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FOOD-CONTACT SURFACES COATED WITH ANTIMICROBIAL POLYMERIC MATERIALS

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ABSTRACT

The growing demand for improved food safety has fueled significant interest in antimicrobial polymeric coatings for food contact surfaces. This review offers a thorough examination of various antimicrobial coatings, including natural biopolymer-based, synthetic, and hybrid composites, spotlighting their modes of action and effectiveness in combating microbial contamination. It explores key antimicrobial agents such as metal-based compounds, natural antimicrobials, and synthetic chemicals, discussing their unique properties and potential applications. Equally, the review evaluates different testing methods for antimicrobial efficacy and identifies critical performance factors, including environmental conditions, surface properties, and the type of microbial contaminants. The hurdles and limitations of these coatings are also addressed, including concerns about durability, health and environmental impacts, and economic viability. Through detailed case studies, this review synthesizes current knowledge and offers insights into future research, with a particular focus on biodegradable polymers and innovative natural antimicrobials. The findings emphasize the potential of antimicrobial coatings to enhance food safety and inform the development of sustainable food packaging technologies, supporting advancements in health-conscious and environmentally friendly industrial applications.

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ПОВЕРХНОСТИ С АНТИМИКРОБНЫМИ ПОЛИМЕРНЫМИ ПОКРЫТИЯМИ, КОНТАКТИРУЮЩИЕ С ПИЩЕВЫМИ ПРОДУКТАМИ

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КЛЮЧЕВЫЕ СЛОВА:
антимикробные покрытия, безопасность пищевых продуктов, полимерные материалы, микробное загрязнение, поверхности, контактирующие с пищевыми продуктами

АННОТАЦИЯ

Растущий спрос на повышение безопасности пищевых продуктов обусловил значительный интерес к антимикробным полимерным покрытиям для поверхностей, входящих в контакт с пищевыми продуктами. В этой статье подробно рассматриваются различные антимикробные покрытия, в том числе изготовленные на основе природных биополимеров, синтетических и гибридных композитов, освещаются механизмы их действия и эффективность в профилактике микробного загрязнения. В статье рассматриваются такие основные противомикробные средства, как соединения на основе металлов, природные противомикробные препараты и синтетические химикаты, обсуждаются их уникальные свойства и потенциальные сферы применения. Кроме того, в обзоре оцениваются различные методы тестирования антимикробной эффективности и выявляются критические факторы эффективности, включая условия окружающей среды, свойства поверхности и тип микробиологических загрязнений. Также рассматриваются препятствия и ограничения, связанные с применением таковых покрытий, включая проблемы их долговечности, их воздействие на здоровье потребителя и на окружающую среду, а также экономическую целесообразность их применения. На основе подробных тематических исследований этот обзор обобщает современные знания, и предлагает идеи для будущих исследований, уделяя особое внимание биоразлагаемым полимерам и инновационным противомикробным средствам природного происхождения. Полученные результаты подчеркивают потенциал антимикробных покрытий в деле повышения безопасности пищевых продуктов, и служат основой для разработки экологически и экономически рациональных технологий упаковки пищевых продуктов, способствуя их продвижению в области промышленных применений, ориентированных на поддержание здоровья человека и экологии окружающей среды.

1. Introduction

Using of antimicrobial polymeric coatings in the food industry marks a significant advancement in ensuring food safety and maintaining quality standards [1]. These coatings are specifically designed to reduce microbial contamination risks on the food contact surfaces [2], thus handling critical concerns such as foodborne illnesses, spoilage, and the economic losses associated with these issues [3]. By embedding antimicrobial agents within polymer matrices [4], these coatings actively inhibit or eliminate microbial growth on surfaces that come into direct contact with food products [5]. This innovation plays a pivotal role in food processing, packaging, and storage, where contamination is a constant challenge [6]. Over time, research efforts have focused on enhancing the functionality of these coatings [7], utilizing natural, synthetic [8], and hybrid antimicrobials with diverse mechanisms of action to combat various microbial pathogens [9]. As well, these coatings are engineered to withstand various environmental conditions, including fluctuations in temperature and humidity common in food production and storage environments [10].

Ensuring the hygiene and safety of food contact surfaces is essential to prevent microbial contamination and uphold food safety standards [11]. Surfaces such as conveyor belts, cutting boards, storage containers, and packaging materials are frequently exposed to microorganisms that thrive in food environments [12]. Contamination of these surfaces can compromise food safety and facilitate the transmission of foodborne pathogens to the consumers [13], posing significant public health risks [14]. Pathogens such as *Escherichia coli, Salmonella* spp., and *Listeria* spp. have often been linked to insufficient sanitation and poor hygiene practices in food production and handling facilities [15]. While traditional cleaning and sanitation methods are efficient [16], yet they may not fully eradicate resilient microorganisms or address biofilm formation [17], which provides a protective habitat for pathogens and fosters persistent contamination [18].

Antimicrobial coatings offer an additional, long-lasting layer of protection against microbial contamination on food contact surfaces [19]. These coatings provide continuous antimicrobial activity, effectively reducing microbial loads and preventing biofilm formation, which routine cleaning methods may struggle to manage [20]. By incorporating these coatings, the food industry can comply with safety regulations [21]. Moreover, antimicrobial coatings reduce the need for frequent cleaning cycles, minimize chemical substances usage [22], and help protect food processing equipment from microbial-induced corrosion and degradation, ultimately extending its operational lifespan [23].

This review delves into the incorporation of antimicrobial properties into polymeric coatings for food contact surfaces [24], focusing on their types, mechanisms of action, and factors influencing their effectiveness [25]. It examines natural biopolymer-based coatings, synthetic polymer coatings [26], and hybrid systems, focusing on their unique properties and benefits in combating microbial threats in food environments [27]. The review evaluates the antimicrobial agents embedded into these coatings, such as metal-based compounds, natural antimicrobials, and synthetic chemicals, alongside laboratory and field-testing methods to assess their efficacy under varying environmental conditions. Emphasizing prevention of biofilm formation and long-term activity, it also addresses issues like regulatory constraints, safety concerns, and cost implications of large-scale applications. By offering insights into the limitations and future directions for sustainable, biodegradable solutions, this review serves as a valuable resource for food safety professionals and manufacturers, thus aiming to enhance food contact surface safety. The aim of this research is to provide a comprehensive realization of antimicrobial polymeric coatings, to enable their effective application in order to improve food safety and public health.

2. Objects and methods

Scientific articles used for this review were retrieved from Scopus, PubMed, ScienceDirect, and Google Scholar databases. These databases were selected for their broad coverage of peer-reviewed scientific literature in antimicrobial coatings, polymeric materials, microbial contamination, food contact surfaces and food safety. The inclusion criteria focused on articles addressing antimicrobial coatings, food safety, polymeric materials, microbial contamination, food contact surfaces. Only English-language publications from 2015 to 2025 were considered to ensure recent and relevant findings. E-books, book chapters, review articles, and research papers that met these criteria were included. Exclusion criteria involved articles unrelated to microbial contamination in antimicrobial coatings, food safety, polymeric materials, microbial contamination, food contact surfaces, those lacking scientific evidence, or those outside the defined scope. The initial search retrieved a large number of studies from each database using specific keywords. Duplicate records were identified and removed using reference management software to maintain accuracy and prevent redundancy. Titles, abstracts, and full texts of the remaining articles were screened to ensure relevance to the review's objectives. The final selection was based on the studies' scientific quality, methodological soundness, and alignment with the scope of this review. The keywords used in the searches included: antimicrobial coatings, food safety, polymeric materials, microbial contamination, and food contact surfaces.

3. Types of antimicrobial polymeric coatings

Antimicrobial polymeric coatings are crucial for improving food safety by preventing microbial contamination on food contact surfaces [28]. These coatings are divided into three main categories: natural biopolymer-based coatings, synthetic polymeric ones, and hybrid or composite coatings [29]. Each type offers unique properties, advantages, and mechanisms, making them suitable for various food industry applications [30]. Getting familiar and acknowledging these coatings is essential for assessing their effectiveness in resolving the foodborne pathogens issues and spoilage concerns [31].

3.1. Natural biopolymer-based coatings

Natural biopolymer-based coatings are derived from biological sources such as plants, animals, and microorganisms [32]. They are valued for their biocompatibility, biodegradability, and antimicrobial properties, that make them safe for food applications without toxicity risks [33]. These coatings, including chitosan, alginate, gelatin, and cellulose derivatives, provide eco-friendly alternatives to synthetic coatings, which may raise concerns about environmental pollution persistence and chemical residues [34].

3.1.1. Chitosan

Chitosan, a polysaccharide sourced from chitin found in crustacean and insect exoskeletons, is widely studied for its antimicrobial properties [35]. Its amino groups interact with microbial cell walls, disrupting them and causing cell death [36]. Chitosan also forms semi-permeable films that reduce oxidation and spoilage, extending food shelf life [37]. Its antimicrobial efficacy can be enhanced by adding essential oils (e. g., thyme or oregano) or nanoparticles (e. g., silver or zinc oxide), improving its mechanical properties and broadening its antimicrobial spectrum of activity [38].

3.1.2. Alginate

Alginate, a polysaccharide from brown seaweed, is a popular biopolymer in food coatings due to its excellent film-forming properties and biocompatibility [39]. It forms hydrogels in the presence of divalent ions like calcium. While alginate itself features only limited antimicrobial activity, it effectively carries antimicrobial agents such as organic acids, essential oils, or bacteriocins [40]. It is commonly used to coat fresh-cut fruits, vegetables [41], fish, and poultry, due to enhancing moisture retention and inhibiting microbial growth [42]. Alginate's gel-like film supports the controlled release of antimicrobial agents, offering sustained protection [43]. For example, alginate coatings with nisin are able to inhibit growth of *Listeria monocytogenes*. Alongside, alginate reduces moisture loss and oxidation, maintaining food texture and freshness [44].

3.1.3. Gelatin

Gelatin, a protein derived from collagen hydrolysis, is valued for its high-quality film formation and compatibility with antimicrobial agents [45]. It is used in edible coatings for meats, seafood, and dairy products prone to spoilage [46]. Gelatin-based films are often enhanced with organic acids, enzymes, or essential oils to combat pathogens like *Escherichia coli* and *Staphylococcus aureus* [47]. The antimicrobial effect depends on incorporated agents [48], such as cinnamon or clove essential oils [49]. Gelatin coatings also act as moisture and oxygen barriers, thus reducing lipid oxidation and microbial growth to preserve food quality [50].

3.1.4. Cellulose derivatives

Cellulose derivatives, such as methylcellulose and hydroxypropyl methylcellulose, are widely used in food coatings for their film-forming ability, biodegradability, and transparency [51]. Though inherently non-antimicrobial [52], cellulose films can be functionalized with organic acids or essential oils, such as rosemary or tea tree oil, to inhibit pathogens like *Salmonella* spp. and *Listeria* spp. [53]. These coatings are ideal for fresh produce, maintaining texture and freshness by reducing moisture loss while preserving visual appeal [54]. Table 1 provides an overview of key polymeric coatings used in antimicrobial applications, including their sources, commonly incorporated antimicrobial agents, primary food applications, and benefits for food safety and preservation. Table 2 presents case studies, showcasing the antimicrobial effectiveness of natural biopolymer-based coatings, featuring their use with various agents on various food products, targeting specific microorganisms, and achieving notable results in enhancing food safety and quality.

Natural biopolymer-based antimicrobial coatings, such as alginate, chitosan [71], gelatin, and modified cellulose, offer significant benefits for food safety and quality preservation. These biopolymers create effective barriers against microbial contamination and promote environmental sustainability through their biodegradability [72]. By incorporating natural antimicrobial agents, these coatings improve food standards and extend shelf life [73], this way meeting consumer demand for safer

Table 1. **Overview of antimicrobial polymeric coatings, their origins, and applications**

Таблица 1. **Обзор антимикробных полимерных покрытий, источников их происхождения и способов применения**

Coating type	Source	Antimicrobial agents	Applications	Key benefits
Chitosan-based	Crustaceans (e. g., shrimp)	Essential oils, organic acids	Fruits, vegetables, meats	Biodegradable, broad-spectrum activity [55]
Alginate-based	Brown seaweed	Nisin, organic acids	Fresh-cut produce, poultry, seafood	Moisture retention, prolonged shelf life [56]
Gelatin-based	Animal collagen	Essential oils, enzymes	Meat, seafood, dairy products	Biocompatibility, oxygen barrier [57]
Cellulose Derivatives	Plant cell walls	Organic acids, essential oils	Fresh produce, bakery items	Transparent, moisture control [58]
Polyethylene (PE)	Petrochemical	Silver nanoparticles, quaternary ammonium	Fresh produce, bakery, dairy items	Moisture barrier, microbial resistance [59]
Polypropylene (PP)	Petrochemical	Chitosan, essential oils	Ready-to-eat meals, microwave containers	High heat resistance, flexible [60]
Polyvinyl chloride (PVC)	Petrochemical	Triclosan, silver ions	Fresh meat, fish, produce	Oxygen barrier, high clarity
Polylactic acid (PLA)	Corn starch, sugarcane	Natural plant extracts	Ready-to-eat meals, deli wraps	Compostable, renewable source
Polyglycolic Acid (PGA)	Sugar fermentation	Silver nanoparticles	Vacuum-sealed meat, fish	Excellent gas barrier, biodegradable
Polyhydroxyalkanoates (PHA)	Bacterial fermentation	Organic acids, essential oils	Fresh produce, dairy packaging	Fully biodegradable, high versatility [61]

Table 2. **Case studies on the antimicrobial effectiveness of natural biopolymer-based coatings**

Таблица 2. **Примеры исследований антимикробной эффективности покрытий, изготовленных на основе природных биополимеров**

Biopolymer coating	Antimicrobial agent	Food product	Target microorganisms	Efficacy outcome
Chitosan	Oregano essential oil	Fresh-cut apples	*E. coli, S. aureus, Salmonella* spp.	Reduced microbial load, extended shelf life [62]
Alginate	Nisin	Ready-to-eat turkey slices	*Listeria monocytogenes*	Inhibited *Listeria sp.* growth, enhanced preservation [63]
Gelatin	Carvacrol	Fresh strawberries	*Botrytis cinerea, E. coli*	Reduced fungal and bacterial contamination, longer freshness [64]
Cellulose Derivative	Clove essential oil	Fresh tomatoes	*E. coli, Pseudomonas* spp.	Lowered microbial counts, maintained color and firmness [65]
starch-based coating	Garlic extract	Fresh-cut carrots	*S. aureus, Listeria monocytogenes*	Inhibited microbes, reduced spoilage
Pectin-based coating	Cinnamon essential oil	Fresh cherries	*Alternaria* spp., *Penicillium* spp.	Suppressed fungal growth, delayed ripening [66]
Xanthan gum	Green tea extract	Fresh fish fillets	*Vibrio* spp., *Pseudomonas* spp.	Reduced spoilage microorganisms, odor control [67]
Pullulan	Lemon peel extract	Fresh lettuce	*E. coli, Listeria monocytogenes*	Improved microbial safety, maintained texture
Carboxymethyl cellulose	Thyme ESSENTIAL OIL	Fresh chicken breast	*Salmonella enterica, Campylobacter* spp.	Reduced pathogen growth, extended shelf life [68]
Agar-based coating	Black pepper extract [69]	Fresh mangoes	*Colletotrichum* spp., *Aspergillus* spp.	Controlled fungal infections, prolonged shelf life [70]

solutions of natural preservation [74]. The accompanying case studies provide a thorough overview of each biopolymer's function and practical applications, making this section a comprehensive guide to natural biopolymer-based coatings [75].

3.2. Synthetic polymeric coatings

Synthetic polymeric coatings, derived from petrochemical sources, are commonly used in food packaging for their durability, flexibility, and specific barrier properties [76]. These coatings protect against moisture, oxygen, and microbial contamination, extending shelf life and food safety [77]. Popular synthetic polymers like polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC) are often enhanced with antimicrobial agents to create active packaging solutions that inhibit microbial growth [78].

3.2.1. Polyethylene (PE)

PE is widely used due to its excellent moisture barrier, flexibility, and chemical resistance. It is available in low-density (LDPE) and high-density (HDPE) forms, with LDPE used for flexible packaging and HDPE for rigid containers [79]. PE can be infused with antimicrobial agents like silver nanoparticles and organic acids to reduce growth of pathogens (*e. g., E. coli, Listeria monocytogenes*). Its low permeability also helps maintain freshness in food products like baked goods, fruit and vegetables produce, and dairy [80].

3.2.2. Polypropylene (PP)

PP is known for its clarity, chemical resistance, and high thermal stability, making it ideal for microwaveable food containers and high-temperature applications [81]. It is less prone to cracking and can be modified with antimicrobial agents such as silver compounds and chitosan [82]. PP's low moisture transmission rate helps maintain the texture and moisture of fresh fruit and vegetables produce, meats, and other perishable foods [83].

3.2.3. Polyvinyl chloride (PVC)

PVC is a strong, transparent, and flexible polymer used for packaging fresh meat, poultry, and vegetable produce. It provides a strong oxygen barrier, slowing oxidation and preserving freshness [84]. When enhanced with antimicrobial agents like triclosan or silver ions, PVC inhibits microbial growth, particularly in meat and fish packaging [85]. However, concerns about certain additives have led to the exploration of safer antimicrobial alternatives [86]. As shown in Table 3, case studies compare synthetic antimicrobial coatings with natural biopolymer-based alternatives for food preservation.

Synthetic polymeric coatings, such as polyethylene, polypropylene, and polyvinyl chloride, are crucial in food packaging due to their protective properties and versatility [89]. Enhanced with antimicrobial agents, these coatings actively reduce microbial contamination, supporting food safety and extending shelf life [90]. By inhibiting spoilage organisms and pathogens, they offer a capable and cost-effective solution for preserving food quality.

3.3. Hybrid and composite coatings

Hybrid and composite coatings, that combine natural and synthetic polymers, offer enhanced food preservation [91]. These coatings integrate the biodegradability and biocompatibility of natural polymers with the strength and durability of the synthetic ones. This synergy improves antimicrobial efficacy, mechanical stability, and prolonged shelf life for perishable foods[92].

Natural polymers like chitosan [93] and alginate are combined with synthetic polymers such as polyethylene (PE) and polypropylene (PP) to create effective antimicrobial films [32]. These coatings allow better control over antimicrobial agent release, thus offering sustained protection against microbial growth [9].

3.3.1. Benefits of hybrid and composite coatings

Hybrid coatings provide multiple advantages. Natural polymers like chitosan and alginate offer inherent antimicrobial properties, improving food safety and shelf life [94]. They are biodegradable, and relevant to environmental concerns [95], while synthetic polymers like PVA, PE, and PP add strength and durability, making the coatings suitable for food packaging and handling [96].

3.3.2. Examples of hybrid and composite coatings

Chitosan-polyethylene composites: Combine chitosan's antimicrobial activity with polyethylene's barrier properties, suitable for fresh produce and perishable items [97].

Alginate-polyvinyl alcohol (PVA) coatings: Offer biodegradability, barrier function, and flexibility, ideal for fresh fruits and vegetables. Antimicrobial agents like nisin or lysozyme enhance effectiveness [98].

Gelatin-polypropylene films: Combine gelatin's film-forming properties with polypropylene's strength, ideal for meats and dairy products [99].

Cellulose-polyvinyl chloride (PVC) Composites: Provide a durable, biodegradable option for high-moisture foods, protecting against microbes like *Listeria* spp. and *Salmonella* spp. [100].

3.3.3. Complications and considerations in hybrid coatings

Developing hybrid coatings presents obstacles, including ensuring compatibility between natural and synthetic components with differing solubilities, thermal properties, and mechanical behaviors [101]. Achieving uniform distribution of antimicrobial agents within the matrix can also impact effectiveness [102]. While hybrid coatings are more eco-friendly than fully synthetic ones, their biodegradability depends on the ratio of natural components to synthetic materials [103]. Efforts are underway to explore biodegradable synthetic polymers and bio-based additives to enhance sustainability without sacrificing antimicrobial performance or durability [104]. Table 4 demonstrates the effectiveness of hybrid/composite antimicrobial coatings in reducing microbial growth, prolonging shelf life, and preserving the sensory quality of various perishable food products.

Hybrid and composite coatings combine the strengths of natural and synthetic polymers to create effective antimicrobial barriers, offering a balance of durability and environmental sustainability. Their customization for specific food safety needs makes them a promising solution for food packaging and preservation.

4. Mechanisms of antimicrobial action in polymeric coatings

Antimicrobial polymeric coatings prevent microbial growth on food surfaces through various mechanisms [114]. These can be broadly classified into release-based and contact-active mechanisms, both essential for optimizing coating formulations for food preservation [115].

4.1. Release-based mechanisms

Release-based mechanisms involve the gradual release of antimicrobial agents, such as silver ions, from the polymeric matrix [116]. This sustained release ensures long-lasting antimicrobial action. Silver ions disrupt bacterial cell membranes, inhibit enzymatic activity, generate reactive oxygen species [117], and cause genotoxic effects [118], leading

Table 3. **Case studies comparing synthetic antimicrobial coatings and natural biopolymer-based alternatives for food preservation**

Таблица 3. **Примеры сравнения синтетических антимикробных покрытий и их альтернатив, изготовленных на основе природных биополимеров, применяемых для сохранения свежести пищевых продуктов**

Coating type	Synthetic coating	Natural coating	Food product	Target microorganisms
Polyethylene vs. chitosan	Polyethylene + silver nanoparticles	Chitosan + oregano oil	Fresh-cut apples	*E. coli, S. aureus, Salmonella* spp. [87]
Polypropylene vs. gelatin	Polypropylene + essential oils	Gelatin + carvacrol	Fresh strawberries	*Botrytis cinerea, E. coli*
PVC vs. alginate	PVC + triclosan	Alginate + nisin	Fresh-cut turkey	*Listeria monocytogenes*
PLA vs. starch	PLA + silver Nanoparticles	starch + garlic Extract	Fresh-cut carrots	*S. aureus, Listeria monocytogenes*
Polypropylene vs. pectin	Polypropylene + citric acid	pectin + Cinnamon oil	Fresh cherries	*Alternaria* spp., *Penicillium* spp.
PVC vs. xanthan gum	PVC + silver ions	xanthan gum + Green tea extract	Fish fillets	*Vibrio* sp., *Pseudomonas* sp.
Polyethylene vs. cellulose	Polyethylene + zinc oxide	Cellulose + clove oil	Fresh tomatoes	*E. coli, Pseudomonas* spp.
PP vs. Carboxymethyl cellulose	PP + silver ions	CMC + thyme essential oil	Fresh chicken breast	*Salmonella enterica, Campylobacter* spp.
PLA vs. agar	PLA + organic acids	Agar + Black Pepper Extract	Fresh mangoes	*Colletotrichum sp., Aspergillus* spp. [88]
PVC vs. pullulan	PVC + silver ions	Pullulan + lemon peel extract	Fresh lettuce	*E. coli, Listeria monocytogenes*

Table 4. **Performance data of hybrid/composite antimicrobial coatings in food preservation, detailing various natural and synthetic polymer combinations, antimicrobial agents, target microorganisms, and key performance results**

Таблица 4. **Данные об эффективности гибридных/композитных антимикробных покрытий, используемых для сохранения свежести пищевых продуктов, с подробным описанием различных комбинаций природных и синтетических полимеров, антимикробных агентов, целевых микроорганизмов и ключевых результатов действия покрытий**

Natural polymer	Synthetic polymer	Antimicrobial agent(s)	Food product	Target microorganisms
Chitosan	Polyethylene (PE)	Silver nanoparticles	Fresh produce	*E. coli, S. aureus* [105]
Alginate	Polyvinyl alcohol (PVA)	nisin	Fresh-cut apples	*Listeria monocytogenes*
Gelatin	Polypropylene (PP)	Thyme essential oil	Poultry	*Salmonella* spp., *E. coli* [106]
Cellulose	Polyvinyl chloride (PVC)	Zinc oxide	Fish fillets	*Vibrio* spp., *Pseudomonas* spp. [107]
Pectin	Polyethylene (PE)	Cinnamon oil	Fresh strawberries	*Botrytis cinerea* [108]
Xanthan gum	Polypropylene (PP)	Green tea extract	Leafy greens	*E. coli, Listeria monocytogenes* [109]
Starch	Polyvinyl alcohol (PVA)	Carvacrol	Fresh tomatoes	*Salmonella* spp., *E. coli* [110]
Carboxymethyl cellulose (CMC)	Polyethylene (PE)	Garlic extract	Ready-to-eat meats	*Listeria monocytogenes, S. aureus* [111]
Chitosan	Polypropylene (PP)	Oregano oil	Fresh blueberries	*Alternaria* spp., *Penicillium sp.* [112]
Gelatin	Polyvinyl chloride (PVC)	Silver nanoparticles	Fresh chicken	*Campylobacter* spp., *S. aureus* [113]

to bacterial death [119]. The release kinetics can be adjusted to prolong antimicrobial activity, as demonstrated by chitosan and polyethylene coatings, which maintain activity for over 30 days against pathogens like *E. coli* and *S. aureus* [120].

4.2. Contact-active mechanisms

Contact-active coatings kill microbes directly upon contact, offering immediate antimicrobial effects [121]. These coatings act through the surface properties like charge, topography, and antimicrobial functional groups to disrupt microbial cells [122]. For example, quaternary ammonium compounds (QACs) and chitosan can damage bacterial membranes. In the same manner, micro/nano-scale features can physically rupture microbial cells [123]. These coatings also prevent biofilm formation, providing immediate protection. Coatings with silver nanoparticles or QACs exhibit both release and contact-active mechanisms [124], enhancing antimicrobial efficacy [125]. These mechanisms are crucial for enhancing food safety and quality by providing sustained or immediate antimicrobial protection [126].

4.3. Biofilm prevention and disruption

Biofilm formation on food contact surfaces is a significant food safety challenge, as it protects harmful microbes from cleaning and sanitizing processes [127]. Biofilm-preventing and disrupting antimicrobial coatings are essential for minimizing contamination risks [128]. These coatings prevent microbial adhesion and actively disrupt existing biofilms, ensuring cleaner and safer surfaces in food environments [129].

4.3.1. Mechanisms of biofilm prevention

Anti-adhesive surface properties: Hydrophobic coatings, like PTFE, reduce microbial attachment by minimizing surface contact [130].

Incorporation of antimicrobial agents: Coatings with antimicrobial agents, such as silver ions or essential oils, kill microbes and prevent biofilm formation [131].

Surface topography manipulation: Micro/nanostructured surfaces hinder microbial attachment by physically disrupting adhesion points [132].

Electrostatic repulsion: Charged coatings repel microbial cells with a similar charge, preventing initial adhesion [133].

4.3.2. Mechanisms of biofilm disruption

Enzymatic degradation: Enzyme-infused coatings break down the biofilm's EPS matrix, thus facilitating its removal [134].

Release of reactive oxygen species (ROS): ROS damage microbial cells in biofilms, weakening the structure for its easier removal [135].

Interruption of quorum sensing: Coatings that block bacterial communication prevent biofilm maturation [136].

Mechanical disruption: Micro-textured surfaces can fragment biofilm structures with minimal mechanical force [137].

4.3.3 Examples of biofilm-preventing and disrupting coatings

Silver-embedded coatings: Silver ions prevent microbial adhesion and degrade biofilms, effective against pathogens like *Listeria* spp. and *E. coli* [138].

Essential oil-based coatings: Natural oils like thymol and eugenol prevent and disrupt formation of biofilms, offering a food-safe option [139].

Chitosan and quaternary ammonium surfaces: Chitosan's positive charge and quaternary ammonium compounds effectively prevent adhesion and disrupt biofilms [140].

Biofilm prevention and disruption mechanisms are key aspects of antimicrobial polymeric coatings in the food industry, providing enhanced protection for food contact surfaces through physical and chemical deterrents to microbial adhesion and biofilm formation.

5. Types of antimicrobial agents in polymeric coatings

This section explores antimicrobial agents used in polymeric coatings for food contact surfaces, categorized into metal-based, natural, and synthetic chemicals [141]. Metal-based agents (e. g., silver, copper, zinc oxide) provide strong antimicrobial action and durability [142]. Natural antimicrobials (e. g., essential oils, enzymes) are valued for their biodegradability and health benefits [143], ideal for sustainable applications. Synthetic agents (e. g., quaternary ammonium compounds) are effective but yet raise concerns about their toxicity and environmental impact [144].

5.1. Metal-based agents in antimicrobial polymeric coatings

Metal-based agents, commonly used in nanoparticle form, offer broad-spectrum antimicrobial activity against bacteria, fungi, and viruses [145]. These agents, including silver, copper, and zinc oxide, disrupt microbial growth through their particular mechanisms, enhancing the hygiene of food contact surfaces [146].

5.1.1. Silver-based agents

Silver nanoparticles (AgNPs) are incorporated into polymer coatings to maximize surface area. Silver ions (Ag+) disrupt cellular processes, causing cell death through oxidative stress and interference with DNA replication [147].

Applications: Used in food processing equipment and packaging to reduce growth of pathogens like *E. coli*, *Salmonella* spp., and *Listeria* spp. [148].

5.1.2. Copper-based agents

Copper, often in nanoparticle form, is an effective antimicrobial agent. Copper ions disrupt microbial cell membranes, generate reactive oxygen species (ROS), and inhibit biofilm formation [149].

Applications: Used on food preparation surfaces and high-touch areas to prevent microbial colonization, effective against *E. coli* and *Staphylococcus aureus* [150].

5.1.3. Zinc oxide (ZnO) nanoparticles

ZnO nanoparticles exhibit antimicrobial properties through ROS generation and disruption of microbial enzymes, making it effective against a wide range of microorganisms [151].

Applications: Used in food packaging and production surfaces, effective against *E. coli*, *Staphylococcus aureus*, and *Bacillus subtilis*.

5.1.4. Advantages of metal-based antimicrobial agents

Broad-spectrum activity: Effective against bacteria, fungi, and viruses.

Durability: Stable under exposure to various environmental conditions, suitable for long-term use in food processing [152].

Multiple mechanisms: Metal ions target various cellular functions, reducing microbial resistance.

Compatibility: Easily incorporated into different polymers [153].

5.1.5. Complications and considerations

Despite their effectiveness, metal-based agents may leach over time, thus potentially reducing their functional longevity. High metal concentrations can raise safety concerns, especially for food contact applications [154]. Regulatory guidelines are necessary to ensure both efficacy and safety [155].

5.2. Natural antimicrobials

Natural antimicrobial agents, derived from plant extracts [156], essential oils, and enzymes, are popular in polymeric coatings due to their eco-friendly properties [157], low toxicity, and biodegradability. These agents offer broad-spectrum antimicrobial efficacy against foodborne pathogens and can extend food shelf life when incorporated into coatings [144].

5.2.1. Essential oils

Essential oils (EOs) like oregano, thyme, cinnamon, and rosemary are effective against bacteria, fungi, and viruses [158]. Their antimicrobial activity is due to components like thymol and carvacrol, which disrupt microbial cell structures [145].

Mechanism: EOs increase membrane permeability, causing cell leakage and death, and some, like oregano and thyme, also prevent oxidation [146].

Applications: EOs are used in food packaging and edible coatings to protect against pathogens like *Salmonella* spp and *E. coli*, extending the shelf life of meats, produce, and dairy products [147].

5.2.2. Enzymes

Enzymes such as lysozyme, lactoferrin, and nisin are effective antimicrobial agents against Gram-positive bacteria, known for their natural origin and specificity [148].

Mechanism: Lysozyme breaks down bacterial cell walls, lactoferrin inhibits bacterial growth by binding iron, and nisin disrupts cell membranes [149].

Applications: Enzyme-based coatings are used in packaging for meat, cheese, and fresh produce, extending product shelf life [43].

5.2.3. Plant extracts

Plant extracts like garlic, green tea, and cranberry contain antimicrobial bioactive compounds such as phenolic compounds and flavonoids, offering a biodegradable alternative to synthetic antimicrobials [150].

Mechanism: These extracts disrupt cell walls [159], hinder nucleic acid synthesis, and interfere with microbial metabolism [160]. For instance, garlic extract contains allicin, which inhibits bacterial and fungal pathogens [151].

Applications: Plant extracts are used in coatings for fruits, vegetables, seafood, and meats to reduce spoilage and growth of pathogenic bacteria [152].

5.2.4. Advantages of natural antimicrobials

Safety and biodegradability: Generally recognized as safe (GRAS) and eco-friendly.

Multiple mechanisms: Reduces microbial resistance risk.

Consumers' acceptance: Increasing demand for natural ingredients in food.

Synergistic effects: Can be combined with other antimicrobials for enhanced effectiveness.

5.2.5. Complications and limitations

Stability: Volatile compounds like essential oils may lose efficacy over time or under harsh conditions.

Sensory impact: Flavors or odors may be imparted to food, which could be undesirable. [154]

Cost and availability: Extraction and purification are often more expensive and dependent on seasonality.

Variable efficacy: Efficacy can vary based on concentration, formulation, and environmental conditions.

Natural antimicrobials, such as essential oils, enzymes, and plant extracts, offer effective alternatives to synthetic agents in antimicrobial coatings [161]. They protect food safety by disrupting cell membranes, binding nutrients, and interfering with metabolism [162]. However, optimizing their stability, sensory properties, and integration into polymeric matrices is crucial for deploying their full potential in food contact applications [163].

5.3. Synthetic chemical agents

Synthetic chemical agents like Quaternary Ammonium Compounds (QACs) and Triclosan are commonly used in antimicrobial coatings due to their broad-spectrum activity against bacteria, fungi, and viruses [164]. They enhance food safety by preventing contamination on food contact surfaces. These agents offer stability [165], prolonged activity, and effectiveness at low concentrations. However, concerns about environmental impact, microbial resistance, and regulatory restrictions require careful evaluation of their using [166].

5.3.1. Quaternary ammonium compounds (QACs)

QACs, such as benzalkonium chloride, disrupt integrity of microbial cell membranes by binding to negatively charged surfaces, thus causing leakage and cell death. They are effective against various pathogens, including *Staphylococcus aureus* and *Escherichia coli* [167]. QACs create contact-active surfaces that kill microbes on contact without releasing chemicals into the environment. Despite their efficacy, concerns over microbial resistance have led to increased research for alternatives and prevention of microbial resistance development [168].

5.3.2. Triclosan

Triclosan inhibits bacterial fatty acid biosynthesis by blocking the enoyl-acyl carrier protein reductase enzyme. It acts at low concentrations, offering broad-spectrum antimicrobial activity against bacteria and fungi [169]. However, concerns over its environmental persistence, bioaccumulation, and the rise of Triclosan-resistant bacteria have led to regulatory restrictions for its using [170]. As a result, safer and more sustainable alternatives are preferred for food-contact applications [171].

5.3.3. Advantages and limitations of synthetic chemical agents

The key benefits of synthetic agents like QACs and triclosan are their potent, long-lasting antimicrobial activity and effectiveness at low concentrations. However, their potential toxicity, environmental persistence, and risks of resistance development pose necessity for serious trials [172]. Hybrid approaches combining synthetic agents with natural antimicrobials or using encapsulation techniques are being explored to find the way to reduce environmental impact [173]. Despite these limitations, synthetic agents remain crucial in high-hygiene settings, with ongoing research focused on optimizing their use in sustainable antimicrobial solutions [174].

6. Evaluation of antimicrobial efficacy in polymeric coatings

This section covers methods to assess the effectiveness of polymeric coatings in preventing or eliminating microbial contaminants on food contact surfaces [175]. Both laboratory and field testing approaches, such as microbial count reduction and zone of inhibition tests, are essential to ensure coatings meet food safety and preservation performance standards, particularly in food safety. Comparative studies help identify strengths and weaknesses across various coatings and agents.

6.1. Laboratory and field testing methods

Evaluation combines laboratory and field methods to ensure that coatings meet safety standards, maintain efficacy, and perform well in real-world conditions [176].

6.1.1. Laboratory testing methods

Agar diffusion test: Tests antimicrobial action by observing the inhibition zone around a coating on an agar plate.

Colony count method: Measures microbial reduction by counting viable colonies after exposure to a coated surface [177].

Time-kill assay: Evaluates antimicrobial activity over time by counting viable cells at certain intervals.

Biofilm assay: Assesses the coating's ability to prevent or disrupt biofilm formation.

Minimum inhibitory concentration (MIC) testing: Determines the lowest concentration of antimicrobial agent needed to inhibit microbial growth [178].

6.1.2. Field testing methods

Swab testing in food processing environments: Measures microbial load on coated surfaces.

Environmental monitoring: Tracks microbial levels in food production or packaging facilities over time.

Simulated food processing: Tests coatings under real processing conditions, including exposure to temperature, humidity, and food residues.

Sensory analysis: Checks if the coating affects the sensory properties of food products.

Shelf-life testing: Assesses the longevity of antimicrobial coatings and their impact on food preservation [179].

6.1.3. Integrating laboratory and field testing

Combining laboratory tests for optimization with field tests for real-world validation ensures comprehensive evaluation of antimicrobial coatings across diverse conditions [180].

Testing methods, including the zone of inhibition test, microbial count reduction test, MIC test, time-kill assay, biofilm inhibition assay [181], and others, provide insights into coating efficacy, durability, and practical applicability in maintaining food safety and extending shelf-life [182].

Comparative studies are essential for evaluating antimicrobial polymeric coatings, offering insights into the performance of various coating types and antimicrobial agents [183].

7. Key factors affecting antimicrobial performance

The effectiveness of antimicrobial polymeric coatings depends on several factors that influence their performance in real-world applications [184].

7.1. Temperature and humidity

Temperature and humidity significantly impact the stability and efficacy of coatings. High temperatures can enhance antimicrobial release but may also degrade the materials [185]. Excessive humidity can compromise the coating's integrity [186], reduce effectiveness, and promote microbial growth. Optimal temperature and humidity are essential for long-term performance of the coatings in food preservation applications [187].

7.2. Surface characteristics and coating thickness

Surface texture affects microbial adhesion, as smoother surfaces improve antimicrobial efficacy [188]. Coating thickness influences the duration of antimicrobial effects but may alter material properties like flexibility and transparency [189]. The application method also affects coating uniformity and adhesion [190].

7.3. Type of microbial contaminant

The type of microorganism, including bacteria and fungi [191], affects the coating's effectiveness. Gram-positive and gram-negative bacteria give different responses to antimicrobial agents [192], and biofilms can shield microbes, reducing antimicrobial coating efficacy. Tailoring coatings to the microbial profile enhances food safety and reduces foodborne illness risks [193].

8. Hurdles and limitations of antimicrobial polymeric coatings

Antimicrobial polymeric coatings face setbacks in durability [93], health/environmental impact, and cost/practicality for industrial use. Key issues include:

8.1. Durability and longevity of antimicrobial effects

Coatings degrade over time due to the factors like temperature, moisture, UV light, and microbial activity, reducing their antimicrobial efficacy. Degradation mechanisms include hydrolysis, photodegradation, thermal degradation, and microbial breakdown.

Mechanical wear and tear from handling and cleaning can reduce the efficacy of antimicrobial coatings, especially in high-use environments like food processing [71]. Researches are needed to develop more durable coatings that retain antimicrobial properties under harsh conditions [194].

8.2. Health and environmental concerns

The use of synthetic antimicrobials in coatings raises health concerns, such as toxicity and the potential for chemical leaching into food, posing long-term risks. Not to mention, these agents can harm the environment by promoting antimicrobial resistance development and ecological imbalances [195]. Regulatory roadblocks exist, as many countries have strict rules regarding chemical additives in food contact materials.

8.3. Cost and practicality in industrial application

The high cost of developing antimicrobial polymeric coatings, due to advanced materials and production methods, is a major barrier to their widespread adoption in the food industry. Small and medium-sized enterprises (SMEs) may struggle to invest in these technologies, limiting competition [196]. To boot, drawbacks like compatibility with existing processes, scalability, and the need for specialized equipment complicate industrial application. Manufacturers must weigh the cost-effectiveness of these coatings against their benefits in food safety and shelf life. Ongoing researches are needed to create affordable, scalable, and user-friendly solutions for easy integration into food processing systems [197]. To fully realize the potential of these coatings, it is essential to address durability, health and environmental concerns, and cost-effectiveness.

9. Conclusion

This review highlights the critical role of antimicrobial polymeric coatings in enhancing food safety and preventing microbial contamination on food contact surfaces. Both natural biopolymer coatings, such as chitosan and alginate, and synthetic polymers like polyethylene and polypropylene, demonstrate significant antimicrobial efficacy. However, stumbling blocks such as coating durability, health safety and environmental concerns related to synthetic agents, and cost-effectiveness remain. Future research should prioritize the development of biodegradable and environmentally friendly polymers to reduce ecological impact and address regulatory concerns about synthetic antimicrobial agents. Incorporating natural antimicrobials, such as essential oils or plant extracts, into the coatings would offer safer, more sustainable alternatives. On top of that, research into hybrid and composite coatings, which combine the benefits of both natural and synthetic materials, would enhance antimicrobial performance and longevity, providing resistance to environmental factors like temperature fluctuations, moisture, and UV light. Exploring nanotechnology-based coatings and the synergy between antimicrobial coatings and other food preservation technologies, like modified atmosphere packaging, offers promising solutions for improving food safety and extending shelf life. Confronting scalability and cost-effectiveness through more affordable manufacturing processes is essential for widespread adoption in the food industry. Long-term studies on the safety and regulatory compliance of these coatings will ensure their safe use, and cooperation with regulatory bodies will help establish guidelines to meet safety standards. Continued researches, innovations, and interdisciplinary collaboration will be essential for overcoming current limitations and advancing antimicrobial coatings, ultimately contributing to safer food systems, improved public health, and more sustainable practices in food industries.

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