fresh and processed foods. The third is that antimicrobial polymers or films are used to protect the equipment most susceptible to the microorganisms like conveyors, packaging machines, fillers, gloves, etc. [131]. The antimicrobial agents applied in the food packaging application are selected based on various factors such as the activity of active agents, source of agent, method of extraction, the composition of active agent, rate of the microorganism's growth, mode of action, storage condition, and physiological condition of the microbes [44]. The effectiveness of antimicrobial packaging is generally compared to the direct incorporation of antimicrobial agents in food materials. The reasons behind this are the attachment of antimicrobial agents with polymer film or layer and, secondly, as preservative agent inactivation over a more extended period [134]. The rate of antimicrobial agent diffusion from the incorporated matrix to food is also a vital phenomenon [135]. The concentration of the active components in the packaging material affects the physical and functional properties of the developed material. Additionally, it imparts color and opacity to the polymers. Several findings on the incorporation of bioactive antioxidant and antimicrobial components into packaging material have been reported where the effectiveness of those components shows their great potential to inhibit the spoilage microorganisms and delay color, flavor, and staling effect of the fresh produces.

7.1 Fruits and vegetables

Fruits and vegetables are excellent nutrient reservoirs due to their high fiber, mineral, and vitamin content, but they decay quickly due to high moisture and water activity. They are highly susceptible to microbial influence because they are made up of living tissues, resulting in off-flavor, enzymatic browning, and texture degradation [136]. To address the issues raised by these unwanted changes in the characteristics of fruits and vegetables, to meet the ever-growing consumer demand, food packaging has developed various novel concepts for improving shelf life while maintaining the safety and quality of fresh products. Active packaging maintains the fresh produce quality by intervening in the metabolic process with alteration in the specially designed packaging environment. A package that preserves the food in such a way that it tackles the multiple elements that affect the quality and shelf life of packed foods, such as respiration, lipid oxidation, staling, dehydration, deterioration due to microbes, and pest infestation. These situations can be addressed in various ways by adopting appropriate active-packaging technologies. As a result, food spoilage can be reduced depending on the packed food requirement's nature [136]. To change the headspace conditions within the food container, active packaging systems frequently involve the scavenging of spoiling factors substances such as oxygen, carbon dioxide, ethylene, flavor/odor, and excessive water content. Other active packaging technologies incorporate active compounds into the packaging matrix, such as carbon dioxide, antioxidants, and antimicrobials, to emit them on the package environment or headspace. Fruits and vegetables are susceptible to microbial degradation due to physical damage during harvesting, transportation, packaging, and processing [137]. The initially mixed flora of microflora found in fruits and vegetables are *E. coli* and *Erwinia*. However, the primary cause of contamination of fruits and vegetables are yeasts, and molds, especially when stored under aerobically refrigeration conditions [138]. Antimicrobial packaging releases the active compounds in a controlled manner to the surface of food above the minimum inhibitory level required of the target microorganisms. They selected the optimum active packaging material as antimicrobial chemicals suitable with the packaging matrix. Antimicrobial chemicals should be selected from materials with intermediate polarity (hydrophilicity/hydrophobicity) that do not strongly interact with the packaging material when they attach to the matrix or are freed from it [139]. Antioxidant packaging development to stabilize the oxidation reaction could be brought together using antioxidant components of fruits and vegetables. Incorporating antioxidant components from natural sources like plants is the primary source of antioxidants for developing active packaging films. The antioxidant agents such as ascorbic acid, phenolic compounds, and carotenoids with another synergistic factor effect could be brought suitable packaging to the extent of the shelf life of fruits and vegetables [140].

7.2 Meat and fish products

The animal protein need for the human diet is met by meat and sea products, which comprise both fresh and processed meat and seafood. Because of microbial invasion, such as pathogenic organisms like Listeria monocytogenes, the quality of meat and fish products rapidly degrades, posing a huge challenge for the packaging sector to tackle the problem of microbial recontamination in diverse ready-to-eat foods [141]. The rapid quality degradation of meat and fish products is due to high fat and moisture content, making it vulnerable and prompt biological and chemical reactions such as lipid oxidation, protein denaturation/degradation, or decaying of the foods, limiting its shelf life. These reactions generate harmful, undesirable compounds that can alter the food's color, flavor, and taste, such as melanosis and melanin [142]. Intrinsic factors like pH, water activity, and the redox potential of fresh meat produce trigger the spoiling reactions. Meat and fish products generally have a water activity range from 0.85, which is considered a suitable environment for the growth of most microorganisms [143]. Meat processing and preservation have become compulsory for delivering meat products long-distance without affecting the physical, chemical, biological, and nutritional quality. Low-temperature storage, freezing, controlled water activity storage, brine solution, and using chemicals are the older and not safer way to preserve the quality of meat products. Active packaging such as antimicrobial and antioxidant agents in the polymer matrix, sachet, or immobilization in the film are growing techniques to prolong the quality of meat and fish products [144]. There are number of investigations available which confirm the effectiveness of antioxidant and antimicrobial film to extend the self-life. An increasing trend has been noticed in recent years by food processing sectors through replacing the traditional way of storage by implementing active packaging in the meat and fish product storage. As of now, the meat processing sectors understand the value of innovative preservation methods through the application of antimicrobial and antioxidant packaging that allow to maintain the quality and inhibit the spoilage microorganisms at the same time.

8 Challenges and future perspective

The consumer's awareness increased, and their expectations regarding food quality are also high; they expect proper packaging and sustainability. Therefore, packaging development must be considered raw material sources, biocompatibility, longevity, food preservation mechanism, disposal strategy, and environmental impact. When we discuss the active packaging of the products, the sources of the active components, such as antimicrobial and antioxidant components, are crucial [145]. The safety concerns, regulatory parameters, economic aspects, production capacity, commercial viability, sensory attributes, and, most important, consumer acceptance, are the main factors to be considered when active components are incorporated into the packaging matrix. Food products that come in direct contact with active packaging should be safe. To ensure their safety and wholesomeness, the regulatory requirement at various levels must be followed when the active packaging material is developed. In the USA, active packaging falls under the Federal Food, Drug, and Cosmetic Act (FFDCA), US of food and drug administrations (USFDA) [146]. The number of active compounds intentionally incorporated into the packaging film or sheets becomes part of the food, regulated as food additives, and classified under the GRAS category. Antimicrobial compounds incorporated into packaging fall under regulation 1282/2011 on active and intelligent material and articles intended to contact food amendment regulation 1935/590/EC and 1989/109/EC [147].

Polymer incorporated with active packages serves as an excellent reservoir for supplying the food system; still, much work needs to be done regarding its food packaging applications. As a function of real-time concentration, the kinetics of active components delivery to the food must be considered in packaging design. The extraction of the active components from the plant and animal host is also a great deal of discussion. The extraction method, solvents, drying, storage of the components for longer viabilities need to be discussed thoroughly. Health claims attributed to active packaging are rare due to various legal severe and standards constraints. Health claims require scientific evidence and authorization from the different legislative bodies. The most viable active packaging, such as antioxidant and antimicrobial packaging, can be produced with existing infrastructure and logistic systems. Active packaging has to be convenient and easy to use, so it can not interrupt consumers' lifestyles.

Future work should utilize the naturally available resources to reduce food spoilage and hazards. Natural resources have an abundant active ingredient, which can be extracted to be used in food processing and food packaging application. Scientists need to work on the commercial aspect of the natural components. The extraction, optimization, incorporation method, and concentration optimization are major future works in the active packaging application.

9 Conclusion

Active packaging in the food application is developing a great trust due to recent innovations in packaging design, packaging performance, material science, engineering, thermodynamics, and consumers' demands. Active packaging is receiving considerable attention as the new emerging technologies that can improve the quality, stability, and safety of food, reducing the chemical intervention in the food material and incorporating active compounds like antioxidants and antimicrobial bring remarkable assurance to the consumers. The authors in this communication mainly highlighted the natural derived antioxidant and antimicrobial compounds-based biopolymer. The active component's sources, mechanism of antioxidant and antimicrobial of those components discussed thoroughly. The natural sources of active compounds bring a safer and more sustainable approach to the food processing industry. Natural active components from plants, animals, microorganisms, enzymes, mushrooms, and bacteriophages act by lysis of cells, leading to ATP depletion and eventually causing cell death. At the same time, the new plant or animal resources can be turned into a great source of active compounds for the development of active packaging solutions. In conclusion, these naturally derived active compounds provide a great opportunity for advanced active food packaging development that is chemical-free, environment friendly and causes minimum or no side effects to human health. There are remarkable innovations in recent times for maintaining the quality of food products for longer shelf life. However, still, much work needs to establish a new normal for the upcoming generations.

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Declarations

Conflict of interest The authors declare no competing interests.

References

1. Mir SA, Dar BN, Wani AA, Shah MA (2018) Effect of plant extracts on the techno-functional properties of biodegradable packaging films. Trends Food Sci Technol 80:141–154. https://doi.org/10.1016/J.TIFS.2018.08.004
2. Attaran SA, Hassan A, Wahit MU (2017) Materials for food packaging applications based on bio-based polymer nanocomposites: A review. J Thermoplast Compos Mater 30:143–173. https://doi.org/10.1177/2F0892705715588801
3. Piergiovanni L, Limbo S (2016) Food packaging materials. Springer. https://doi.org/10.1007/978-3-319-24732-8
4. Shaikh S, Yaqoob M, Aggarwal P (2021) An overview of biodegradable packaging in food industry. Curr Res Food Sci 4:503–520. https://doi.org/10.1016/j.crfs.2021.07.005
5. Aryan Y, Yadav P, Samadder SR (2019) Life Cycle Assessment of the existing and proposed plastic waste management options in India: A case study. J Clean Prod 211:1268–1283. https://doi.org/10.1016/j.jclepro.2018.11.236
6. Luckachan GE, Pillai CKS (2011) Biodegradable polymers-a review on recent trends and emerging perspectives. J Polym Environ 19:637–676. https://doi.org/10.1007/s10924-011-0317-1
7. ASTM D (2004) 6400–04 Standard specification for compostable plastics. J ASTM Int, West Conshohocken, PA.
8. Li J-H, Miao J, Wu J-L et al (2014) Preparation and characterization of active gelatin-based films incorporated with natural antioxidants. Food Hydrocoll 37:166–173. https://doi.org/10.1016/j.foodhyd.2013.10.015
9. Siripatrawan U, Harte BR (2010) Physical properties and antioxidant activity of an active film from chitosan incorporated with green tea extract. Food Hydrocoll 24:770–775. https://doi.org/10.1016/j.foodhyd.2010.04.003
10. Guarda A, Rubilar JF, Miltz J, Galotto MJ (2011) The antimicrobial activity of microencapsulated thymol and carvacrol. Int J Food Microbiol 146:144–150. https://doi.org/10.1016/j.ijfoodmicro.2011.02.011
11. Ganiari S, Choulitoudi E, Oreopoulou V (2017) Edible and active films and coatings as carriers of natural antioxidants for lipid food. Trends Food Sci Technol 68:70–82. https://doi.org/10.1016/j.tifs.2017.08.009
12. Tiwari BK, Valdramidis VP, O'Donnell CP et al (2009) Application of natural antimicrobials for food preservation. J Agric Food Chem 57:5987–6000. https://doi.org/10.1021/jf900668n
13. Oroian M, Escriche I (2015) Antioxidants: Characterization, natural sources, extraction and analysis. Food Res Int 74:10–36. https://doi.org/10.1016/j.foodres.2015.04.018
14. Barbosa-Pereira L, Cruz JM, Sendón R et al (2013) Development of antioxidant active films containing tocopherols to extend the shelf life of fish. Food Control 31:236–243. https://doi.org/10.1016/j.foodcont.2012.09.036
15. Gómez-Estaca J, López-de-Dicastillo C, Hernández-Muñoz P et al (2014) Advances in antioxidant active food packaging. Trends Food Sci Technol 35:42–51. https://doi.org/10.1016/j.tifs.2013.10.008
16. Adámez JD, Samino EG, Sánchez EV, González-Gómez D (2012) In vitro estimation of the antibacterial activity and antioxidant capacity of aqueous extracts from grape-seeds (Vitis vinifera L.). Food Control 24:136–141. https://doi.org/10.1016/j.foodcont.2011.09.016
17. Ziogas V, Tanou G, Molassiotis A et al (2010) Antioxidant and free radical-scavenging activities of phenolic extracts of olive fruits. Food Chem 120:1097–1103. https://doi.org/10.1016/j.foodchem.2009.11.058
18. Martillanes S, Rocha-Pimienta J, Cabrera-Bañegil M, et al (2017) Application of phenolic compounds for food preservation: Food additive and active packaging. Phenolic Compd Act London, UK IntechOpen 39–58https://doi.org/10.5772/66885
19. Butsat S, Siriamornpun S (2010) Antioxidant capacities and phenolic compounds of the husk, bran and endosperm of Thai rice. Food Chem 119:606–613. https://doi.org/10.1016/j.foodchem.2009.07.001
20. Zielinski AAF, Haminiuk CWI, Alberti A et al (2014) A comparative study of the phenolic compounds and the in vitro antioxidant activity of different Brazilian teas using multivariate statistical techniques. Food Res Int 60:246–254. https://doi.org/10.1016/j.foodres.2013.09.010
21. Carlsen MH, Halvorsen BL, Holte K et al (2010) The total antioxidant content of more than 3100 foods, beverages, spices, herbs and supplements used worldwide. Nutr J 9:1–11. https://doi.org/10.1186/1475-2891-9-3
22. Lu X, Li N, Qiao X et al (2017) Composition analysis and antioxidant properties of black garlic extract. J food drug Anal 25:340–349. https://doi.org/10.1016/j.jfda.2016.05.011
23. Balboa EM, Conde E, Moure A et al (2013) In vitro antioxidant properties of crude extracts and compounds from brown algae. Food Chem 138:1764–1785. https://doi.org/10.1016/j.foodchem.2012.11.026
24. Lü J, Lin PH, Yao Q, Chen C (2010) Chemical and molecular mechanisms of antioxidants: experimental approaches and model systems. J Cell Mol Med 14:840–860. https://doi.org/10.1111/j.1582-4934.2009.00897.x
25. Lee DS (2014) Antioxidative packaging system. In: Innovations in food packaging. Elsevier 111–131. https://doi.org/10.1016/B978-0-12-394601-0.00006-0
26. Cooksey K (2005) Effectiveness of antimicrobial food packaging materials. Food Addit Contam 22:980–987. https://doi.org/10.1080/02652030500246164
27. Taghvaei M, Jafari SM (2015) Application and stability of natural antioxidants in edible oils in order to substitute synthetic additives. J Food Sci Technol 52:1272–1282. https://doi.org/10.1007/s13197-013-1080-1
28. Iheaturu NC, Nwakaudu AA, Nwakaudu MS, Owuamanam CI (2018) The use of natural antioxidant active polymer packaging for food preservation: A review. Futo J Ser 4:94–112
29. Choe E, Min DB (2006) Mechanisms and factors for edible oil oxidation. Compr Rev food Sci food Saf 5:169–186. https://doi.org/10.1111/j.1541-4337.2006.00009.x
30. Ligon SC, Husár B, Wutzel H et al (2014) Strategies to reduce oxygen inhibition in photoinduced polymerization. Chem Rev 114:557–589. https://doi.org/10.1021/cr3005197
31. Zhou L, Elias RJ (2013) Understanding antioxidant and prooxidant mechanisms of phenolics in food lipids. In: Lipid Oxidation. Elsevier 297–321. https://doi.org/10.1016/B978-0-9830791-6-3.50012-6
32. Tajkarimi MM, Ibrahim SA, Cliver DO (2010) Antimicrobial herb and spice compounds in food. Food Control 21:1199–1218. https://doi.org/10.1016/j.foodcont.2010.02.003
33. Raybaudi-Massilia RM, Mosqueda-Melgar J, Martín-Belloso O (2008) Edible alginate-based coating as carrier of antimicrobials to improve shelf-life and safety of fresh-cut melon. Int J Food Microbiol 121:313–327. https://doi.org/10.1016/j.ijfoodmicro.2007.11.010
34. Careaga M, Fernández E, Dorantes L et al (2003) Antibacterial activity of Capsicum extract against Salmonella typhimurium and Pseudomonas aeruginosa inoculated in raw beef meat. Int

J Food Microbiol 83:331–335. https://doi.org/10.1016/S0168-1605(02)00382-3
35. Tornuk F, Cankurt H, Ozturk I et al (2011) Efficacy of various plant hydrosols as natural food sanitizers in reducing Escherichia coli O157: H7 and Salmonella Typhimurium on fresh cut carrots and apples. Int J Food Microbiol 148:30–35. https://doi.org/10.1016/j.ijfoodmicro.2011.04.022
36. Zaika LL (1988) Spices and herbs: their antimicrobial activity and its determination 1. J Food Saf 9:97–118. https://doi.org/10.1111/j.1745-4565.1988.tb00511.x
37. Witkowska AM, Hickey DK, Alonso-Gomez M, Wilkinson M (2013) Evaluation of antimicrobial activities of commercial herb and spice extracts against selected foodborne bacteria. J Food Res 2:37. https://doi.org/10.5539/jfr.v2n4p37
38. Al-Sum BA, Al-Arfaj AA (2013) Antimicrobial activity of the aqueous extract of mint plant. Sci J Clin Med 2:110–113
39. Lee S-Y, Gwon S-Y, Kim S-J, Moon BK (2009) Inhibitory effect of commercial green tea and rosemary leaf powders on the growth of foodborne pathogens in laboratory media and oriental-style rice cakes. J Food Prot 72:1107–1111. https://doi.org/10.4315/0362-028X-72.5.1107
40. Kong B, Wang J, Xiong YL (2007) Antimicrobial activity of several herb and spice extracts in culture medium and in vacuum-packaged pork. J Food Prot 70:641–647. https://doi.org/10.4315/0362-028X-70.3.641
41. Fernandez-Lopez J, Zhi N, Aleson-Carbonell L et al (2005) Antioxidant and antibacterial activities of natural extracts: application in beef meatballs. Meat Sci 69:371–380. https://doi.org/10.1016/j.meatsci.2004.08.004
42. Han JH (2005) Antimicrobial packaging systems. In: Innovations in food packaging. Elsevier. 80–107. https://doi.org/10.1016/B978-0-12-311632-1.X5031-1
43. Yildirim S, Röcker B, Pettersen MK et al (2018) Active packaging applications for food. Compr Rev Food Sci Food Saf 17:165–199. https://doi.org/10.1111/1541-4337.12322
44. Sung S-Y, Sin LT, Tee T-T et al (2013) Antimicrobial agents for food packaging applications. Trends Food Sci Technol 33:110–123. https://doi.org/10.1016/j.tifs.2013.08.001
45. Sofi SA, Singh J, Rafiq S et al (2018) A comprehensive review on antimicrobial packaging and its use in food packaging. Curr Nutr Food Sci 14:305–312. https://doi.org/10.2174/1573401313666170609095732
46. Xue J, Davidson PM, Zhong Q (2013) Thymol nanoemulsified by whey protein-maltodextrin conjugates: The enhanced emulsifying capacity and antilisterial properties in milk by propylene glycol. J Agric Food Chem 61:12720–12726
47. Moleyar V, Narasimham P (1986) Antifungal activity of some essential oil components. Food Microbiol 3:331–336
48. Dorman H, Deans SG (2000) Antimicrobial agents from plants: antibacterial activity of plant volatile oils. J Appl Microbiol 88:308–316. https://doi.org/10.1046/j.1365-2672.2000.00969.x
49. Juven BJ, Kanner J, Schved F, Weisslowicz H (1994) Factors that interact with the antibacterial action of thyme essential oil and its active constituents. J Appl Bacteriol 76:626–631. https://doi.org/10.1111/j.1365-2672.1994.tb01661.x
50. Bajpai VK, Rahman A, Dung NT et al (2008) In vitro inhibition of food spoilage and foodborne pathogenic bacteria by essential oil and leaf extracts of Magnolia liliflora Desr. J Food Sci 73:M314–M320. https://doi.org/10.1111/j.1750-3841.2008.00841.x
51. Delaquis PJ, Mazza G (1995) Antimicrobial properties of isothiocyanates in food preservation. Food Technol 49:73–84
52. Helander IM, Alakomi H-L, Latva-Kala K et al (1998) Characterization of the action of selected essential oil components on Gram-negative bacteria. J Agric Food Chem 46:3590–3595. https://doi.org/10.1021/jf980154m
53. Conner DE, Beuchat LR (1984) Sensitivity of heat-stressed yeasts to essential oils of plants. Appl Environ Microbiol 47:229–233. https://doi.org/10.1128/aem.47.2.229-233.1984
54. Burt S (2004) Essential oils: their antibacterial properties and potential applications in foods—a review. Int J Food Microbiol 94:223–253. https://doi.org/10.1016/j.ijfoodmicro.2004.03.022
55. Hyldgaard M, Mygind T, Meyer RL (2012) Essential oils in food preservation: mode of action, synergies, and interactions with food matrix components. Front Microbiol 3:12. https://doi.org/10.3389/fmicb.2012.00012
56. Falleh H, Ben JM, Saada M, Ksouri R (2020) Essential oils: A promising eco-friendly food preservative. Food Chem 330:127268. https://doi.org/10.1016/j.foodchem.2020.127268
57. Mohamed SAA, El-Sakhawy M, El-Sakhawy MA-M (2020) Polysaccharides, protein and lipid-based natural edible films in food packaging: A review. Carbohydr Polym 238:116178. https://doi.org/10.1016/j.carbpol.2020.116178
58. Asgher M, Qamar SA, Bilal M, Iqbal HMN (2020) Bio-based active food packaging materials: Sustainable alternative to conventional petrochemical-based packaging materials. Food Res Int 137:109625. https://doi.org/10.1016/J.FOODRES.2020.109625
59. Buendía L, Soto S, Ros M et al (2019) Innovative cardboard active packaging with a coating including encapsulated essential oils to extend cherry tomato shelf life. LWT 116:108584. https://doi.org/10.1016/j.lwt.2019.108584
60. Pinto T, Aires A, Cosme F et al (2021) Bioactive (Poly) phenols, Volatile Compounds from Vegetables. Medicinal and Aromatic Plants Foods 10:106. https://doi.org/10.3390/foods10010106
61. Ali A, Chen Y, Liu H et al (2019) Starch-based antimicrobial films functionalized by pomegranate peel. Int J Biol Macromol 129:1120–1126. https://doi.org/10.1016/j.ijbiomac.2018.09.068
62. Sultana A, Kathuria A, Gaikwad KK (2022) Metal-organic frameworks for active food packaging. A review. Environ Chem Lett. https://doi.org/10.1007/s10311-022-01387-z
63. Elliott M, Chithan K (2017) The impact of plant flavonoids on mammalian biology: implications for immunity, inflammation and cancer. In: The flavonoids. Routledge. 619–652. https://doi.org/10.1201/9780203736692
64. Przybyłek I, Karpiński TM (2019) Antibacterial properties of propolis. Molecules 24:2047. https://doi.org/10.3390/molecules24112047
65. Havsteen B (1983) Flavonoids, a class of natural products of high pharmacological potency. Biochem Pharmacol 32:1141–1148. https://doi.org/10.1016/0006-2952(83)90262-9
66. Harborne JB, Baxter H (1999) The handbook of natural flavonoids. Volume 1 and Volume 2. John Wiley and Sons.
67. Bueno JM, Ramos-Escudero F, Saez-Plaza P et al (2012) Analysis and antioxidant capacity of anthocyanin pigments. Part I: General considerations concerning polyphenols and flavonoids. Crit Rev Anal Chem 42:102–125
68. Scalbert A (1991) Antimicrobial properties of tannins. Phytochemistry 30:3875–3883. https://doi.org/10.1016/0031-9422(91)83426-L
69. Chung K-T, Wong TY, Wei C-I et al (1998) Tannins and human health: a review. Crit Rev Food Sci Nutr 38:421–464. https://doi.org/10.1080/10408699891274273
70. Molino S, Casanova NA, Rufián Henares JA, Fernandez Miyakawa ME (2019) Natural tannin wood extracts as a potential food ingredient in the food industry. J Agric Food Chem 68:2836–2848. https://doi.org/10.1021/acs.jafc.9b00590
71. Costabile A, Sanghi S, Martin-Pelaez S et al (2011) Inhibition of Salmonella Typhimurium by tannins in vitro. J Food Agric Env 9:119–124

72. Taguri T, Tanaka T, Kouno I (2004) Antimicrobial activity of 10 different plant polyphenols against bacteria causing foodborne disease. Biol Pharm Bull 27:1965–1969. https://doi.org/10.1248/bpb.27.1965
73. Sung SH, Kim KH, Jeon BT et al (2012) Antibacterial and antioxidant activities of tannins extracted from agricultural by-products. J Med Plants Res 6:3072–3079. https://doi.org/10.5897/JMPR11.1575
74. López de Dicastillo C, Nerín C, Alfaro P et al (2011) Development of new antioxidant active packaging films based on ethylene vinyl alcohol copolymer (EVOH) and green tea extract. J Agric Food Chem 59:7832–7840. https://doi.org/10.1021/jf201246g
75. García DE, Carrasco JC, Salazar JP, et al (2016) Bark polyflavonoids from Pinus radiata as functional building-blocks for polylactic acid (PLA)-based green composites. Express Polym Lett 10https://doi.org/10.3144/expresspolymlett.2016.78
76. Zhai Y, Wang J, Wang H et al (2018) Preparation and characterization of antioxidative and UV-protective larch bark tannin/PVA composite membranes. Molecules 23:2073. https://doi.org/10.3390/molecules23082073
77. Bouarab Chibane L, Degraeve P, Ferhout H et al (2019) Plant antimicrobial polyphenols as potential natural food preservatives. J Sci Food Agric 99:1457–1474. https://doi.org/10.1002/jsfa.9357
78. Cowan MM (1999) Plant products as antimicrobial agents. Clin Microbiol Rev 12:564–582. https://doi.org/10.1128/CMR.12.4.564
79. Kuete V, Alibert-Franco S, Eyong KO et al (2011) Antibacterial activity of some natural products against bacteria expressing a multidrug-resistant phenotype. Int J Antimicrob Agents 37:156–161. https://doi.org/10.1016/j.ijantimicag.2010.10.020
80. Ojala T, Remes S, Haansuu P et al (2000) Antimicrobial activity of some coumarin containing herbal plants growing in Finland. J Ethnopharmacol 73:299–305. https://doi.org/10.1016/S0378-8741(00)00279-8
81. Benbettaïeb N, Chambin O, Assifaoui A et al (2016) Release of coumarin incorporated into chitosan-gelatin irradiated films. Food Hydrocoll 56:266–276. https://doi.org/10.1016/j.foodhyd.2015.12.026
82. Brody AL, Budny JA (1995) Enzymes as active packaging agents. In: Active food packaging. Springer. 174–192. https://doi.org/10.1007/978-1-4615-2175-4_7
83. Meyer AS, Isaksen A (1995) Application of enzymes as food antioxidants. Trends Food Sci Technol 6:300–304. https://doi.org/10.1016/S0924-2244(00)89140-2
84. Lopez-Rubio A, Gavara R, Lagaron JM (2006) Bioactive packaging: turning foods into healthier foods through biomaterials. Trends Food Sci Technol 17:567–575. https://doi.org/10.1016/j.tifs.2006.04.012
85. Savadogo A, Ouattara ATC, Bassole HNI, Traore SA (2006) Bacteriocins and lactic acid bacteria-a minireview. African J Biotechnol 5https://doi.org/10.5897/AJB05.388
86. Müller-Auffermann K, Grijalva F, Jacob F, Hutzler M (2015) Nisin and its usage in breweries: a review and discussion. J Inst Brew 121:309–319. https://doi.org/10.1002/jib.233
87. Huang E, Hussein WE, Campbell EP, Yousef AE (2021) Applications in food technology: antimicrobial peptides. In: Biologically Active Peptides. Elsevier. 745–770. https://doi.org/10.1016/B978-0-12-821389-6.00006-6
88. Johnsen L, Fimland G, Nissen-Meyer J (2005) The C-terminal domain of pediocin-like antimicrobial peptides (class IIa bacteriocins) is involved in specific recognition of the C-terminal part of cognate immunity proteins and in determining the antimicrobial spectrum. J Biol Chem 280:9243–9250. https://doi.org/10.1074/jbc.M412712200
89. Montville TJ, Chen Y (1998) Mechanistic action of pediocin and nisin: recent progress and unresolved questions. Appl Microbiol Biotechnol 50:511–519. https://doi.org/10.1007/s002530051328
90. Espitia PJP, Pacheco JJR, de Melo NR et al (2013) Packaging properties and control of Listeria monocytogenes in bologna by cellulosic films incorporated with pediocin. Brazilian J Food Technol 16:226–235. https://doi.org/10.1590/S1981-67232013005000028
91. Espitia PJP, de Soares N, FF, Teófilo RF, et al (2013) Physical–mechanical and antimicrobial properties of nanocomposite films with pediocin and ZnO nanoparticles. Carbohydr Polym 94:199–208. https://doi.org/10.1016/j.foodhyd.2013.06.005
92. Arqués JL, Fernández J, Gaya P et al (2004) Antimicrobial activity of reuterin in combination with nisin against foodborne pathogens. Int J Food Microbiol 95:225–229. https://doi.org/10.1016/j.ijfoodmicro.2004.03.009
93. Hernández-Carrillo JG, Orta-Zavalza E, González-Rodríguez SE et al (2021) Evaluation of the effectivity of reuterin in pectin edible coatings to extend the shelf-life of strawberries during cold storage. Food Packag Shelf Life 30:100760. https://doi.org/10.1016/j.fpsl.2021.100760
94 Schaefer L, Auchtung TA, Hermans KE et al (2010) The antimicrobial compound reuterin (3-hydroxypropionaldehyde) induces oxidative stress via interaction with thiol groups. Microbiology 156:1589. https://doi.org/10.1099/2Fmic.0.035642-0
95. Vollenweider S, Lacroix C (2004) 3-Hydroxypropionaldehyde: applications and perspectives of biotechnological production. Appl Microbiol Biotechnol 64:16–27. https://doi.org/10.1007/s00253-003-1497-y
96. Asare PT, Greppi A, Stettler M et al (2018) Decontamination of minimally-processed fresh lettuce using reuterin produced by Lactobacillus reuteri. Front Microbiol 9:1421. https://doi.org/10.3389/fmicb.2018.01421
97. Kutter E, Sulakvelidze A (2004) Bacteriophages: biology and applications. Crc press. https://doi.org/10.1201/9780203491751
98. Fiorentin L, Vieira ND, Barioni W Jr (2005) Oral treatment with bacteriophages reduces the concentration of Salmonella Enteritidis PT4 in caecal contents of broilers. Avian Pathol 34:258–263. https://doi.org/10.1080/01445340500112157
99. Raya RR, Varey P, Oot RA et al (2006) Isolation and characterization of a new T-even bacteriophage, CEV1, and determination of its potential to reduce Escherichia coli O157: H7 levels in sheep. Appl Environ Microbiol 72:6405–6410. https://doi.org/10.1128/AEM.03011-05
100. Theron MM, Lues JFR (2010) Organic acids and food preservation. CRC Press. https://doi.org/10.1201/9781420078435
101. Hsiao C-P, Siebert KJ (1999) Modeling the inhibitory effects of organic acids on bacteria. Int J Food Microbiol 47:189–201. https://doi.org/10.1016/S0168-1605(99)00012-4
102. Hauser C, Thielmann J, Muranyi P (2016) Organic acids: Usage and potential in antimicrobial packaging. In: Antimicrobial food packaging. Elsevier.563–580. https://doi.org/10.1016/B978-0-12-800723-5.00046-2
103. Jayakumar R, Nwe N, Tokura S, Tamura H (2007) Sulfated chitin and chitosan as novel biomaterials. Int J Biol Macromol 40:175–181. https://doi.org/10.1016/j.ijbiomac.2006.06.021
104. Möller H, Grelier S, Pardon P, Coma V (2004) Antimicrobial and physicochemical properties of chitosan− hpmc-based films. J Agric Food Chem 52:6585–6591. https://doi.org/10.1021/jf0306690
105. Krajewska B (2004) Application of chitin-and chitosan-based materials for enzyme immobilizations: a review. Enzyme Microb Technol 35:126–139. https://doi.org/10.1016/j.enzmictec.2003.12.013

106. Tripathi S, Mehrotra GK, Tripathi CKM et al (2008) Chitosan based bioactive film: Functional properties towards biotechnological needs. Asian chitin J 4:29–36
107. Wu T, Jiang Q, Wu D et al (2019) What is new in lysozyme research and its application in food industry? A review. Food Chem 274:698–709. https://doi.org/10.1016/j.foodchem.2018.09.017
108. Administration F and D (2015) Direct food substances affirmed as generally recognized as safe. Food Drug Adm 417–418
109. Barbiroli A, Bonomi F, Capretti G et al (2012) Antimicrobial activity of lysozyme and lactoferrin incorporated in cellulose-based food packaging. Food Control 26:387–392. https://doi.org/10.1016/j.foodcont.2012.01.046
110. Conte A, Buonocore GG, Sinigaglia M, Del Nobile MA (2007) Development of immobilized lysozyme based active film. J Food Eng 78:741–745. https://doi.org/10.1016/j.jfoodeng.2005.11.013
111. Appendini P, Hotchkiss JH (1997) Immobilization of lysozyme on food contact polymers as potential antimicrobial films. Packag Technol Sci An Int J 10:271–279. https://doi.org/10.1002/(SICI)1099-1522(199709/10)10:5/3C271::AID-PTS412/3E3.0.CO;2-R
112. Niaz B, Saeed F, Ahmed A et al (2019) Lactoferrin (LF): a natural antimicrobial protein. Int J Food Prop 22:1626–1641. https://doi.org/10.1080/10942912.2019.1666137
113. Jenssen H, Hancock REW (2009) Antimicrobial properties of lactoferrin. Biochimie 91:19–29. https://doi.org/10.1016/j.biochi.2008.05.015
114. Al-Nabulsi AA, Han JH, Liu Z et al (2006) Temperature-sensitive microcapsules containing lactoferrin and their action against Carnobacterium viridans on bologna. J Food Sci 71:M208–M214. https://doi.org/10.1111/j.1750-3841.2006.00103.x
115. Bafort F, Parisi O, Perraudin J-P, Jijakli MH (2014) Mode of action of lactoperoxidase as related to its antimicrobial activity: a review. Enzyme Res 2014https://doi.org/10.1155/2014/517164
116. Yener FYG, Korel F, Yemenicioğlu A (2009) Antimicrobial activity of lactoperoxidase system incorporated into cross-linked alginate films. J Food Sci 74:M73–M79. https://doi.org/10.1111/j.1750-3841.2009.01057.x
117. Min S, Krochta JM (2005) Inhibition of Penicillium commune by edible whey protein films incorporating lactoferrin, lacto-ferrin hydrolysate, and lactoperoxidase systems. J Food Sci 70:M87–M94. https://doi.org/10.1111/j.1365-2621.2005.tb07108.x
118. Nadarajah D, Han JH, Holley RA (2005) Inactivation of Escherichia coli O157: H7 in packaged ground beef by allyl isothiocyanate. Int J Food Microbiol 99:269–279. https://doi.org/10.1016/j.ijfoodmicro.2004.08.019
119. Otoni CG, Espitia PJP, Avena-Bustillos RJ, McHugh TH (2016) Trends in antimicrobial food packaging systems: Emitting sachets and absorbent pads. Food Res Int 83:60–73
120. Smith JP, Hoshino J, Abe Y (1995) Interactive packaging involving sachet technology. In: Active food packaging. Springer. 143–173. https://doi.org/10.1007/978-1-4615-2175-4_6
121. Khan A, Vu KD, Riedl B, Lacroix M (2015) Optimization of the antimicrobial activity of nisin, Na-EDTA and pH against gram-negative and gram-positive bacteria. LWT-Food Sci Technol 61:124–129. https://doi.org/10.1016/j.lwt.2014.11.035
122. Gasti T, Dixit S, Hiremani VD et al (2022) Chitosan/pullulan based films incorporated with clove essential oil loaded chitosan-ZnO hybrid nanoparticles for active food packaging. Carbohydr Polym 277:118866. https://doi.org/10.1016/j.carbpol.2021.118866
123. Lian H, Shi J, Zhang X, Peng Y (2020) Effect of the added polysaccharide on the release of thyme essential oil and structure properties of chitosan based film. Food Packag Shelf Life 23:100467. https://doi.org/10.1016/j.fpsl.2020.100467
124. Azadbakht E, Maghsoudlou Y, Khomiri M, Kashiri M (2018) Development and structural characterization of chitosan films containing Eucalyptus globulus essential oil: Potential as an antimicrobial carrier for packaging of sliced sausage. Food Packag shelf life 17:65–72. https://doi.org/10.1016/j.fpsl.2018.03.007
125. Aloui H, Khwaldia K (2016) Natural antimicrobial edible coatings for microbial safety and food quality enhancement. Compr Rev Food Sci Food Saf 15:1080–1103. https://doi.org/10.1111/1541-4337.12226
126. Perez-Perez C, Regalado-González C, Rodríguez-Rodríguez CA, et al (2006) Incorporation of antimicrobial agents in food packaging films and coatings. Adv Agric food Biotechnol 193–216
127. Tavassoli-Kafrani E, Gamage MV, Dumée LF, et al (2020) Edible films and coatings for shelf life extension of mango: a review. Crit Rev Food Sci Nutr 1–29https://doi.org/10.1080/10408398.2020.1853038
128. Manzoor S, Gull A, Wani SM et al (2021) Improving the shelf life of fresh cut kiwi using nanoemulsion coatings with antioxidant and antimicrobial agents. Food Biosci 41:101015. https://doi.org/10.1016/j.fbio.2021.101015
129. Rupasinghe HPV, Boulter-Bitzer J, Ahn T, Odumeru JA (2006) Vanillin inhibits pathogenic and spoilage microorganisms in vitro and aerobic microbial growth in fresh-cut apples. Food Res Int 39:575–580. https://doi.org/10.1016/j.foodres.2005.11.005
130 Tomadoni B, del Moreira MR, Pereda M, Ponce AG (2018) Gellan-based coatings incorporated with natural antimicrobials in fresh-cut strawberries: Microbiological and sensory evaluation through refrigerated storage. LWT 97(384–389):389. https://doi.org/10.1016/j.lwt.2018.07.029
131. Appendini P, Hotchkiss JH (2002) Review of antimicrobial food packaging. Innov Food Sci Emerg Technol 3:113–126. https://doi.org/10.1016/S1466-8564(02)00012-7
132. Silvestre C, Duraccio D, Cimmino S (2011) Food packaging based on polymer nanomaterials. Prog Polym Sci 36:1766–1782. https://doi.org/10.1016/j.progpolymsci.2011.02.003
133. Xu FJ, Cai QJ, Li YL et al (2005) Covalent immobilization of glucose oxidase on well-defined poly (glycidyl methacrylate)– Si (111) hybrids from surface-initiated atom-transfer radical polymerization. Biomacromol 6:1012–1020. https://doi.org/10.1021/bm0493178
134. Muriel-Galet V, Cerisuelo JP, López-Carballo G et al (2012) Development of antimicrobial films for microbiological control of packaged salad. Int J Food Microbiol 157:195–201. https://doi.org/10.1016/j.ijfoodmicro.2012.05.002
135. Buonocore GG, Del Nobile MA, Panizza A et al (2003) A general approach to describe the antimicrobial agent release from highly swellable films intended for food packaging applications. J Control release 90:97–107. https://doi.org/10.1016/S0168-3659(03)00154-8
136. Bodbodak S, Rafiee Z (2016) Recent trends in active packaging in fruits and vegetables. In: Eco-friendly technology for postharvest produce quality. Elsevier. 77–125. https://doi.org/10.1016/B978-0-12-804313-4.00003-7
137. Erdogˇrul Ö, Şener H (2005) The contamination of various fruit and vegetable with Enterobius vermicularis, Ascaris eggs, Entamoeba histolyca cysts and Giardia cysts. Food Control 16:557–560. https://doi.org/10.1016/j.foodcont.2004.06.016
138. Pérez-Gago MB, Palou L (2016) Antimicrobial packaging for fresh and fresh-cut fruits and vegetables. Fresh-Cut Fruits Veg 433–482
139. Jung J, Zhao Y (2016) Antimicrobial packaging for fresh and minimally processed fruits and vegetables. In: Antimicrobial food packaging. Elsevier. 243–256. https://doi.org/10.1016/B978-0-12-800723-5.00018-8
140. Janowicz M, Bry J (2019) An overview of fruit and vegetable edible packaging materials. 1–13. https://doi.org/10.1002/pts.2440

141. Valdés A, Ramos M, Beltrán A et al (2017) State of the art of antimicrobial edible coatings for food packaging applications. Coatings 7:56. https://doi.org/10.3390/coatings7040056
142. Nirmal NP, Benjakul S (2011) Retardation of quality changes of Pacific white shrimp by green tea extract treatment and modified atmosphere packaging during refrigerated storage. Int J Food Microbiol 149:247–253. https://doi.org/10.1016/j.ijfoodmicro.2011.07.002
143. Mariutti LRB, Nogueira GC, Bragagnolo N (2011) Lipid and cholesterol oxidation in chicken meat are inhibited by sage but not by garlic. J Food Sci 76:C909–C915. https://doi.org/10.1111/j.1750-3841.2011.02274.x
144. Dave D, Ghaly AE (2011) Meat spoilage mechanisms and preservation techniques: a critical review. Am J Agric Biol Sci 6:486–510. https://doi.org/10.3844/ajabssp.2011.486.510
145. Ilyas RA, Sapuan SM, Megashah LN, et al (2021) Regulations for Food Packaging Materials. Bio-based Packag Mater Environ Econ Asp 467–494
146. Marone PA (2016) Food safety and regulatory concerns. In: Insects as sustainable food ingredients. Elsevier. 203–221. https://doi.org/10.1016/B978-0-12-802856-8.00007-7
147. Regulation EC (2004) No 1935/2004 of the European Parliament and of the Council of 27 October 2004 on materials and articles intended to come into contact with food and repealing Directives 80/590/EEC and 89/109/EEC. Off J Eur Union L 338:4–16
148. Kumar P, Tanwar R, Gupta V, Upadhyay A, Kumar A, Gaikwad KK (2021) Pineapple peel extract incorporated poly (vinyl alcohol)-corn starch film for active food packaging: Preparation, characterization and antioxidant activity. Int J Biol Macromol 187:223–231. https://doi.org/10.1016/j.ijbiomac.2021.07.136
149. Tanwar R, Gupta V, Kumar P, Kumar A, Singh S, Gaikwad KK (2021) Development and characterization of PVA-starch incorporated with coconut shell extract and sepiolite clay as an antioxidant film for active food packaging applications. Int J Biol Macromol 185:451–461. https://doi.org/10.1016/j.ijbiomac.2021.06.179
150. Han Y, Yu M, Wang L (2018) Preparation and characterization of antioxidant soy protein isolate films incorporating licorice residue extract. Food Hydrocoll 75:13–21. https://doi.org/10.1016/j.foodhyd.2017.09.020
151. Arciello A, Panzella L, Dell'Olmo E, Abdalrazeq M, Moccia F, Gaglione R, Agustin-Salazar S, Napolitano A, Mariniello L, Giosafatto CVL (2021) Development and characterization of antimicrobial and antioxidant whey protein-based films functionalized with Pecan (Carya illinoinensis) nut shell extract. Food Packag Shelf Life 29:100710. https://doi.org/10.1016/j.fpsl.2021.100710
152. Rambabu K, Bharath G, Banat F, Show PL, Cocoletzi HH (2019) Mango leaf extract incorporated chitosan antioxidant film for active food packaging. Int J Biol Macromol 126:1234–1243. https://doi.org/10.1016/j.ijbiomac.2018.12.196
153. Cejudo-Bastante MJ, Cejudo-Bastante C, Cran MJ, Heredia FJ, Bigger SW (2020) Optical, structural, mechanical and thermal characterization of antioxidant ethylene vinyl alcohol copolymer films containing betalain-rich beetroot. Food Packag Shelf Life 24:100502. https://doi.org/10.1016/j.fpsl.2020.100502
154. Ju A, Bin Song K (2020) Incorporation of yellow onion peel extract into the funoran-based biodegradable films as an antioxidant packaging material. Int. J. Food Sci Technol 55:1671–1678. https://doi.org/10.1111/ijfs.14436
155. Wang X, Yong H, Gao L, Li L, Jin M, Liu J (2019) Preparation and characterization of antioxidant and pH-sensitive films based on chitosan and black soybean seed coat extract. Food Hydrocoll 89:56–66. https://doi.org/10.1016/j.foodhyd.2018.10.019
156. Hu X, Yuan L, Han L, Li S, Song L (2019) Characterization of antioxidant and antibacterial gelatin films incorporated with Ginkgo biloba extract. RSC Adv 9:27449–27454. https://doi.org/10.1039/C9RA05788A
157. Liu T, Wang J, Chi F, Tan Z, Liu L (2020) Development and characterization of novel active chitosan films containing fennel and peppermint essential oils. Coatings 10:936. https://doi.org/10.3390/coatings10100936
158. Martins C, Vilarinho F, Silva AS, Andrade M, Machado AV, Castilho MC, Sá A, Cunha A, Vaz MF, Ramos F (2018) Active polylactic acid film incorporated with green tea extract: Development, characterization and effectiveness. Ind Crops Prod 123:100–110. https://doi.org/10.1016/j.indcrop.2018.06.056
159. Farhan A, Hani NM (2020) Active edible films based on semi-refined κ-carrageenan: Antioxidant and color properties and application in chicken breast packaging. Food Packag Shelf Life 24:100476. https://doi.org/10.1016/j.fpsl.2020.100476
160. Yong H, Liu J, Qin Y, Bai R, Zhang X, Liu J (2019) Antioxidant and pH-sensitive films developed by incorporating purple and black rice extracts into chitosan matrix. Int J Biol Macromol 137:307–316. https://doi.org/10.1016/j.ijbiomac.2019.07.009
161. Rodríguez GM, Sibaja JC, Espitia PJP, Otoni CG (2020) Antioxidant active packaging based on papaya edible films incorporated with Moringa oleifera and ascorbic acid for food preservation. Food Hydrocoll 103:105630. https://doi.org/10.1016/j.foodhyd.2019.105630
162. Ju A, Bin Song K (2019) Development of teff starch films containing camu-camu (Myrciaria dubia Mc. Vaugh) extract as an antioxidant packaging material. Ind Crops Prod 141:111737. https://doi.org/10.1016/j.indcrop.2019.111737
163 Liu J, Yong H, Liu Y, Qin Y, Kan J, Liu J (2019) Preparation and characterization of active and intelligent films based on fish gelatin and haskap berries (Lonicera caerulea L.) extract. Food Packag. Shelf Life. 22:100417. https://doi.org/10.1016/j.fpsl.2019.100417
164. Han H-S, Bin Song K (2021) Antioxidant properties of watermelon (Citrullus lanatus) rind pectin films containing kiwifruit (Actinidia chinensis) peel extract and their application as chicken thigh packaging. Food Packag Shelf Life 28:100636. https://doi.org/10.1016/j.fpsl.2021.100636
165. Qin Y, Liu Y, Zhang X, Liu J (2020) Development of active and intelligent packaging by incorporating betalains from red pitaya (Hylocereus polyrhizus) peel into starch/polyvinyl alcohol films. Food Hydrocoll 100:105410. https://doi.org/10.1016/j.foodhyd.2019.105410
166. Lan W, Wang S, Zhang Z, Liang X, Liu X, Zhang J (2021) Development of red apple pomace extract/chitosan-based films reinforced by TiO2 nanoparticles as a multifunctional packaging material. Int J Biol Macromol 168:105–115. https://doi.org/10.1016/j.ijbiomac.2020.12.051
167. Khalid S, Yu L, Feng M, Meng L, Bai Y, Ali A, Liu H, Chen L (2018) Development and characterization of biodegradable antimicrobial packaging films based on polycaprolactone, starch and pomegranate rind hybrids, Food Packag. Shelf. Life 18:71–79. https://doi.org/10.1016/j.fpsl.2018.08.008
168. Liu Y, Qin Y, Bai R, Zhang X, Yuan L, Liu J (2019) Preparation of pH-sensitive and antioxidant packaging films based on κ-carrageenan and mulberry polyphenolic extract. Int J Biol Macromol 134:993–1001. https://doi.org/10.1016/j.ijbiomac.2019.05.175
169. Roy S, Rhim J-W (2021) Antioxidant and antimicrobial poly (vinyl alcohol)-based films incorporated with grapefruit seed extract and curcumin. J Environ Chem Eng 9:104694. https://doi.org/10.1016/j.jece.2020.104694
170. Wan Yahaya WA, Abu Yazid N, MohdAzman NA, Almajano MP (2019) Antioxidant activities and Total phenolic content of Malaysian herbs as components of active packaging film in beef

patties. Antioxidants. 8:204. https://doi.org/10.3390/antiox8070204

171. Jamróz E, Kulawik P, Krzyściak P, Talaga-Ćwiertnia K, Juszczak L (2019) Intelligent and active furcellaran-gelatin films containing green or pu-erh tea extracts: Characterization, antioxidant and antimicrobial potential. Int J Biol Macromol 122:745–757. https://doi.org/10.1016/j.ijbiomac.2018.11.008
172. Riaz A, Lagnika C, Luo H, Dai Z, Nie M, Hashim MM, Liu C, Song J, Li D (2020) Chitosan-based biodegradable active food packaging film containing Chinese chive (Allium tuberosum) root extract for food application. Int J Biol Macromol 150:595–604. https://doi.org/10.1016/j.ijbiomac.2020.02.078
173. Rashidi M, Mansour SS, Mostashari P, Ramezani S, Mohammadi M, Ghorbani M (2021) Electrospun nanofiber based on Ethyl cellulose/Soy protein isolated integrated with bitter orange peel extract for antimicrobial and antioxidant active food packaging. Int J Biol Macromol 193:1313–1323. https://doi.org/10.1016/j.ijbiomac.2021.10.182
174. Deshmukh RK, Akhila K, Ramakanth D, Gaikwad KK (2022) Guar gum/carboxymethyl cellulose based antioxidant film incorporated with halloysite nanotubes and litchi shell waste extract for active packaging. Int J Biol Macromol. https://doi.org/10.1016/j.ijbiomac.2021.12.198
175. Woraprayote W, Kingcha Y, Amonphanpokin P, Kruenate J, Zendo T, Sonomoto K, Benjakul S, Visessanguan W (2013) Anti-listeria activity of poly(lactic acid)/sawdust particle biocomposite film impregnated with pediocin PA-1/AcH and its use in raw sliced pork. Int J Food Microbiol 167:229–235. https://doi.org/10.1016/J.IJFOODMICRO.2013.09.009
176. Jin T, Liu L, Zhang H, Hicks K (2009) Antimicrobial activity of nisin incorporated in pectin and polylactic acid composite films against Listeria monocytogenes. Int J Food Sci Technol 44:322–329. https://doi.org/10.1111/J.1365-2621.2008.01719.X
177. Jipa IM, Stoica-Guzun A, Stroescu M (2012) Controlled release of sorbic acid from bacterial cellulose based mono and multilayer antimicrobial films. LWT 47:400–406. https://doi.org/10.1016/J.LWT.2012.01.039
178. Zhuang R, Beuchat LR, Chinnan MS, Shewfelt RL, Huang YW (1996) Inactivation of Salmonella montevideo on Tomatoes by Applying Cellulose-Based Edible Films. J Food Prot 59:808–812. https://doi.org/10.4315/0362-028X-59.8.808
179. Millette M, Le Tien C, Smoragiewicz W, Lacroix M (2007) Inhibition of Staphylococcus aureus on beef by nisin-containing modified alginate films and beads. Food Control 18:878–884. https://doi.org/10.1016/J.FOODCONT.2006.05.003
180. Vartiainen J, Motion R, Kulonen H, Rättö M, Skyttä E, Ahvenainen R (2004) Chitosan-coated paper: Effects of nisin and different acids on the antimicrobial activity. J Appl Polym Sci 94:986–993. https://doi.org/10.1002/APP.20701
181. Carlin F, Gontard N, Reich N, Nguyen-The C (2001) Utilization of Zein Coating and Sorbic Acid to Reduce Listeria monocytogenes Growth on Cooked Sweet Corn. J Food Sci 66:1385–1389. https://doi.org/10.1111/J.1365-2621.2001.TB15219.X
182. Natrajan N, Sheldon BW (2000) Inhibition of Salmonella on poultry skin using protein- and polysaccharide-based films containing a nisin formulation. J Food Prot 63:1268–1272. https://doi.org/10.4315/0362-028X-63.9.1268
183. Cha DS, Choi JH, Chinnan MS, Park HJ (2002) Antimicrobial films based on Na-alginate and κ-carrageenan. LWT - Food Sci Technol 35:715–719. https://doi.org/10.1006/FSTL.2002.0928
184. Fiorentini C, DusermGarrido G, Bassani A, Cortimiglia C, Zaccone M, Montalbano L, Martinez-Nogues V, Cocconcelli PS, Spigno G (2022) Citrus Peel Extracts for Industrial-Scale Production of Bio-Based Active Food Packaging. Foods. 11:30. https://doi.org/10.3390/foods11010030
185. Bi J, Tian C, Zhang G-L, Hao H, Hou H-M (2021) Novel procyanidins-loaded chitosan-graft-polyvinyl alcohol film with sustained antibacterial activity for food packaging. Food Chem 365:130534. https://doi.org/10.1016/j.foodchem.2021.130534
186. Chen F, Chi C (2021) Development of pullulan/carboxylated cellulose nanocrystal/tea polyphenol bionanocomposite films for active food packaging. Int J Biol Macromol 186:405–413. https://doi.org/10.1016/j.ijbiomac.2021.07.025
187. Wu H, Teng C, Liu B, Tian H, Wang J (2018) Characterization and long term antimicrobial activity of the nisin anchored cellulose films. Int J Biol Macromol 113:487–493. https://doi.org/10.1016/j.ijbiomac.2018.01.194
188. Aliheidari N, Fazaeli M, Ahmadi R, Ghasemlou M, Emam-Djomeh Z (2013) Comparative evaluation on fatty acid and Matricaria recutita essential oil incorporated into casein-based film. Int J Biol Macromol 56:69–75. https://doi.org/10.1016/j.ijbiomac.2013.02.007
189. Alboofetileh M, Rezaei M, Hosseini H, Abdollahi M (2014) Antimicrobial activity of alginate/clay nanocomposite films enriched with essential oils against three common foodborne pathogens. Food Control 36:1–7. https://doi.org/10.1016/j.foodcont.2013.07.037
190. Vahedikia N, Garavand F, Tajeddin B, Cacciotti I, Jafari SM, Omidi T, Zahedi Z (2019) Biodegradable zein film composites reinforced with chitosan nanoparticles and cinnamon essential oil: Physical, mechanical, structural and antimicrobial attributes. Colloids Surfaces B Biointerfaces 177:25–32. https://doi.org/10.1016/j.colsurfb.2019.01.045
191. Guerra-Rosas MI, Morales-Castro J, Cubero-Márquez MA, Salvia-Trujillo L, Martín-Belloso O (2017) Antimicrobial activity of nanoemulsions containing essential oils and high methoxyl pectin during long-term storage. Food Control 77:131–138. https://doi.org/10.1016/j.foodcont.2017.02.008
192. Souza VGL, Pires JRA, Vieira ÉT, Coelhoso IM, Duarte MP, Fernando AL (2019) Activity of chitosan-montmorillonite bionanocomposites incorporated with rosemary essential oil: From in vitro assays to application in fresh poultry meat. Food Hydrocoll 89:241–252. https://doi.org/10.1016/j.foodhyd.2018.10.049
193. Abdollahi M, Damirchi S, Shafafi M, Rezaei M, Ariaii P (2019) Carboxymethyl cellulose-agar biocomposite film activated with summer savory essential oil as an antimicrobial agent. Int J Biol Macromol 126:561–568. https://doi.org/10.1016/j.ijbiomac.2018.12.115
194. Min T, Sun X, Yuan Z, Zhou L, Jiao X, Zha J, Zhu Z, Wen Y (2021) Novel antimicrobial packaging film based on porous poly (lactic acid) nanofiber and polymeric coating for humidity-controlled release of thyme essential oil. Lwt 135:110034. https://doi.org/10.1016/j.lwt.2020.110034