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Review

A Review on Antimicrobial Packaging for Extending the Shelf Life of Food

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Abstract: Food packaging systems are continually impacted by the growing demand for minimally processed foods, changing eating habits, and food safety risks. Minimally processed foods are prone to the growth of harmful microbes, compromising quality and safety. As a result, the need for improved food shelf life and protection against foodborne diseases alongside consumer preference for minimally processed foods with no or lesser synthetic additives foster the development of innovative technologies such as antimicrobial packaging. It is a form of active packaging that can release antimicrobial substances to suppress the activities of specific microorganisms, thereby improving food quality and safety during long-term storage. However, antimicrobial packaging continues to be a very challenging technology. This study highlights antimicrobial packaging concepts, providing different antimicrobial substances used in food packaging. We review various types of antimicrobial systems. Emphasis is given to the effectiveness of antimicrobial packaging in various food applications, including fresh and minimally processed fruit and vegetables and meat and dairy products. For the development of antimicrobial packaging, several approaches have been used, including the use of antimicrobial sachets inside packaging, packaging films, and coatings incorporating active antimicrobial agents. Due to their antimicrobial activity and capacity to extend food shelf life, regulate or inhibit the growth of microorganisms and ultimately reduce the potential risk of health hazards, natural antimicrobial agents are gaining significant importance and attention in developing antimicrobial packaging systems. Selecting the best antimicrobial packaging system for a particular product depends on its nature, desired shelf life, storage requirements, and legal considerations. The current review is expected to contribute to research on the potential of antimicrobial packaging to extend the shelf life of food and also serves as a good reference for food innovation information.

Keywords: food packaging; antimicrobial agent; active packaging; shelf life; fruit and vegetables; meat products

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1. Introduction

Packaging is a crucial phase in the food manufacturing process since it preserves the quality of food products for storage, transportation, and end-use [1–3]. Packaging is necessary for fresh and processed food products to protect against external factors such as contaminants, gas composition, spoilage bacteria, mechanical loadings, and physical damage [4–9]. A food product's quality can deteriorate physiologically, chemically, and physically throughout distribution. Food packaging extends the shelf life of food products while ensuring their quality and safety [3,10]. Packaging plays a vital role in the postharvest handling and transportation of fresh and processed food and other biomaterials [4,11–13].

Nowadays, the increase in consumer demand for minimally processed foods prone to spoilage compromises food safety and quality [14–16]. Food spoilage caused by microbial growth or activity is the most prevalent cause of food degradation, making the food unsafe for consumption and resulting in food loss [17,18]. This has spurred the need for innovations in food packaging technologies, which involve contributions from engineers, microbiologists, food scientists, chemists, regulators, and other professionals [19]. One such technological advancement in food packaging is the development of active packaging. Active packaging serves functions other than conventional protection and providing an inert barrier to the external environment, and it is designed to safeguard food quality [20].

Active packaging can be described as a form of packaging in which the package, the product, and the environment interact to extend shelf life or enhance safety or sensory attributes while preserving product quality [21–24]. This is especially significant in fresh and extended shelf life foods. Food shelf life is "the period during which a food retains acceptable characteristics of flavor, colour, aroma, texture, nutritional value, and safety, under defined environmental conditions" [10]. According to Anwar and Warsiki [20], active packaging is designed to detect changes in the internal environment and respond by altering the package's characteristics to prolong the shelf life of foods. That is, active packaging design involves incorporating active substances intended to be released into the food or absorbed into or from the packed food or the environment surrounding the food (Figure 1) [15,24–26]. Hence, active packaging can be grouped into active scavenging systems (absorbers) and active-releasing systems (emitters). While absorbers remove undesirable substances such as moisture, carbon dioxide, oxygen, ethylene, UV light, etc., from food or the environment, emitters add substances such as antimicrobial compounds, carbon dioxide, antioxidants, and flavors to packed food or the headspace [25,27]. An overview of the active packaging grouping is shown in Figure 1. These active packaging systems can be prepared by incorporation, coating, immobilization, or surface modification onto the packaging materials [28].

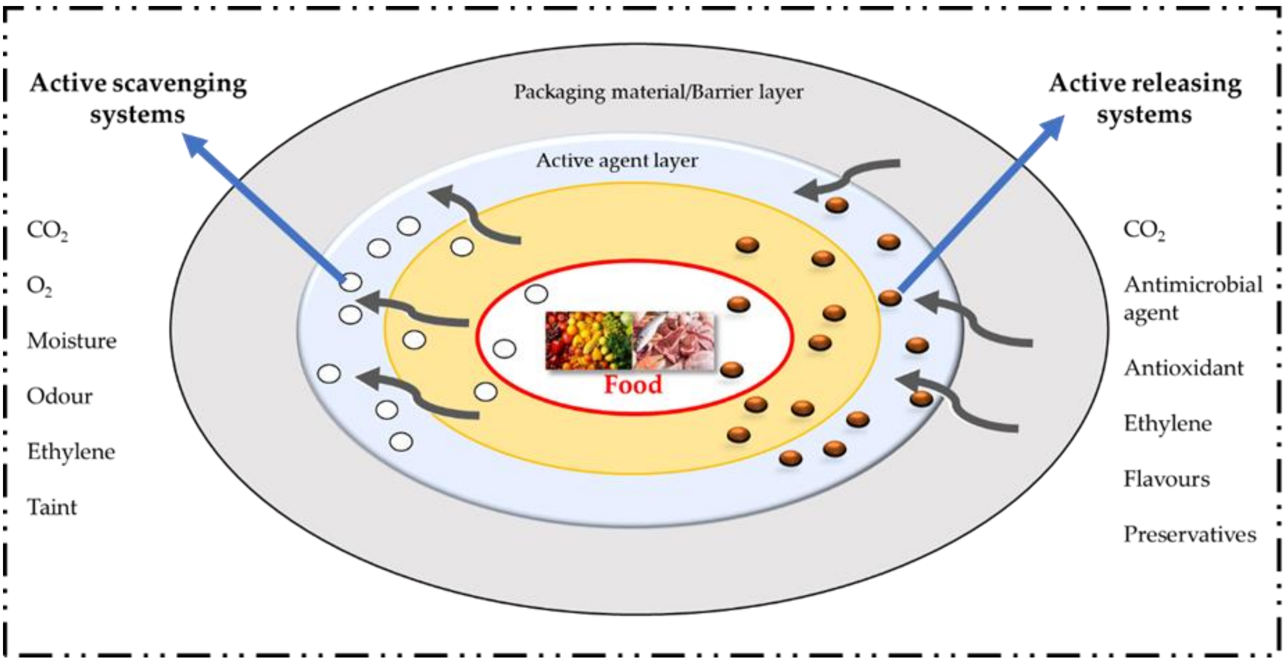

Figure 1. Illustration of the active scavenging and releasing systems used in food packaging.

Over the years, consumers' surge of interest in minimally processed and additive-free foods has resulted in the ongoing development of an intriguing innovation in active packaging known as antimicrobial packaging [10,20]. Antimicrobial packaging systems are based on packaging materials with incorporated antimicrobial agents in the packaging matrix and/or antimicrobial polymers [20]. When a packaging system (or material) obtains antimicrobial activity, it inhibits or prevents microbial development by extending the lag time and reducing the growth rate or decreasing microbe live counts. Hence, antimicrobial packaging helps inhibit spoilage and reduce pathogenic microorganisms by incorporating packaging with antimicrobials, consequently extending food shelf life by prolonging the lag period of microorganisms, thereby diminishing their growth and number [20,29]. Antimicrobial packaging is intended to act against microorganisms and enhance the functions of conventional food packaging, which are (1) shelf life extension, (2) maintenance of quality, and (3) safety assurance [15,22,29].

There are several excellent recent reviews on food packaging systems, particularly with active characteristics, including active packaging in the food industry/foods [23,25,30], active packaging coatings [28,31], active edible films and packaging [31–33], natural antioxidants in active food packaging [34], innovative active, intelligent and smart packaging technologies [35], active packaging applications to muscle foods [36], active packaging films in the meat industry [37], active packaging in bakery products [38], and pectin-based active packaging [39], to name a few examples. Given the promising reports and interventions in antimicrobial packaging research to extend food shelf life and ensure food safety by inhibiting microbial growth in packaged foods and packaging materials, this research area has emerged as an independent focus area with positive consumer response. Therefore, this current review provides a focused and precise concept of antimicrobial packaging for extending the shelf life of food, emphasizing selected representative publications within the last decade.

2. The Basic Concept of Antimicrobial Packaging

Generally, food products are prone to microbial contamination, which is one of the main causes of foodborne diseases and constitutes a major public health concern and economic burden on the food industry [14,40,41]. Antimicrobial food packaging aims at reducing, inhibiting, or retarding the growth of spoilage or pathogenic microorganisms that may be present in the packaged food or packaging material itself. Antimicrobial packaging is an important system used as a delivery mechanism of antimicrobials to limit the growth of microorganisms at all stages from transportation to final consumption [41,42]. Antimicrobial packaging systems involve incorporating antimicrobial agents into packaging materials. The main objectives of these agents are to control or reduce the growth of non-desirable microorganisms on the food surface. They are often transmitted from the container to the food surface and utilized as coatings on various polymeric materials or in the mass of the polymer. An antimicrobial agent's activity is carried out either by contact of microorganisms onto the interior surface of the packaging material or directly in the food through emission or gradual diffusion of the antimicrobial agent from the packaging material to the food [42,43]. Their controlled release throughout the food's shelf life presents a promising active packaging mechanism that ensures safety and improved shelf life [44].

3. Antimicrobial Substances/Agents in Food Packaging

Antimicrobial agents used in active packaging are expected to extend the lag phase and reduce the growth rate of microorganisms, thus prolonging shelf life and maintaining food safety [45]. Essentially, food-grade condition is a crucial requirement for formulating antimicrobial packaging systems. Hence, antimicrobial agents must be present at the food surface above their minimum inhibitory concentration (MIC) to be effective. Due to variations in their physiologies, they have different activities on different pathogenic microorganisms [10]. The antimicrobial agent is integrated either directly into food particles or into polymer film/packaging to suppress the activities of targeted microorganisms, such as *Listeria monocytogenes*, *Mycobacterium smegmatis* (MTCC 943), *Pseudomonas aeroginosa* (MTCC 4676), *Escherichia coli* O157, *Salmonella*, *Staphylococcus aureus*, *Bacillus cereus*, *Campylobacter*, *Clostridium perfringens*, *Aspergillus niger*, *Saccharomyces cerevisiae*, etc. [10]. Microorganism characterization can be very beneficial in the selection of an antibacterial agent.

Despite their efficacy in extending food shelf life, some studies claimed that antimicrobial agents add to the complexity of packaging materials and induce changes in package attributes (mechanical, thermal, permeability properties) as well as alter the appearance of the packaging and the product [46–48]. Albeit, antimicrobial packaging improves the performance of food packaging [49–51].

Various antimicrobial agents may be incorporated into packaging systems. They include organic acids, mineral acids, inorganics, phenolic compounds, and isothiocyanates [22]. These antimicrobial agents can be categorized into natural or chemical (synthetic) agents. Their application often depends on the packaging material. For instance, studies proposed that potassium sorbate and nisin antimicrobial compounds added to a chitosan matrix to create an active packaging film reduced the resistance and increased the flexibility of the active film [52]. Similarly, Sung et al. [53] added *Allium sativum* essence oil (AEO) into plastic films to test for antimicrobial activities against beef-related bacteria, namely *Listeria monocytogenes*, *Escherichia coli*, and *Brochothrix thermosphacta*. The film's mechanical properties were slightly affected by the AEO, and a significant increase in the film crystallinity with a small amount of incorporated AEO was reported [53].

Despite the approval of chemical antimicrobial agents (sodium benzoates and propionates, potassium sorbates, sorbic acid, sulfites, chlorides, nitrites, triclosan, nisin, tartaric acid, etc.) by regulatory agencies, many of these agents continue to pose nutritional or health threats for the end-users [54–57]. As a result, natural antimicrobial agents are gaining much importance and attention due to their antimicrobial activity potential to extend food shelf life and control or prevent the growth of microorganisms [54,58,59]. Additionally, consumer awareness of the potential adverse effect of synthetic or chemical preservatives versus the advantages of natural additives/alternatives has increased the interest in developing and using natural products for food preservation and microorganism control or prevention. These are commonly referred to as natural antimicrobial agents. Natural additives come from organic matter and can be obtained from plants, animals, fungi, and algae; hence, they reduce exposure to potential health hazards [55].

The extensive application of natural antimicrobial agents, primarily as preservatives in fruit and vegetables, has been reported to ensure safety, protect the quality, and extend shelf life [55]. Natural antimicrobials are secondary metabolites possessing antimicrobial activity [54,55,60]. They have antibacterial and antioxidant properties and are considered preferable alternatives to synthetic antimicrobials because they can be derived from various sources, including plants, animals, and microorganisms which are the most common [58,61–63]. According to several studies, most important natural antimicrobial compounds are essential oils obtained from plants (e.g., basil, thyme, oregano, cinnamon, clove, sage, vanillin, and rosemary); enzymes obtained from animal sources (e.g., lysozyme, lactoferrin), bacteriocins from microbial sources (nisin, natamycin, lactocin, pediocin) and organic acids (e.g., sorbic, propionic, citric acid) and naturally occurring polymers (chitosan) [54,64,65].

Plants are considered the most important and rich natural source of antimicrobial substances [54]. These plant compounds have antimicrobial, antioxidant, flavor, and color-enhancing properties. These plant agent qualities lengthen the product's shelf life and improve its organoleptic acceptability. These compounds serve an important function in inhibiting the growth of foodborne pathogens and, as a result, lowering the risk of disease [54,62]. Therefore, they build consumer confidence regarding the consumption of food products. Commercially based plant-origin antimicrobials are commonly produced by SD (steam distillation) and HD (hydro-distillation) methods as well as alternative methods such as SFE (supercritical fluid extraction) from aromatic and volatile oily liquids from flowers, buds, seeds, leaves, twigs, bark, herbs, wood, fruits, and roots of plants [54].

The antimicrobial substances used to activate packaging materials can be included in the groups of metals, chemicals, plant extracts, enzymes, and bacteriocins. The activities of each address a restricted group of microorganisms, but their actions can be combined with those of other hurdles to enlarge the spectrum of microbial targets. To inhibit the growth of undesired microbes in food, natural antimicrobials can be directly added to the product composition, coated on its surface, or incorporated into the packaging material. Introducing active agents into food results in an immediate but short decrease in microbial pathogens, whereas antimicrobial films can sustain their activity for an extended time [54].

Antimicrobial packaging has attracted the attention of many researchers due to the variety of materials used, its advantages and disadvantages, and the ability to improve the shelf life of food and agricultural products. Most importantly, they help reduce, inhibit, or retard spoilage microorganisms' growth in food products, thus preventing food spoilage and decay. One of the current challenges is the impact of antimicrobial agents on packaging properties. For instance, the polymer is common for fabricating packaging layouts [46], and studies have shown that antimicrobial agents alter the barrier properties of polymer films [66,67]. Incorporating antimicrobial agents into polymer films enhances the hydrophobic ratio, increasing the transfer coefficient while decreasing the water vapor permeability (WVP) [68]. Furthermore, some antimicrobial agents, such as lactoperoxidase, lysozyme, and lactoferrin, reduce the permeability properties of polymers [69]. Hence, the use of nano-clay in combination with a polymeric material has been recommended by different studies to improve the mechanical, thermal, and permeability properties [70–72].

In some cases, combining antimicrobial agents with polymers might have drawbacks that limit large-scale production and increase production costs [73]. Although integrating antimicrobial agents and polymers by extrusion is straightforward, some of the antimicrobial agents evaporate due to the high temperature caused by the extrusion process. Furthermore, due to antimicrobial agent dispersion, the extrusion process results in antimicrobial agent loss [74]. As a result, researchers apply antimicrobial agents to the adhesive layer that links the laminate's various layers [75,76]. It has also been proposed to use antimicrobial agent bags in inclusion complexes (ICs) [77,78]. Some researchers, however, do not endorse this strategy due to customer reluctance to purchase this type of packaging. Hence, various antimicrobial agents, including ICs, are inserted at the package's bottom or head (in the form of two or more layers) [79–81]. Table 1 shows the application of various antimicrobial agents in previous research.

Table 1. Overview of the use of several antimicrobial agents in various products.

Antimicrobial Agent	Utilization Method	Food Product	References
Sorbates	Combination of antimicrobial agent with low-density polyethylene material	Cheese	[82]
Potassium Sorbate Chitosan	The starch film incorporated with antimicrobial agents	Sweet potato	[83]
Lysozyme	Layer by layer, assembled chitosan organic rectorite	Pork	[84]
Butylated hydroxytoluene	Incorporating the antimicrobial with High-Density Polyethylene (HDPE)	Cereal	[47]
Sodium benzoate Potassium sorbate	Edible active coatings (EACs) incorporated with antimicrobial agents	Strawberry	[85]
Nisin Chitosan Potassium sorbate Silver substituted zeolite	Active multilayer bags (Low-Density Polyethylene (LDPE)/polyamide)	Chicken drumsticks	[86]
Benzoic acid Sodium metabisulphite Tert-butylhydroquinone Etil-N-lauroyl-L-arginine Cinnamon essential oil Oregano essential oil	Incorporating the antimicrobial substance into the adhesive layer	Tomato puree	[75]
N-α-lauroyl-l-arginine	Casting of oxidized starch gelatin solutions	Chicken fillets	[87]
ß-Cyclodextrin	Packaging with a double-bottom (with trapped antimicrobial volatile)	Apple	[88]
Oregano essential oil	Resveratrol nanoemulsion loaded edible pectin coating	Pork loin	[89]
Encapsulated cumin	Encapsulated cumin seed essential oil-loaded active papers	Beef hamburger	[90]

4. Constructing/Developing an Antimicrobial Packaging

Most food packaging systems are represented by either a package/food system or a package/headspace/food system [24]. A package/food system consists of a solid food product in contact with the packaging material or a low-viscosity or liquid food with no headspace [22,91]. The key migratory processes in this system include diffusion between the packaging material and the food and partitioning at the interface. Depending on the packaging material, type of antimicrobial agent, and the food product, antimicrobial agents are added to the packaging material. The addition may be through immobilization, coating, or simple blending with the packaging materials. The incorporated antimicrobial agents then migrate into the food through diffusion and partitioning [22,24], although immobilized agents cannot migrate [91].

Generally, antimicrobial packaging systems can be considered as migrating or nonmigrating, which is a function of the antimicrobial agent and its integration with the packaging material and food matrix [55,92]. For instance, while the active agent is released into and onto the package headspace and food surface, respectively, from the packaging material in a migrating system, the active agent is immobilized with the material in a nonmigrating system. Direct contact between the packaging material and the food product is not necessary for effective antimicrobial activity in a migrating system. However, it is crucial for antimicrobial activity efficacy in a nonmigrating system [57,92]. However, both primarily serve to protect food from microbial deterioration and spoilage. The mechanism of action of antimicrobial agents integrated into packaging materials is determined by the controlled and delayed release of the agent onto food surfaces. This is essential to maintain a suitable concentration of the agent in the food and effectively suppress microbial development during the food product's shelf life [46,57,93,94].

Figure 2 illustrates an antimicrobial system and the relative behavior of active substances.

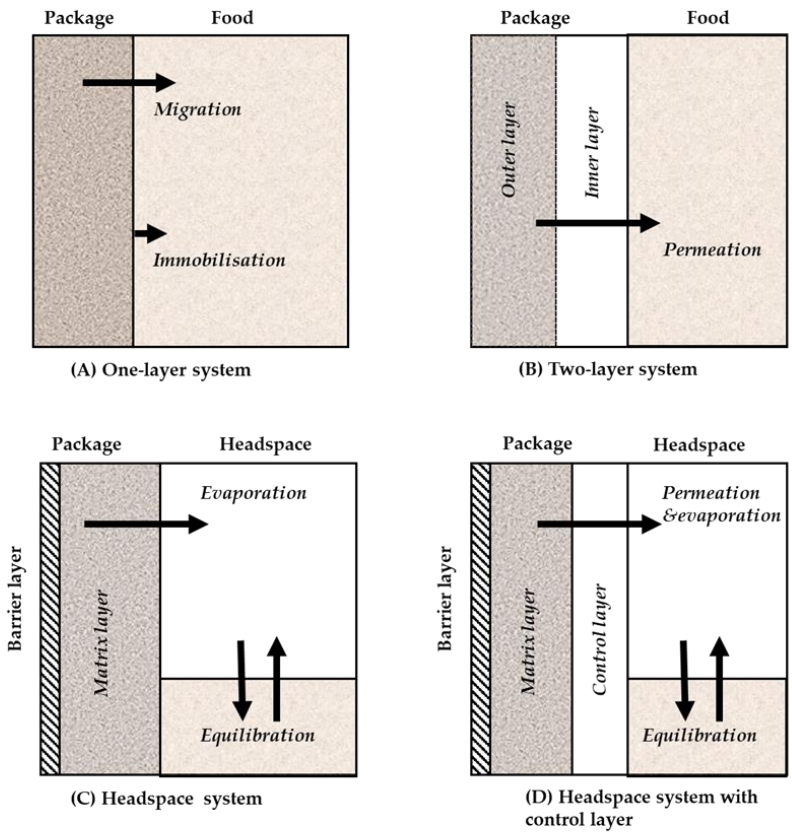

Figure 2. Antimicrobial packaging system (adapted from Jideani and Vogt (2016) [22] and Han (2003) [91]).

In Figure 2A,B, antimicrobial agents are released through diffusion between the packaging material and the food and partitioning at the interface. The inclusion of the antimicrobial agent into the packaging material is chemically bonded via immobilization (Figure 2A). In Figure 2A, the antimicrobial agent is incorporated into the packaging material. To regulate the release rate, particularly in the two-layer system (Figure 2B), the antimicrobial agent (outer layer) is coated on the packaging material (inner layer), or the antimicrobial matrix layer (outer layer) is laminated with the control layer (inner layer). Figure 2C depicts a headspace system. Here, the volatile antimicrobial agent initially integrated into the matrix layer is released into the headspace. Equilibrated sorption/isotherm is used to partition the headspace antimicrobial agent from the food product. A headspace system with a control layer is shown in Figure 2D. The control layer precisely regulates the permeability of the volatile antimicrobial agent and maintains a specific headspace concentration [91,92]. Figure 2C,D show that the antimicrobial agent's volatility permits it to reach the gaseous-phase particle's headspace to contact the food product.

5. Types of Antimicrobial Packaging Systems

Antimicrobial packaging can take many forms, including sachets/pads containing volatile antimicrobial agents; polymers containing volatile and nonvolatile antimicrobial agents; antimicrobial coats on polymer surfaces; ionic or covalent linkages between antimicrobials and polymers due to immobilization techniques; and inherently antimicrobial polymers [43].

5.1. Sachets or Pads Containing Volatile Antimicrobial Agents inside Packages

Sachets or pouches and pads that are sealed loose or affixed to the interior of a container have been the most effective commercial application of antimicrobial packaging and have played a significant role in food preservation [82,95–97]. They are described as pads containing volatile antimicrobial agents inserted inside the food environment to allow the antimicrobial to gradually release and interact with the headspace in the package, inhibiting the microbial growth of the food product's surface [42]. The gradual release of the active agent is propelled by the moisture concentration inside the package [42]. There are two techniques for producing antimicrobial-releasing sachets: sachets that create antimicrobial compounds in situ and release them, and sachets that transport and release antimicrobials [96]. Oxygen scavengers, moisture absorbers, carbon dioxide scavengers and generators, ethanol and chlorine dioxide generators are the most common commercial applications. These commercially available systems for food applications are summarized by Suppakul et al. [16] and Han et al. [19].

Oxygen scavengers are used primarily in meat, bakery, dairy, pasta, and produce packaging to prevent oxidation, microbial growth, and spoilage reactions in foods [24,97,98]. Moisture absorbers inhibit microbial growth by lowering water activity and are mainly used in foods such as cheeses, meats, chips, nuts, gums, and spices [99]. The most common moisture absorber is silica gel because it remains dry and free-flowing even when saturated [30].

Typically, microbial growth is suppressed by the presence of carbon dioxide in a packaging system. Carbon dioxide generators are used in packaging for fresh produce, where an increased concentration of CO_2 coupled with decreased O_2 concentration slows the respiration rate, extending the product's shelf life [30]. They are also considered antimicrobials because of their inhibitory activity against a range of aerobic bacteria and fungi [97]. Carbon dioxide generators are commonly used in meat and poultry packaging [30,100,101]. Excess CO_2 concentration in a package for some CO_2-producing foods may result in the high-level dissolution of CO_2 into the food. Consequently, increasing the package's pressure (or volume) due to low CO_2 permeation leads to undesirable changes in product quality in terms of texture and flavor and package collapse [16,19,102]. To avoid this adverse effect, CO_2 absorbers may be used to prevent package rupture, particularly during storage [97].

The antimicrobial properties of ethanol are widely known. Ethanol generators reduce the rate of staling and oxidative changes in foods such as cheeses, bread, and bakery products as well as the incidence of microbial deterioration [16]. Encapsulated ethanol sachets emit their vapor into the package headspace, maintaining the preservation effect [103,104]. However, one disadvantage is the typical off-flavor of ethanol. Ethanol generators effectively control about ten species of mold, including *Aspergillus* and *Penicillium* species, different species of bacteria, including *Salmonella*, *Staphylococcus*, and *E. coli*, as well as species of spoilage yeast [105].

Chlorine dioxide (ClO_2) is a powerful oxidizing and sanitizing agent used in gaseous or aqueous forms to wash fresh produce to keep them safe from bacterial contamination [106,107]. The effectiveness of chlorine dioxide generators in controlling pathogenic and spoilage microorganisms, thereby increasing food product shelf life, was reported by [108]. Ray et al. (2013) developed a chlorine dioxide (ClO_2)-releasing packaging for fresh produce decontamination. The authors found that the released ClO_2 reduced *Salmonella* spp. and *E. coli* O157:H7 inoculated on the tomatoes to undetectable levels [109].

While sachets, pouches, and pads have several benefits, they have a few drawbacks. Because sachets and pads are often placed in each package manually, packaging time is increased, thereby limiting productivity [95,110]. Another drawback is the inability to use them in liquid foods. Liquids touching the sachet material may cause leakage of its contents. Another disadvantage is consumer acceptability. Loose sachets may be mistaken for food, posing a concern due to the risk of disintegration, contamination, and unintentional consumption [95].

5.2. Polymers with Intrinsic Antimicrobial Properties

Chitosan and poly(ε-lysine) have been the only natural polymers with inherent antimicrobial characteristics [111,112]. These polymers are made of polycations, which can kill microorganisms by acting on their negatively charged cell membranes [113]. That is, they inhibit microbial growth by causing leakage of intracellular constituents of microbial cells [15]. Using bioactive polymers, such as chitosan, has intrinsic antimicrobial action in composites or coatings [10,114,115]. Chitosan is the world's second most prevalent natural polymer after cellulose. It is a promising material owing to its outstanding biodegradability, biocompatibility, antimicrobial activity, non-toxicity, film-forming properties, and economic benefits [114,116–118]. The use of chitosan-based films, coatings, and treatments applied to the food package inherently possesses antimicrobial properties and has resulted in the extension of the shelf life of a wide food range, including fresh produce, meat products, bread, and dairy products [15,116]. Chitosan's antimicrobial activity is primarily influenced by its molecular weight (MW) and degree of deacetylation (DD), among other physicochemical parameters [116,119].

Current chitosan film production processes include direct casting, coating, layer-by-layer assembly, and extrusion. The procedures may be employed for either pure chitosan films or chitosan films mixed with other polymers. Priyadarshi and Rhim [120] presented a comprehensive review of these methods. To enhance the applicability and functionality of chitosan in films and coatings as a food packaging material, it has to be combined with some other biopolymers [120,121]. Polysaccharides, proteins, extracts, and organic acids are examples of these biopolymers. It has also been demonstrated that incorporating nanoparticles into chitosan-based food packaging inhibits the growth of spoilage and pathogenic bacteria, improves food quality and safety, and extends food shelf life [116]. Because of its noble nature, silver is the most utilized nanoparticle. Silver nanoparticles (AgNPs) have antibacterial, antifungal, anti-yeast, and anti-viral properties and may be coupled with non-degradable and edible polymers for active food packaging [122,123]. Chitosan and silver nanoparticles could be homogeneously distributed in a polymer matrix via a green chemistry methodology [114]. Zinc oxide (ZnO) is another essential nanomaterial widely considered safe and utilized as a food additive [124]. They can be incorporated into polymeric matrices to provide antimicrobial activity and improve packaging qualities [125]. Table 2 highlights examples of chitosan films enhanced with polymers and nanomaterials.

Table 2. Some examples of studies with chitosan film enhanced with polymers and nanomaterials.

Packaging Material (Chitosan + Polymer, Chitosan + Nanomaterial)	Target Microorganism	Antimicrobial Functionality	Reference
Chitosan + Gallic acid	Two Gram-negative bacteria: *E. coli* and *Salmonella typhimurium*, and two Gram-positive bacteria: *Bacillus subtilis* and *Listeria innocua*	Gallic acid significantly increased the antimicrobial activities of chitosan films	[126]
Chitosan + Maqui berry (MB) extracts	*L. innocua*, *Serratia marcescens*, *Aeromonas hydrophila*, *Achromobacter denitrificans*, *Alcaligenes faecalis*, *Pseudomonas fluorescens*, *Citrobacter freundii* and *Shewanella putrefaciens*	Pure chitosan film effective against only *S. putrefaciens* and *P. fluorescens* Chitosan with MB films were effective against all the bacteria except *L. innocua*	[127]
Chitosan film + Propolis extract (PE)	Gram-positive bacteria (*S. aureus*) and Gram-negative bacteria (*E. coli*, *Pseudomonas aeruginosa*, and *Salmonella Enteritidis*)	Chitosan alone did not show any inhibition against tested bacteria Antimicrobial activity was evident for chitosan + PE	[128]
Chitosan + Rosemary essential oil (REO)	*Listeria monocytogenes*, *Pseudomonas putida*, *Streptococcus agalactiae*, *E. coli*, and *Lactococcus lactis*	Notable inhibitory activity on microorganisms	[129]
Chitosan + Glycerol	*E. coli*, *S. aureus* and *A. niger*	High content of chitosan film had antimicrobial properties compared with a low chitosan content film Chitosan film with increasing glycerol had no bacteriostatic effect	[130]
Chitosan + Peptide	*E. coli* and *B. subtilis*	All developed films exhibited antibacterial activity No significant improvement in antibacterial activity with the addition of soy or corn peptides	[131]
Chitosan + Squid gelatin hydrolysates (SGH)	*Aspergillus parasiticus*	Fungistatic activity of the chitosan films was not significantly improved with the addition of 10% SGH Fungistatic index increased by 34% by adding 20% SGH	[132]
Chitosan + Olive leaf extract (OLE)	*E. coli*, *L. monocytogenes*, and *Campylobacter jejuni* subsp. *jejuni*	Chitosan + OLE films have significant antimicrobial activity against *L. monocytogenes* and *C. jejuni* but are not evident for *E. Coli.*	[133]
Chitosan + AgNPs or Zinc oxide nanoparticles (ZnONPs)	*S. aureus*, *E. coli*, *Salmonella typhamrium*, *B. cereus*, and *Listeria monocyte.*	Developed chitosan nanocomposite films showed high antimicrobial activity	[134]
Chitosan + ZnONPs	Gram-positive bacterium *Bacillus subtilis* (*B. subtilis*) and Gram-negative bacterium (*E. coli*)	Twofold and 1.5-fold increment in the antimicrobial activity was observed for *B. subtilis* and *E. coli*, respectively, with increased ZnONPs concentration in the films from 0(w/w) to 2%(w/w)	[135]
Chitosan + AgNPs	Gram-positive bacteria: *S. aureus* and pathogenic yeast: *Candida albicans* (*C. albicans*)	Developed film significantly inhibited the growth of *S. aureus* and showed marked antifungal activity against *C. albican*	[136]
Chitosan + ZnONPs + Gallic acid	Gram-positive *B. subtilis* and Gram-negative *E. coli*	Resultant film was efficient against the microorganisms and has a great potential application for improving the shelf life of food products	[137]

Table 2. *Cont.*

Packaging Material (Chitosan + Polymer, Chitosan + Nanomaterial)	Target Microorganism	Antimicrobial Functionality	Reference
Chitosan/pullulan (CS/PL) nanocomposite films + clove essential oil (CEO) loaded Chitosan-ZnO hybrid nanoparticles	*Pseudomonas aeruginosa (P. aeruginosa)*, *S. aureus*, and *E. coli*	Developed film enhanced antioxidant activity and showed strong antibacterial activity against the target microorganisms	[138]
Chitosan/Zein films + *Mosla chinensis* EOs nanoemulsions (NEs) and NPs	*P. aeruginosa*, *B. subtilis*, *E. coli* and *S. aureus*	Bacterial growth of *S. aureus*, *B. subtilis* and *E. coli* was inhibited in both EO-loaded NP and NE films.	[139]
Chitosan + polyvinyl alcohol (PVA) + Fe_2O_3/TiO_2 ($FeTiO_2$) NPs	*E. coli*, *S. aureus*, *A. niger* and *C. albicans*	Nanocomposites films had good antibacterial activity	[140]
Chitosan + Guar gum + PVA + Moringa extract (ME)	*E. coli* and *S. aureus*	PVA and guar gum did not show any antibacterial activity Incorporating ME enhanced the antibacterial activity against *S. aureus* and *E. coli* bacteria	[141]
Chitosan + turmeric essential oil (TEO) + magnetic-silica nanocomposites	*Bacillus cereus*	TEO exhibited antioxidant and antibacterial activities against *Bacillus cereus* Chitosan film incorporated with the bionanocomposite had a stronger antibacterial effect against *B. cereus* than the chitosan film containing only TEO	[142]

Sun et al. [126] prepared chitosan film with different gallic acid concentrations. The authors evaluated the developed films' antimicrobial, mechanical, physical, and structural properties. Antimicrobial activity was assessed against two Gram-negative bacteria, *E. coli* and *Salmonella typhimurium*, as well as two Gram-positive bacteria, *B. subtilis*, and *L. innocua*. Chitosan films infused with gallic acid considerably increased their antimicrobial properties, and the films reduced microbial growth by 2.5-log reduction. In another recent investigation, Li et al. [131] developed chitosan/peptide films by incorporating peptides (0.4%, *w*/*v*) from soy, corn, and caseins into chitosan films. Peptides are protein fragments that exist as host defense molecules in the innate immune systems of invertebrates and vertebrates with unique functional activities (e.g., antimicrobial, antioxidant, antithrombotic) [143]. The antibacterial activity of films was tested against *E. coli* and *B. subtilis.* Due to the presence of chitosan, all the films demonstrated antimicrobial activity. The inclusion of soy or corn peptides did not significantly increase the antibacterial activity of the films. However, adding casein peptides increased the film's antibacterial activity and inhibited the growth of *E. coli* and *B. subtilis*.

Qin et al. [144] developed active packaging films by integrating AgNPs and anthocyanin-rich purple corn extract (PCE) into chitosan. The chitosan/AgNPs/PCE film had the best barrier, mechanical, antioxidant, and antimicrobial properties [144]. Enhanced antimicrobial activity was shown against four foodborne pathogenic bacteria strains (*E coli*, *S. aureus*, *Salmonella*, and *L. monocytogenes*). Notably, the chitosan/AgNPs/PCE film's antimicrobial properties were the strongest, while the chitosan/PCE film had the lowest antimicrobial properties. The enhanced activity could be related to AgNPs' interaction with membrane proteins, enzymes, and nucleic acids, leading to cell lysis and death [145], and the presence of abundant anthocyanins in PCE [127,146]. Mohamed and Madian [136] successfully developed chitosan films doped with silver nanoparticles. The authors showed that incorporating silver nanoparticles into chitosan film significantly increased its mechanical characteristics and antimicrobial activity. Compared with pure chitosan film, silver nanoparticles doped with chitosan films showed significant antibacterial activity against

S. aureus [136]. Yadav et al. [137] developed an active packaging film made of chitosan and ZnONPs loaded with gallic acid (Ch-ZnO@gal) using the casting method. The antibacterial activity of the films was evaluated against both bacterial strains, i.e., Gram-positive *B. subtilis* and Gram-negative *E. coli*. The developed film possessed significant antibacterial potential compared to pure chitosan film. The findings were related to the impact of reactive oxygen species released by ZnONPs loaded with gallic acid and Zn^{2+} ions. They attack the negatively charged cell wall, causing leakage and, eventually, bacterial death [147–149].

5.3. Antimicrobial Coating or Adsorption on Polymer Surfaces

Here, the packaging is coated with a matrix that acts as a carrier for the antimicrobial agent. Antimicrobials that cannot tolerate polymer processing temperatures or heat-sensitive antimicrobials, such as volatile chemicals, are often coated onto the packaging materials by the cast film method [15,43,47,150]. Because of the ease of the procedure, coating has been the most preferred method of applying antimicrobial agents to polymer surfaces. By definition, a coating is a "thin layer of material, generally thinner than 1 micron, applied onto a plastic or cellulose substrate," which can improve adhesion between two layers, improve water and oxygen barrier qualities, or enhance surface attributes such as wettability [46,47]. Conventional coatings, which are primarily composed of synthetic polymers derived from petroleum, have predominated in the use of antimicrobial food-packaging films. These include polyvinylidene chloride (PVDC), polyvinyl alcohol (PVOH), and ethylene vinyl alcohol (EVOH) [46]. Due to environmental concerns over synthetic polymer-based packaging materials, there is a rising interest in edible film coatings. Coatings made from edible biopolymers have improved biodegradable antimicrobial active packaging [29,151]. Furthermore, the choice of an antimicrobial polymeric film is determined by the application's intended use and, thus, by the qualities of the polymeric films.

Before the application of antimicrobial agents, plastic films are frequently surface modified to improve the adhesion of antimicrobials to the polymer matrix [47]. The application is achieved by UV radiation. Furthermore, several methods, such as microencapsulation and the use of polymer nanocomposites, have been developed to include antimicrobial agents in the coating to prevent further problems caused by heat and mechanical stress. According to [46,152], an antimicrobial coating's design necessitates a detailed knowledge of the interactions between the active substance, coating, substrate, and food. Certain conditions must be met before an antimicrobial coating may be employed in food packaging applications:

1. The active coating should adhere to the film substrate efficiently and be inert for direct food contact;
2. The concentration of the released active agent should be controlled to ensure effective antimicrobial action;
3. The final active coated structure should be suitable for the specific food product, which implies that the produced material must have the same qualities as traditional passive packaging.

Fungicides were mixed into waxes to coat fruits and vegetables, and shrink films coated with quaternary ammonium salts were used to wrap potatoes in the early phases of antimicrobial packaging development [15,29,153,154]. Typical plastic films and biopolymers used in the development of antimicrobial-coated packaging include low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), polypropylene (PP), polyvinyl chloride (PVC), polyethylene terephthalate (PET), and polylactic acid (PLA) [155]. Some instances of antimicrobial-coated studies included chitosan/essential oil-coated polypropylene (PP) films [156], chitosan/propolis-coated PP films [157], nisin-coated polyethylene films [158], chitosan-coated polylactic acid (PLA) films containing multiple organic acids [159], zataria multiflora essential oil (ZEO)-coated PP films [160], clove oil-coated LLDPE [161], cellulose nanofibers (CNFs)/PLA coated with ethanolic extract of propolis [162], nisin-coated polyvinyl alcohol (PVA) films [163], nisin-coated PLA film [164], PLA films coated with clove oil/argan oil and chitosan [165], nanostructured aluminum-doped zinc oxide-coated PLA films [166], bacteriocins-coated polyethylene terephthalate (PET) films [167], plantaricin BM-1 and chitosan-coated polyethylene terephthalate/polyvinylidene chloride/retort casting polypropylene (PPR) plastic [168], etc.

5.4. Direct Incorporation of Antimicrobial Agents into Polymers

Several antimicrobial agents can be integrated directly into the packaging material, particularly films [97]. Antimicrobial film-forming materials are created by incorporating antimicrobial agents into a polymer matrix, releasing them onto the food surface to interact with microbes [42]. The rationale for incorporating antimicrobials into polymeric packaging materials is to extend the shelf life of the packed foods by preserving the foods against microbial spoilage and hazardous food-borne microorganisms as well as preventing surface growth in foods where a large portion of spoilage and contamination occurs [42,169]. Antimicrobials such as bactericides, enzymes, chelators, metal ions, or organic acid can be introduced into polymers during the melting process or by solvent compounding [43,59].

During the polymer/film processing, thermal polymer processing techniques such as extrusion, co-extrusion, or injection molding can be employed for thermally stable antimicrobials (e.g., silver substituted zeolites) in which they are included in the melt [43,97]. The solvent compounding method is more suitable for heat-sensitive antimicrobials such as enzymes and volatile compounds. In this case, the antimicrobial and the polymer must be soluble in the same solvent. Due to the great diversity of proteins, carbohydrates, and lipids (which function as plasticizers) that generate films, biopolymers are an excellent choice for this film formation process. These polymers and blends are soluble in water, ethanol, and a wide range of antimicrobial-compatible solvents [43].

To achieve antimicrobial activity, the direct incorporation of antimicrobials into a polymer matrix/system is a convenient method and results in different release profiles. For instance, Rocha et al. [170] described the additive release of the antimicrobial agents as a simple matrix diffusion process with degradation occurring after the active component is released. Several factors influence the antimicrobial activity by the diffusion of antimicrobials from the film; these include the size, shape, polarity of the diffusing molecule, degree of molecular crosslinking, and the chemical structure of the film [170]. It is worth mentioning that the type of antimicrobial, its concentration, and target microorganism affect the film's antimicrobial activity. Table 3 shows some antimicrobials incorporated into polymers that showed antimicrobial activity against some microorganisms.

Table 3. Summary of selected studies on antimicrobials incorporated into polymers.

Antimicrobials	Polymer	Target Microorganisms	References
Potassium sorbate	Starch film	*S. aureus*, *Candida* spp., *Salmonella* spp. and *Penicillium* spp.	[171]
	Starch–clay nanocomposite	*A. niger*	[172]
	Linear low-density polyethylene (LLDPE)	Yeast	[173]
Sorbic acid	Polypropylene (PP)-based film	*E. coli*, *S. aureus* and *A. niger*	[162]
	Polypropylene-based composite films	*E. coli*, *S. aureus* and *A. niger*	[174]
	Starch-poly (butylene adipate co-terephthalate) (PBAT) films	*E. coli*, *S. aureus*, *Salmonella Typhimurium*, *Pseudomonas aeruginosa*, *Aeromonas Hydrophyla*, *B. cereus* and *L. innocua*	[175]
Nisin	Hydroxypropyl methylcellulose (HPMC), chitosan (CTS), sodium caseinate (SC), and polylactic acid (PLA) films	*L. monocytogenes* and *S. aureus*	[176]
	Poly (butylene adipate-co-terephthalate) (PBAT) films	*L. monocytogenes*, *S. aureus*, *Clostridium perfringens*, and *B. cereus*	[177]
	Mater-Bi (MB)-based film	*L. monocytogenes*, *Salmonella enteritidis*, *E. coli*, and *S. aureus.*	[178]

Table 3. *Cont.*

Antimicrobials	Polymer	Target Microorganisms	References
Zinc oxide nanoparticles	Poly(lactide) (PLA)/poly(butylene adipate-co-terephthalate) (PBAT) blend films	*E. coli* and *L. monocytogenes*	[179]
	PLA-based nanocomposite films	*E. coli* and *L. monocytogenes*	[180]
	PLA-based films	*S. aureus*, *Bacillus atrophaeus*, *B. cereus*, *E. coli*, and *Candida albicans*	[181]

5.5. Antimicrobial Immobilization of Polymers through Ion or Covalent Bonds

Another way to enhance the release of antimicrobial agents is to immobilize the agent onto polymers. These polymers are appealing because they can be hydrolyzed to produce harmless compounds that can be metabolized in vivo and the environment [46,47,182]. The presence of functional groups on both the polymer and the antimicrobial agents or compound is required for immobilization, and ionic or covalent bonds are created between the two [46]. Antimicrobial substances with the appropriate functional groups include enzymes, peptides, organic acids, and polyamines. One of the most researched techniques in food packaging is the immobilization of peptides and enzymes [182]. Polymers having functional groups include ethylene vinyl acetate, ethylene methyl acrylate, ethylene acrylic acid, ethylene methacrylic acid, ionomer, polystyrene, nylon, etc. [15]. Most polymeric films used in food packaging have inert surfaces and low surface energy, resulting in poor antimicrobial bonding ability. A surface activation phase is necessary to enhance the polymer surface energy before antimicrobial immobilization, which can be accomplished by either physical or chemical (wet) techniques [155].

Crosslinkers or spacer molecules that attach the polymer surface to the bioactive agent are often essential for immobilization. Dextran, chitosan, ethylenediamine, and polyethyleneimine are common macromolecules that can function as a spacer or crosslinker in the film production process [155,183]. They can enhance the formation of covalent bonds between the activated film and the antimicrobial compound while not being a part of the bond. That is, spacer molecules provide motion flexibility, which aids in the interaction of the active component of the antimicrobial agent with the microorganisms on the food surface [15]. The active agents are typically designed and intended to be released into the food or to function at the food product's surface. However, the type of bonding, either ionic or covalent, influences the release of these agents from immobilized polymers. While ionic bonding allows for a gradual release of antimicrobial agents into the food, covalent bonding allows for less concern about microbial agent diffusion [15]. It is vital to ensure that there is no chemical migration from packaging materials to foods and that there is no residual free chemical after the immobilization reaction.

Immobilization creates a stable binding between the active agent and the functionalized polymer surface, allowing long-term activity. It ensures no bioactive substance migrates into the food, providing a regulatory benefit [97]. However, close interaction with food needs regulatory approval [97]. It is worth noting that immobilization may limit the antimicrobial effectiveness of some antimicrobials, such as antimicrobial proteins/peptides, due to structural changes and denaturation by solvents [15,43]. Various substrates are used to retain and increase the action of polymer-immobilized agents, such as naringinase immobilized in cellulose acetate films [15,155].

A recent study by [184] showed the covalent immobilization of antimicrobial polypropylene (PP) film using -poly(lysine) (EPL). To create a reactive blend (PP/PP-g-MA), PP was combined with polypropylene-graft-maleic anhydride (PP-g-MA). It was blended with ε-poly(lysine) and styrene-maleic anhydride copolymer (SMA) to produce PP-SMA-EPL antimicrobial film due to covalent attachment through the imide ring formation between EPL, SMA, and PP/PP-g-MA. The resultant film showed effectiveness against *E. coli* and *L. innocua.* In another recent investigation, Doshna et al. [185] used a reactive extrusion to create active antimicrobial packaging utilizing polypropylene as the base polymer, polylysine as the immobilized antimicrobial, and dicumyl peroxide as the free radical initiator and cross-linker. After 1 h of incubation at 37 °C, the antimicrobial active packaging material reduced *P. aeruginosa* by 1-log [185].

6. Antimicrobial Packaging Effectiveness/Applications

Antimicrobial packaging plays a critical role in inhibiting the development of targeted microorganisms on foods while increasing food safety and extending shelf life without compromising food quality. It is not intended to replace appropriate manufacturing and handling methods but rather to provide an extra barrier for microorganisms to overcome [92]. Antimicrobial packaging has been used in a variety of food products. This section discusses the application of antimicrobial packaging.

6.1. Antimicrobial Packaging for Fresh and Minimally Processed Fruits and Vegetables

Fresh and minimally processed fruits and vegetables are perishable and easily compromised by postharvest physiological changes and microbial contamination throughout postharvest transportation, processing, storage, and retail display [116,186]. Minimally processed foods and vegetables, for instance, are extensively researched due to the difficulty in retaining their fresh-like quality over lengthy periods, and the goal of minimally processed products is to provide convenience and excellent quality [54]. Incorporating antimicrobial agents into the packaging of fruits and vegetables could be a strategy for controlling the effects of microorganisms, extending shelf life, and providing higher quality products. As reported by Giannakourou and Tsironi [42] and Jung and Zhao [186], there are three forms of antimicrobial packaging that have been documented for use on fresh and minimally processed fruits and vegetables, namely:

1. Antimicrobial sachets: sachets containing volatile antimicrobial agents enclosed in the packaging;
2. Antimicrobial films: the inclusion of volatile or nonvolatile antimicrobial chemicals into packaging film composition;
3. Antimicrobial edible coatings: directly applying antimicrobial edible coatings or films to the food surface.

Antimicrobial systems employ synthetic and natural active agents to inhibit microbial development, as previously discussed. Essential oils (EO) and plant extracts, organic acids and their salts, and chitosan are a few examples. Metals and metal oxides such as silver (Ag) and zinc oxide (ZnO) have also demonstrated significant promise as antimicrobial packaging agents to create more cost-effective and safe food packaging solutions for fruits and vegetables [187]. Table 4 presents some examples of developed antimicrobial systems to reduce microbial growth in fruit and vegetables.

Table 4. Summary of examples of antimicrobial packaging systems utilized to reduce microbial growth in fruit and vegetables.

Antimicrobial System	Fruit/Vegetable Products	Target Microorganisms	Findings	References
Essential oil (EO) sachets EOs: oregano and lemon grass EO	Mango	*Colletotrichum gloeosporides*, *Lasiodiplodia theobromae*, *Xanthomonas campestris pv. mangiferae indica* and *Alternaria alternate*	Presence of EOs did not affect the physicochemical attributes of the produce Active sachets incorporated with EOs reduced the growth of tested fungi Lemongrass was more effective	[188]
Edible pectin film enriched with the essential oil from cinnamon leaves (CLO)	Fresh-cut peach	*Salmonella enterica* subsp. *enterica serovar Choleraesuis*, *L. monocytogenes*, *E. coli*, and *S. aureus*	Developed film decreased bacteria growth Antibacterial-enriched pectin film performed best at a CLO concentration of 36.1 g/L	[189]
Essential oil (EO) sachets EOs: oregano, cinnamon, and lemon grass EO	Papaya	*Alternaria alternata*, *Fusarium semitectum*, *Lasiodiplodia theobromae* and *Rhizopus stolonifer*	Reduction in the growth of microorganisms was observed Cinnamon sachet had the most significant reduction in microorganisms at the end of storage	[190]
Ethylene-vinyl acetate (EVA) blended with Low-density polyethylene (LDPE), incorporating EOs EOs: clove leaf oil (CL), sweet basil oil (SB) and cinnamon bark oil (CB)	Fresh-cut tomatoes	*E. coli* (Gram-negative bacteria) and *S. aureus* (Gram-positive bacteria)	Best performance was shown with blended film incorporated with CB Quality was preserved in blended films that incorporated EOs compared to films without EO	[191]
Poly(lactic acid)–cellulose nanocrystals (PLA–CNC)–oregano films	Mixed vegetables	*L. monocytogenes*	Strong antimicrobial potential of PLA–CNC–oregano films was evident	[192]
Polyamide incorporated with carvacrol essential oil	Cherry tomatoes Lychee Grapes	*Alternaria alternata*, *B. cinerea*, *Penicillium digitatum*, *Penicillium expansum*, and *A. niger*	Reduced decay development on various fresh produce (cherry tomato, lychee, and grape) packed in active bags Developed film exhibited excellent antifungal properties	[193]
Polyvinyl alcohol encapsulated with oregano EO	Fresh-cut lettuce	*Dickeya chrysanthemi*, molds and yeasts (MY), and total mesophilic aerobic bacteria (MAB)	Texture and color were not affected Substantial growth inhibitory effects against MY and total MAB	[194]
Polyvinyl alcohol (PVA) film incorporated with oregano essential oil	Tomatoes	*Salmonella enterica*, total molds and yeasts (MY), and mesophilic aerobic bacteria (MAB)	Quality of the packed produce was preserved	[195]

Table 4. *Cont.*

Antimicrobial System	Fruit/Vegetable Products	Target Microorganisms	Findings	References
Essential oil (EO) sachets Chitosan/alginate beads containing EOs and vanillin EOs: clove and lavender	Grapes	*Botrytis cinerea*	Chitosan/alginate beads emitting clove EO maintained produce quality	[196]
Starch film incorporated with chitosan nanoparticles (CNP)	Cherry tomatoes	*B. cereus*, *S. aureus*, *E coli* and *Salmonella typhimurium*	CNP concentration influenced the antimicrobial activity of the starch/CNP films CNP suppressed Gram-positive bacteria more effectively than Gram-negative bacteria Extended shelf life of packed cherry tomatoes in developed films	[197]
Low-density polyethylene (LDPE) with silver nanoparticles (AgNPs)	Strawberry	Molds and yeasts (MY), and *E. coli*	Nano-silver packages improved the storage life and maintained fruit quality	[198]
Starch-based composite films incorporated with lemongrass essential oil	Chillies	*E. coli*, *B. cereus*, *S. aureus*, *Salmonella typhimurium*, *A. niger*, *Mucor ruber* and *Candida albicans*	Lemongrass essential oil was effective in microbial growth inhibition Developed film proved efficient for chili preservation	[199]

Espitia et al. [125] developed EO sachets to be utilized in an antimicrobial packaging system. The authors tested the activities of incorporated oregano, cinnamon, and lemongrass EO in vitro against different phytopathogenic fungi, namely, *Alternaria alternata*, *Fusarium semitectum*, *Lasiodiplodia theobromae*, and *Rhizopus stolonifer.* Furthermore, the study assessed the sachet's activity in terms of microbial growth on papaya fruit. Treated sachets with EOs substantially reduced the growth of mesophilic aerobic bacteria, yeasts, and mold. An antimicrobial packaging film based on polyamide with incorporated carvacrol EO was developed by Shemesh et al. [193]. The antimicrobial activity of the resultant polyamide films was tested against *Alternaria alternata*, *Botrytis cinerea*, *Penicillium digitatum*, *Penicillium expansum*, and *A. niger.* The films were further used for packaging different fresh produce: cherry tomatoes, lychee, and grapes, to investigate their fungicidal effects on postharvest pathogens. The film demonstrated great antifungal activity against the examined fungal molds and outstanding performance in suppressing decay and increasing the shelf life of the products.

In another study by Kwon et al. [194], the authors studied the efficacy of polyvinyl alcohol (PVA) film incorporated with oregano EO (OPVA) to inhibit the proliferation of microorganisms in the storage of packed cherry tomatoes. OPVA films containing 2% and 3% OEO had antimicrobial effects on *Salmonella enterica*, molds and yeasts (MY), and mesophilic aerobic bacteria (MAB), even after storage for 7 days. The film did not influence the physical properties of the tomatoes, and the quality was preserved. A recent study by Shapi'i et al. [197] developed an antimicrobial packaging system of starch film incorporated with chitosan nanoparticles (CNP). The findings showed that 15 to 20% w/w starch/CNP films could inhibit bacteria (*B. cereus*, *S. aureus*, *E. coli*, and *Salmonella typhimurium*) growth. The in vivo investigation, i.e., microbial count in wrapped cherry tomatoes, showed that starch/CNP film (15% w/w) was more effective in suppressing microbial development in cherry tomatoes than pure starch films. According to Perdana et al. [199], starch/chitosan film infused with lemongrass essential oil has a strong potential for limiting the growth of microorganisms such as Gram-positive and Gram-negative bacteria, yeast, and molds. The produced film proved successful for chili preservation by limiting water loss and microbial development and delaying ripening during storage.

6.2. Antimicrobial Packaging for Meat Products

Meat is an ideal product for the growth of spoilage microorganisms. Microbial growth in packed meats promotes pathogen development and undesirable organoleptic changes over time [64,200,201]. According to published research, red and white meat have a high potential for bacterial development due to their high water activity [202,203]. As a result, antimicrobial packaging is utilized to protect against spoilage microorganisms during meat preservation by applying specific chemical agents/compounds (both in the packaging material and/or in the packaging area). In meat products, the efficiency of antimicrobial packaging can be determined by monitoring the appropriate microbial count or quality parameters that are indirectly connected to microbial growth [204]. Since most antimicrobial packaging applications rely on the active antimicrobial agents migrating from the package matrix into the food, its migratory dynamics serve as a regulating factor for effective microbial suppression [205]. Therefore, the technique to optimize antimicrobial packaging is to target specific spoilage or pathogenic organisms with the active agent adapted to its migratory kinetics [152,205]. Furthermore, reducing the impact of active antimicrobial packaging on the visual and sensory qualities of the packed product to the consumer is crucial for the appropriate use of antimicrobial packaging in meat [206].

Meat antimicrobial packaging solutions have evolved over the previous decade. Various film applications, such as chitosan-based films, biodegradable polysaccharide and protein-based films containing active agents, and synthetic packaging films with antimicrobial agents, have been researched for antimicrobial activity and used to package meat and meat products [87,207]. Polyvinyl chloride (PVC) and polystyrene were the two most common packaging materials used for meat packing (with the inclusion of antibacterial agents in films). However, studies have shown that they are unsuitable for meat products and that recycling is challenging [47,208]. As a result, biodegradable polyurethane was proposed as a meat packaging material. Natural biopolymers (chitosan), organic acids or their related acid anhydrides, alcohols, bacteriocins (nisin and pediocin), chelators, and enzymes (lysozyme), among others, are some of the types of antimicrobial agents suggested and investigated for meat packaging problems [24,181]. Although the inclusion of lactic acid bacteria (LAB) into biopolymer films is an intriguing novel approach [181], these bacteria are resistant to CO_2, which is widely used in vacuum or modified atmosphere packaging (MAP) [209]. Additionally, while exposing meat products to antimicrobial agents such as essential oils have some influence on microbial development, the adverse organoleptic effects of the intense odor caused by application to meat limit their use to a certain extent [206].

Recent research provides new insights into the efficiency of antimicrobial compounds and silver-containing packaging in preventing beef deterioration [210,211]. Some researchers, however, have pointed out the drawbacks of employing silver to restrict antibacterial packaging. As a result, the use of nanoparticle coating during the packaging process of meat products, including antibacterial compounds as well as silver, was recommended [85,212,213]. For instance, Soysal et al. [86] investigated the impact of antimicrobial agents (nisin, chitosan, potassium sorbate (PS), or silver substituted zeolite (AgZeo)) incorporated into low-density polyethylene (LDPE) on the physicochemical and microbiological quality of chicken drumsticks. The use of active bags resulted in a lower level of total aerobic mesophilic bacteria (APC), total coliform, mold, and yeast count in chicken drumsticks. The chitosan-containing film was the most successful in extending the shelf life and improving the quality of the drumsticks. At 5 °C for 6 days, the active bags reduced APC and total coliform in the order chitosan > nisin > AgZeo > PS, while mold and yeasts were reduced in the sequence chitosan > PS > nisin > AgZeo > PS.

Overall, the meat products' packaging methods depend on the reaction of the used materials and the antimicrobial agents. Table 5 summarizes the use of antimicrobial agents in packaging various meat products and the objective of the previous investigations.

Table 5. Antimicrobial packaging and its application for meat products.

Antimicrobial Agent	Product	Aim	References
Lysozyme	Pork	Determination of the antibacterial properties of the composite mats and the product's lysozyme activity	[82]
Nisin Chitosan Potassium sorbate Silver substituted zeolite (AgZeo)	Chicken drumsticks	Evaluating the effectiveness of several antimicrobial agents on the product's microbiological characteristics	[85]
N-α-lauroyl-l-arginine ethyl ester monohydrochloride (LAE)	Chicken fillets	Evaluate the efficacy of antimicrobial starch-gelatin films containing LAE	[87]
Nano-encapsulated *Satureja khuzestanica* essential oils (SKEO)	Lamb meat	Assessment of chitosan coatings incorporated with SKEO	[214]
Mentha piperita EO (MPO) Bunium *percicum* EO (BPO) nanocellulose (NC),	Ground beef	Produce active PLA films incorporated with different concentrations of BPO, MPO, and cellulose nanofibers Assess antibacterial and sensory effects on ground beef	[204]
Encapsulated cumin	Beef hamburger	Studying the impact of active paper on the microbiological and physical qualities of beef hamburger	[90]
Nanochitosan *Polylophium involucratum* essential oil (PEO)	Lamb meat	Evaluated the effects on the chemical, microbial, and sensory characteristics of minced lamb	[215]
Garlic EO (GEO)	Sausages	Develop active edible films (based on whey protein (WP) or chitosan (CH)) incorporated with GEO or nanoencapsulated GEO (NGEO) Assess antimicrobial effects in packed sausages	[216]
Gelatin/palm wax/lemongrass essential oil (GPL)	Ground beef	Determine the effectiveness of the GPL-coated Kraft paper in maintaining the quality of ground beef	[217]

6.3. Antimicrobial Packaging for Dairy Products

Although dairy products are rich in nutrients, including high-quality proteins, minerals, vitamins, and energy-containing fats [218], they also provide a suitable environment for the growth of a wide range of microbes [218,219]. Pathogenic microorganisms pose a health risk to customers [219]. Packaging plays an essential role in protecting dairy products after production. It is capable of effectively extending the shelf life of these products [220]. Antimicrobial packaging has shown great promise in improving microbiological safety and preserving dairy products. Among the several dairy products, antimicrobial agents in cheese packaging have received much attention [221]. These enhanced packaging can provide excellent microbiological control and higher food safety requirements. Among these are edible films and coatings. Table 6 shows brief studies on antimicrobial packaging systems applicable to cheese.

Table 6. Examples of antimicrobial packaging applicable to cheese.

Cheese Types	Description	References
Saloio cheese	Whey protein isolate coating as a carrier of lactic acid, natamycin, or chitooligosaccharides Edible coating containing natamycin and lactic acid was selected as the best option for cheese	[50]
Kashar cheese	Zein and zein–wax coating with lysozyme, catechin, and gallic acid. Lysozyme-based film prevented the growth of *L. monocytogens*	[222]
Cheddar cheese	Low-density polyethylene (LDPE) and cellulose films coated with peptide of *Bacillus licheniformis* Me1 Proven biopreservative efficiency of the activated films in limiting pathogen development	[223]
Mozzarella cheese	Sachets from microcellular foam starch containing rosemary oil and thyme oil Volatile oils also showed inhibitory effects on the growth of lactic acid bacteria (LAB) and total aerobic bacteria (TAB).	[224]
Minas Frescal cheese	Starch/halloysite/nisin nanocomposite films Inhibited *L. monocytogenes*, *S. aureus*, and *Clostridium perfringens* Excellent barrier for preventing cheese contamination	[225]
Feta cheese	Zein-based edible films incorporated with *Zataria multiflora boiss* essential oil (EO) Inclusion of EO reduced the count of viable *Salmonella enteritidis*, *L. monocytogenes*, *E. coli*, and *S. aureus*	[226]
Ultra-filtrated (UF) cheese	Organoclay nanoparticles incorporated into LDPE films Developed packaging able to maintain UF cheese quality without toxicity	[227]
Ultra-filtrated (UF) cheese	LDPE films incorporated with silver (Ag), copper oxide (CuO), and zinc oxide (ZnO) nanoparticles Optimum antibacterial effect with LDPE films containing Cu-ZnO and with no Ag nanoparticles	[228]
Mozzarella cheese	Cellulose acetate films incorporated with pink pepper EO Films reduced the microbiological growth in cheese	[229]
Yunnan cottage cheese	Poly(lactic acid) (PLA) film incorporated with titanium dioxide (TiO_2) or Ag nanoparticles Prolonged cheese shelf life	[230]
Ultra-filtrated (UF) cheese	Cellulosic paper coated with chitosan-zinc oxide nanocomposite containing nisin Presence of *L. monocytogenes* in cheese was significantly reduced by nisin-containing films	[231]
Ultrafiltered white cheese	Cellulose–chitosan (CC) films containing monolaurin (ML) 0.5 and 1% ML into CC films reduced *L. monocytogenes* on cheese by 2.4–2.3 log	[232]

Table 6. *Cont.*

Cheese Types	Description	References
Kashar cheese	Alginate and zein films containing natamycin Natamycin concentration increased the antifungal activities of the films	[233]
Sliced cheddar cheese	Starch films containing sodium benzoate (ASF-SB), citric acid (ASF-CA), and both (ASF-CASB) Effective in reducing *L. innocua* on cheddar cheese surface	[234]
Telemea cheese	Alginate films with silver nanoparticles and lemongrass EO Films exhibited strong antibacterial activity against *B. cereus*, *S. aureus*, *E. coli*, and *Salmonella Typhi*	[235]
Mozzarella cheese	Polyethylene (PE) films containing linalool or thymol Increase in the concentration of active agents increased the antimicrobial activities of the films against *E. coli*, *S. aureus*, *L. innocua*, and *Saccharomyces cervicea* Increased shelf life of cheese	[236]

To elaborate on a few studies, Fajardo et al. [237] demonstrated that chitosan–natamycin film improved the storability and extended the shelf life of Saloio cheese packaging [237]. Incoronato et al. [238] investigated the deterioration of Fior di Latte cheese quality using antimicrobial packaging containing silver nanoparticles. It was discovered that the developed active package limited the growth of spoilage bacteria without altering the product's functional dairy microbiota or sensory properties [238]. Otero et al. [239] tested the antimicrobial activity of two packaging films: polypropylene (PP) and polyethylene terephthalate (PET), coated with different concentrations of essential oil from *Origanum vulgare* (OR) and Ethyl Lauroyl Arginate HCl (LAE) against two strains of *E. coli*. Zamorano sheep cheese was packaged with the films, and results showed that PET films coated with ≥6% LAE concentrations had the greatest potential to reduce *E. coli* in the product [239].

Adding cinnamon bark oil (CBO) as an active ingredient produced an antibacterial film from chicken bone gelatine (CBG). The films' antimicrobial activity against *L. monocytogenes* and *E. coli* was examined, and the films were utilized for packaging mozzarella cheese to study their capacity to prevent microbiological deterioration. Results showed that the antimicrobial of the CBG film is a function of the CBO concentration. Furthermore, the microbial population was reduced during storage when the produced film was used for packaging mozzarella cheese inoculated with *L. monocytogenes*. Küçük et al. [233] developed alginate and zein films with natamycin as an antifungal agent to limit/prevent mold formation on the surface of kashar cheeses. At the end of the storage period, zein films with high natamycin concentrations demonstrated greater antifungal efficacy against *A. niger* and *Penicillium camembert*. In a recent investigation, Motelica et al. [235] produced alginate-based films infused with silver nanoparticles and lemongrass essential oil for cheese packaging. The antimicrobial agents (silver nanoparticles and lemongrass essential oil) interacted synergistically. The films developed demonstrated strong antibacterial activity against two Gram-positive strains (*B. cereus* and *S. aureus*) and two Gram-negative strains (*E. coli* and *Salmonella Typhi*) with the greatest results achieved against *B. cereus*. Films could preserve and extend the shelf life of the packed cheese for up to 14 days.

7. Antimicrobial Packaging Regulatory Status

Over the last decade, technological advancements have been made in packaging food and agricultural products to prevent microbial degradation. The relevance of antimicrobial packaging regulatory status leads to improved antimicrobial system efficacy. Despite extensive studies into the benefits of antimicrobial packaging, several concerns remain contentious, such as controlling the release of antimicrobial agents into packaging, preserving the quality (physical and mechanical qualities) of packaging, and ensuring food safety [221]. As a result, assessing the potential hazards from oral exposure to these components that may migrate into food must be made to protect the consumer [24]. Antimicrobial active systems should be used following the standards of several regulatory authorities, such as the Food and Drug Administration (USA), the European Food Safety Authority (European

Union), and others. They establish the legal foundation for their correct use, safety, and marketing [7,27]. The active (antimicrobial) compound and the inert carrier are the two primary components of an active antimicrobial system. Active agents being purposely released from the packaging system into the food would fall under food additives. Hence, they must meet specific scientific and technological standards, while the carrier must fulfil the safety criteria for food contact materials [240]. Often, standards for food contact materials are stringent to avoid the migration of undesired components into the food. Understanding appropriate regulatory choices, as well as environmental sustainability problems, would aid commercialization efforts. Finally, consumer acceptability and purchase intent boost the adoption of innovative packaging technologies, notably antimicrobial active packaging.

8. Conclusions

The technology of antimicrobial packaging is rapidly evolving. This method employs antimicrobial agents or substances in a polymer matrix to reduce the growth of spoilage food pathogens by targeting specific microorganisms to extend food shelf life. A thorough understanding of antimicrobial packaging enables researchers and food industries to develop appropriate methods for reducing microbial risks and improving food quality. This review provided a comprehensive basic concept of antimicrobial packaging technology and a summary of recent studies on antimicrobial packaging to extend the shelf life of food products, emphasizing fresh and minimally processed fruits and vegetables, meat, and dairy products. Although potent in reducing the growth of microbes in food, the effectiveness and synergistic effects of antimicrobial packaging can be improved when combined with other preservation hurdles, which may be dependent on the spoilage properties, required shelf life, and consumer preferences. However, some issues exist, including recycling management, reasonable prices for producers and consumers, and the complexity of the production process are challenges for scientists and researchers. The shelf life and safety of fresh fruits, vegetables, dairy, and meat products can be enhanced by adjusting the level of active agents in the packages. Additionally, an inspection of the diffusion rate of the antimicrobial agents from the film and their subsequent effectiveness on food products from the chemical view is still debatable. For this reason, establishing a multidisciplinary approach is imperative based on the scientific work of researchers and scholars. Furthermore, increasing the effectiveness and efficiency of antimicrobial packaging necessitates the identification of more natural antimicrobial compounds that are effective in improving their stability in packaging systems and ensuring the safety of their commercial applications. Similarly, for any application, selecting the best antimicrobial packaging systems for a given product is essential. The selection can be determined by the nature of the produce, storage conditions, required shelf life, and regulatory requirements.

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