Recent Progress and Emerging Trends of Antimicrobial Edible Food Packaging

ABSTRACT

Recent developments in antimicrobial edible food packaging have opened new horizons for food safety and sustainability. Due to increasing consumer awareness, there is a growing concern over environment-friendly packaging materials which do not accentuate microbial contamination causing foodborne illness and spoilage. Novel edible packaging materials embedded with antimicrobial agents have been developed by scientists to tackle this issue. This development aims to increase the shelf life while minimizing the use of non-biodegradable plastics. Natural antimicrobial applications are beneficial in these innovations. The use of essentialoils antimicrobial peptides, and plant extracts within biopolymers such as as polysaccharides and proteins for potential antimicrobial edible films has gained considerable attention. Furthermore, nanotechnology has significantly improved the mechanical properties and antimicrobial activities of these biopolymers. In future applications, these biological materials may be tailored according to specific food applications, their sensory properties will be improved further by incorporation of different flavours/odours etc., and production processes will be scaled up for commercial purposes. As an emerging trend in this field, smart technology integrated with antimicrobial edible films is also expected to allow consumers to evaluate real-time data on product quality based on freshness indicators such as microbiological contamination. Moreover, future research should develop fully biodegradable film options through nanotechnology-driven scientific research efforts, which would influence future packaging industries greatly with less environmental impact while satisfying the demand of the modern society.

Key Words: Antimicrobial packaging, edible packaging, nanotechnology, smart packaging, biodegradable packaging

1. Introduction

Enormous use of non-biodegradable plastic packaging, especially for food packaging, has raised concerns about its impact on the human health and the environment. Nowadays, food industry is not only interested in packaging the food in some cheap and durable packages made of petroleum-based plastic. A paradigm shift has taken place in the food packaging in the last few decades. As the consumers are becoming more health and environment conscious, food processors are now looking for safe, biodegradable, environment friendly food packaging which at the same time can extend further the shelf life of the product. For further extension of shelf life and better maintenance of food quality, active packaging is being used for food at commercial level and antimicrobial packaging is a good example of such active packaging. In the past few years, there has been a growing interest in researching and developing antimicrobial packaging which is evident from the significant rise in the number of publications on this particular subject in recent years. When antimicrobial substances are coated on the internal surface of the traditional synthetic polymer based packaging materials, the antimicrobial coat protects the food from microbial growth and extend the shelf life, but there is still concerns about deleterious effect of plastics on health of consumers and the environment. There comes the innovation in packaging materials i.e. use of antimicrobial substances in biodegradable polymer based packaging which makes the packaging materials edible and environment friendly. The antimicrobial edible packaging not only ensures food safety by inhibiting microbial growth but also preserves the food quality and sensory attributes.

This paper focuses on the development of antimicrobial edible packaging, recent advances and future trends in this area.

Antimicrobial edible packaging as an alternative can be a promising solution. Nowadays modern lifestyle increased the demand for ready-to-eat foods which are convenient but also prone to contamination and spoilage. The increasing demands for food safety and quality standards in food industries supports the innovations in the field of edible and antimicrobial packaging. The antimicrobial edible packaging not only ensures food safety by inhibiting microbial growth but also preserves the food quality and sensory attributes. This packaging can provide a significant advantage by reducing the need to control pathogens at the factory level. These packaging materials could be stimulated by light, mechanical action or any other forms of outside push and would release antimicrobial agents that would create a protective environment around the food which will help in reducing spoilage and contamination (Punia Bangar *et al*., 2021a; Chawla *et al*., 2021). This paper focuses on the development of antimicrobial edible packaging, recent advances and future trends in this area.

1.1Significance of Antimicrobial Edible Packaging

Antimicrobial edible packaging has been recognised as a promising advancement to extend the shelf life of food products and enhance food safety. This innovation has gathered attention and shows increasing studies exploring its potential. Many antimicrobial agents, such as nisin, pediocin, ethylenediaminetetraacetic acid, bacteriocins, ozone, and lysozyme, etc. have been successfully integrated into edible packaging materials. These agents have shown effectiveness against many foodborne microorganisms such as bacteria, yeasts, moulds, etc. however, some researchers show concern that microorganisms may develop antimicrobial resistance over time, which could reduce the effectiveness of these agents. Moreover, the potential health effects of eating food that comes into direct contact with antimicrobial agents may raise concerns among consumers. These concerns may come from the fear of ingesting synthetic or chemical substances which leads to broader public health and safety considerations.Hence, it is important to do extensive research on antimicrobial edible packaging's long-term effects which will help in addressing potential side effects and consumer concerns and will provide a comprehensive understandingof its implications from technological, environmental, commercial, and social perspectives.(Chawla et al., 2021; Motelica et al., 2020; Trajkovska Petkoska et al., 2021b.

1.2 Edible packaging film and coating

Edible packaging films and coatings are thin, consumable layers used to enhance the quality and safety of food products. They are typically less than 0.3 mm thick and can replace or support natural food layers. They protect the food products from undesirable changes such as moisture loss, oxidation, and microbial growth and should not negatively affect the sensory properties of the food, such as its taste, smell, or texture (Senturk Parreidt *et al.,* 2018).

Edible coatings can be applied through spraying, dipping and spreading. Electro-spraying results in smaller droplets, while dipping gives thicker coatings required for fruits and vegetables as well as meat products, with thickness adjusted by factors like viscosity, density and surface tension. An electrostatic technique can also be used to create multiple layers using physical or chemical interactions, used for confectionery products. In the spreading method, the coating is brushed onto the food surface.

The edible and biodegradable properties of protein-based films and coating materials depend on the composition and production method. When food-grade proteins and safe techniques are used, they are safe for consumption and eco-friendly. However, if non-edible additives or harmful chemicals are used in the formulation, they make it inedible. Polysaccharides, proteins and lipid based (Figure 1) edible packaging materials are used for food and these will be discussed in the subsequent section. Biodegradation should only occur after the packaging has served its intended purpose and does not pose any risk to human health. These films offer sustainable alternatives to traditional packaging, but their composition and production methods must be carefully controlled to ensure their safety and effectiveness (Marta Henriques *et al.*, 2016).

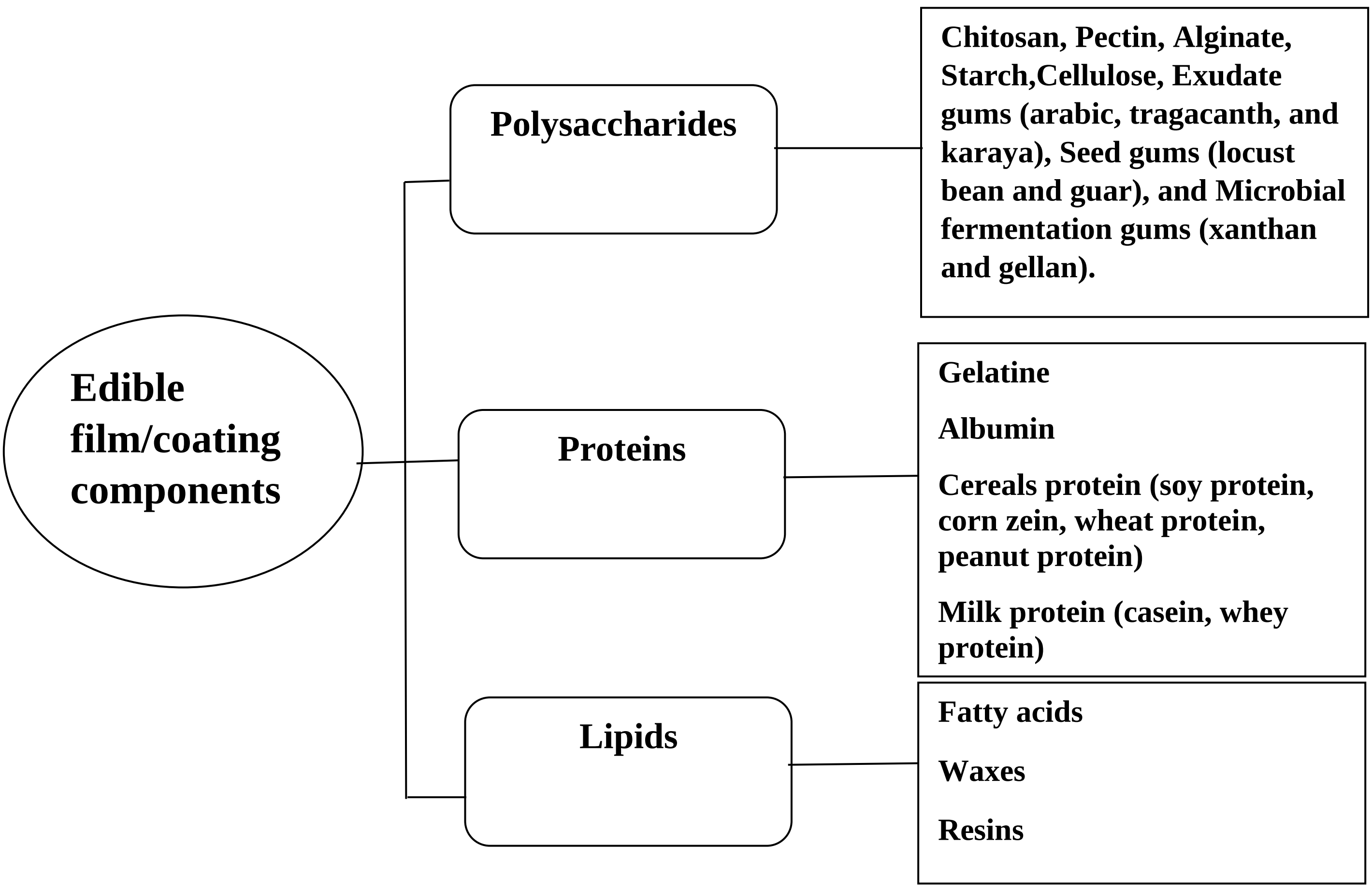

Figure 1. Basic components used for making edible film or coating

2. Antimicrobial Packaging

Antimicrobial packaging is a type of active packaging that is intended to prevent or limit the growth of harmful microorganisms in both food products and the packaging materials themselves. It can be achieved by using antimicrobial substances or by incorporating polymers with inherent antimicrobial properties. Antimicrobial agents consist of organic acids, enzymes, fungicides, and natural ingredients, including spices. Nisin and lysozyme have antimicrobial and antioxidant properties, making them suitable for use as natural food preservatives (Gumienna & Górna, 2021), derived from bacteria and are effective against a wide range of microorganisms, including bacteria and fungi. These preservatives are approved for use in many countries and are considered as safe for human consumption

Antimicrobial packaging can take several forms, including films, coatings, pads, labels, and sachets. They can be customized to meet the specific needs of different food products. For example, some packaging materials may be designed to release antimicrobial substances gradually over time, while others block moisture, oxygen, or light. In general, antimicrobials can be used in the food packaging in the following ways:

1. Sachets or pads containing volatile antimicrobial agents like oxygen absorbers, moisture absorbers, or ethanol vapour generators.
2. Incorporating both volatile and non-volatile antimicrobial agents directly into polymers. Non-volatile agents require direct contact with food, while volatile ones do not.
3. Coating or absorbing antimicrobials onto the polymer surface, used for high-temperature sensitive agents.
4. Immobilize antimicrobials to polymers using ion or covalent linkages.
5. Using inherently antimicrobial polymers like chitosan and poly-L-lysine. (Appendini & Hotchkiss, 2002).

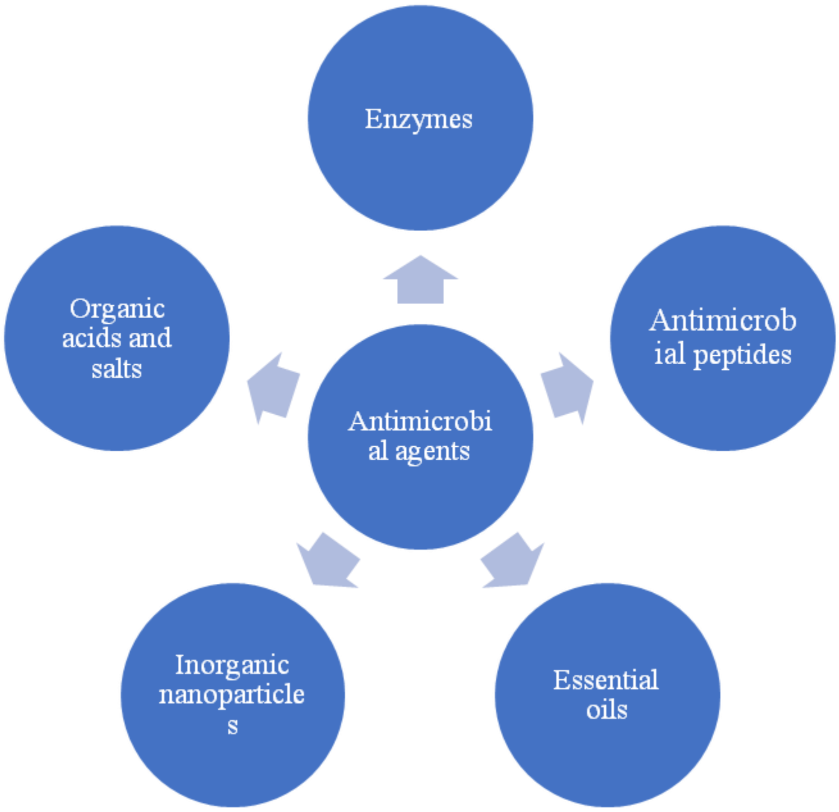

Figure 2. Common antimicrobial agents used in antimicrobial packaging

Table 1. Advantages and disadvantages of synthetic and bio-based polymers as antimicrobial packaging material(Chawla et al., 2021)

Polymers	**Advantages**	**Disadvantages**
Synthetic	Cheap Lightweight Easily manufactured High availability Flexible modulation of morphology and crystallinity Different polarity	Petroleum-based Long degradation time Mostly limited to plastic material production Risk to environment
Bio-based polymers	Biodegradable and biocompatible Edible Renewable resources Significant reduction in packaging volume Controlled release of active agents Controllable shelf life Moderate mechanical properties Environment friendly Non-toxic	Poor water and moisture barrier Expensive manufacturing

2.2 Natural Antimicrobial Agents

Various natural antimicrobial agents, like essential oils from plants, animal-based enzymes (such as lysozyme, lactoferrin), bacteriocins from microbes (such as nisin, pediocin), and biopolymers (like chitosan), have been studied for their ability to fight pathogens and spoilage bacteria in different food items.The integration of antimicrobial agents into biopolymer-based coatings could greatly enhance shelf-life extension and food safety preservation by creating bioactive packaging systems. Edible coatings not only serve as selective barriers against gas, moisture, and solute transfer but also help inhibit microbial growth in solid and semisolid food items by slowing down the release of antimicrobial agents from the coating material. This ensures a prolonged high concentration of antimicrobial agents on the food's surface(Appendini& Hotchkiss, 2002).

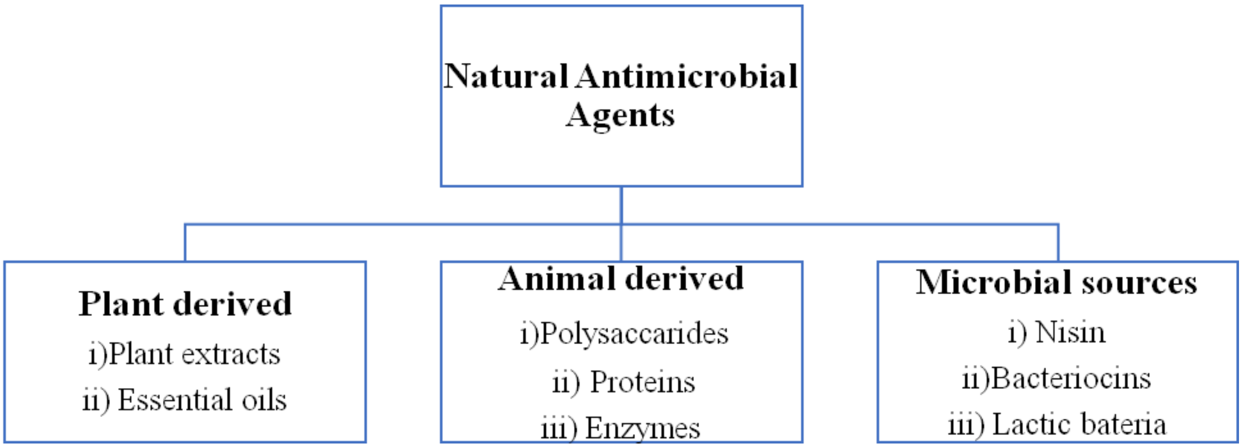

Figure 3. Natural antimicrobial agents' classification (Aloui &Khwaldia, 2016)

2.2.1 Plant and animal-derived natural antimicrobial agents

Plant-based essential oils and extracts have been utilized for many years as additives in food, to enhanceflavour, extend food freshness and control bacteria growth due to their high number of secondary metabolites, such as phenolic compounds, iso-flavonoids, terpenes, ketones, aliphatic alcohols, acids, and aldehydes(Tiwari et al., 2009).To inhibit the growth of foodborne pathogens in food systems, a thorough understanding of essential oils and extracts antimicrobial properties such as mode of action, minimum inhibitory concentration (MIC), target microorganisms, and interactions with food components and other antimicrobial compounds is crucial. Higher concentrations of EOs and extracts are required to be effective because of interaction with lipids and proteins which can put human health at risk by causing poisonings, genetic mutations, and teratogenic effects.(Hyldgaard et al., 2012).The effectiveness of plant-derived compounds against microbes is influenced by the type of microorganism, amount of initial culture, growth medium, extraction technique, and method for assessing antimicrobial activity.Plant extracts and essential oils restrict the growth of pathogens by affecting their cell structure and essential functions. Gram-positive bacteria are more vulnerable due to their simpler structure compared to gram-negative (Cunha et al., 2018).

Natural antimicrobials from animal sources, such as *lysozyme*, *lactoferrin*, *lactoperoxidase*, *chitosan*, *megainin*, *pleurocidin*, *curvacin A*, *spheniscin*, and free fatty acids, found in products like milk, eggs, and crustaceans(Juneja et al., 2012). Chitosan comes from chitin,whose water solubility is restricted, requiring dissolution in an acid to create film-forming solutions. Chitosanfilms show antimicrobial effects on both Gram-positive and Gram-negative bacteria, as well as fungi but are influenced by various factors like the type of pathogen, pH, structural features (such as deacetylation level and molecular weight), origin, and chitosan concentration

(Genskowsky et al., 2015).Casein and whey proteins show important physical characteristics in edible films along with their nutritional benefits, like water solubility and emulsifying ability.Whey proteincan be used as films/coatings to safeguard against chemical or microbial damage, ultimately prolonging shelf life. TheWP films show higher mechanical and barrier characteristicscompared to polysaccharides and other films made from protein sources(Kandasamy et al., 2021).Lactoperoxidasecan have bacteriostatic and/or bactericidal effects on microorganisms, including bacteria, fungi, and viruses(Bafort et al., 2014).

2.2.2 Microorganisms-derived natural antimicrobial agents

Bacteriocins are a limited spectrum of inhibitory peptides that have been identified in various lineages of Bacteria and a few members of the Archaea. These peptides, which are produced by ribosomes, prevent the growth of closely related microorganisms. The bacteriocins can be encoded by genes found on either the chromosome or plasmids. Nisin, a type of bacteriocin, is considered safe for preserving vegetables, dairy, cheese, meats, and other food items because it helps prevent contamination by microorganisms in the production process.(Deegan et al., 2006).

Table 2. Some Examples of Natural Antimicrobials in Edible films and coatings

Antimicrobial agent	Edible film matrix	Food product	Targeted microorganisms	Result	References
Plant based					
Oregano essential oil	Whey protein isolate	NA	*Penicillium commune*	Active films exhibited antimicrobial activity against Penicillium commune at concentrations of 1.0% and 1.5%.	(Oliveira et al., 2017)
Cinnamon essential oil (CEO)	Whey protein concentrate (WPC)	NA	*Lactobacillus lactis,Pseudomonas putida, Streptococcus agalactiae, Escherichia coli,Listeria monocytogenes, Bacillus subtilis*	Reduced the water vapor permeability of the films and water solubility by 38.03 and 29.4%, respectively. demonstrated significant antibacterial activity against gram-positive and gram-negative strains, and displayed effective inhibition of the fungi examined.	(Bahram et al., 2014)
Kojic acid (KA) and clove essential oil (CEO)	Fully deacetylated chitosan (FDCH)	White prawn shrimp (*Litopenaeus vannamei*)	*Aerobic bacteria*	Prevented the growth of pathogenic microorganisms. Had a beneficial impacton sensory characteristics.	(Liu et al., 2020)
Pomegranate peel (PGP)	Starch-based film	NA	*Salmonella, S.aureus*	Prevented the growth of both bacteria.	(Ali et al., 2019)
Cinnamon essential oil (CEO)	sodium alginate-calcium	Paneer	NA	the shelf-life of paneer samples to 13 days from 5-6 days. efficiently maintain the quality of the paneer samples during storage	(Raju & Sasikala, 2016)
Cinnamomum cassia, Cinnamomum zeylanicum, and Rosmarinus officinalis essential oils	Whey protein concentrate (WPC)	Salami	NA	Highest water vapor transmission rate. Retard lipid oxidation induced by UV light in food	(Ribeiro-Santos et al., 2018)

Animal based					
Lactoperoxidase	Whey protein isolate (WPI)	NA	*Penicillium commune*	prevented the growth of *P. commune*. Does not have a notable impact on elastic modulus, tensile strength, percent elongation, oxygen permeability, and color values	(Min & Krochta, 2005)
Chitosan (CH)	Sodium caseinate (SC)	Carrot, Cheese and Salami	aerobic bacteria and yeast and mold	Demonstrated potent bactericidal activity against microorganisms studied, resulting in decreases of 2 to 4.5 log CFU/g	(Moreira et al., 2011)
Lactoperoxidase system (LPOS)	Whey protein - alginate	chicken thigh meat	aerobic mesophilic bacteria, *Enterobacteriaceae* and *Pseudomonas aeruginosa*	Chicken thigh meat showed the highest inhibitory activity against bacterial growth when coated with 8% LPOS	(Molayi et al., 2018)
Activated Lysozyme	Whey protein and oleic acid	Smoked salmon slices	*Listeria innocua*	Reduces bacteria levels and prolongs freshness of product after opening packet when stored in the refrigerator.	(Boyacı et al., 2016)
Lactoferrin with lysozyme	Chitosan film	NA	*Escherichia coli O157:H7 and Listeria monocytogenes*	Decreased growth of *L. monocytogenes* and *E. coli O157: H7*, resulting in an approximate 3-log reduction.	(Brown et al., 2008)
Lactoferrin, Lysozyme, and the Lactoperoxidase System	Whey protein	NA	5-strain cocktails of *S. enterica* and *E. coli O157:H7*	Completely inhibited both *S. enterica* and *E. coli O157:H7* at 4 log CFU/cm^2	(Min et al., 2005)
Microorganisms based					
Bifidobacterium lactis, *Lactobacillus acidophilus, and Lactobacillus casei*	Chitosan, sodium alginate, carboxymethyl cellulose	UF soft Cheese	*Staphylococcus aureus, Salmonella typhimurium, Listeria monocytogenes, Escherichia coli, Bacillus cereus, Aspergillus niger, and Aspergillus flavus*	Strong antimicrobial activity against all pathogenic microbes. probiotic bacteria count exceeded 8.00 log CFU/g during storage	(El-Sayed et al., 2021)
Enterococcus avium DSMZ17511	Food-grade agar	Cheese	*Listeria monocytogenes*	Viability of the pathogen decreased by 1 log unit	(Guitián et al., 2019)
Lactobacillus sakei NRRL B-1917 cell-free supernatant	Whey protein isolate (WPI)	Beef	*Escherichia coli* ATCC 25922, *Listeria monocytogenes*	*L. monocytogenes* reduced by 1.4 log10 CFU/g after 120 h, and *E. coli* by 2.3 log10 CFU/g after 36 h	(Beristain-Bauza et al., 2017)
Lactobacillus paracasei	hydroxypropyl cellulose, konjac flour	NA	*Listeria monocytogenes, Staphylococcus aureus, Escherichia coli, Salmonella typhimurium*	Inhibited the growth of all pathogenic micro-organisms	(Dai et al., 2018)
Nisin Z peptide	Hydroxypropylmethyl cellulose	Mozzarella cheese	*Staphylococcus aureus, Listeria innocua*	Prevented mesophilic microorganisms during storage of 8 days	(Freitas et al., 2020)
Enterococcus faecalis L2B21K3 and L3A21K6	Sweet whey, gelatin/glycerol	Ripened cheese	*Listeria monocytogenes*	Inhibit the migration of pathogens. thickness, swelling index, and tensile strength were high.	(Silva et al., 2023)

2.2.3 Polysaccharide and protein-based antimicrobial edible packaging

Polysaccharides are important materials for antimicrobial edible packaging, with great optical and sensory (odourless) properties along with great barrier capabilities against CO_2 and O_2 due to tightly packed Hydrogenbonds. However, their hydrophilicity leads to high water vapour permeability. To overcome this issue, researchers modify their chemical structure or add hydrophobic components. Chitosan, cellulose, starch, pectin, and alginate are among the most studied polysaccharides.

Zein, gelatin, whey, and soy proteins are the most common proteins used for forming antimicrobial films. Protein mainly exists in two forms: fibrin and globular protein. Generally, heat treatment is required to denature proteins and the bonds between denatured proteins to determine the film’s strength. These films offer great oxygen barriers but have high water vapour permeability and low molecular properties. However, this can be overcome by modifying the proteins' properties by binding them with hydrophobic materials or specific polymers.(M. Wang et al., 2024)

3. Methods of Casting Edible Packaging

3.1. Wet Formation (Solvent Casting)

Solvent casting is the most common method for developing edible films. This involves Dissolving the biopolymer in a solvent like water or ethanol to create a film-forming solution, then pouring the solution into molds or Teflon-coated plates. After that dry the film, remove it, and store it at the right humidity and temperature (Rodríguez et al., 2020). During FFS preparation, all components are mixed into a uniform solution using gentle stirring, ultrasonication, and occasionally increasing the temperature to aid in dissolving the components in the solvents(Abral et al., 2019). Air bubbles must be eliminated from the FFS. The final film's physical and chemical characteristics depend on controlled variables, the biopolymer solution's composition, and the film's thickness(Senturk Parreidt et al., 2018)

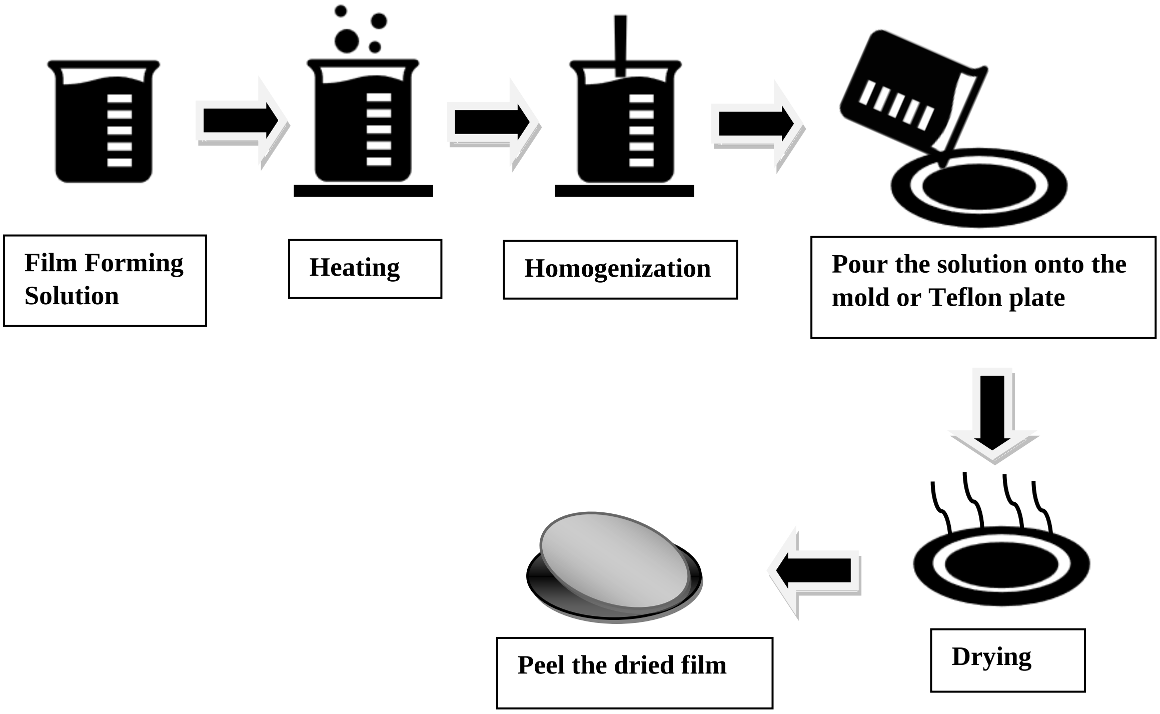

Figure 4. Schematic representation of Solvent Casting method of edible film

3.2. Dry Formation Casting Techniques

The dry process is primarily categorized into extrusion, compression moulding, and injection molding techniques. The extrusion technique, widely used for synthetic plastic films, alters the film material's structure through heat, pressure, and minimal moisture levels. In this process, the biodegradable plastic materials are initially transformed into pellets and then extruded along with appropriate plasticizing agents(Vedove et al., 2021)to enhance their flexibility and strength. Plasticizers reduce brittleness in polysaccharides and protein filmsand enhance the mechanical properties while minimizing the film permeability(Dinika et al., 2020).During compression moulding, film-forming substances are exposed to elevated pressure and heat within the mould until they become solid. The compression method is commonly used in conjunction with the extrusion method, where it is used to prepare the film-formingmaterial before the thermoforming process. A compression-moulded film may possess greater thickness and increased flexibility compared to a solvent-castfilm(Krishna et al., 2012).Injection moulding,used for plastic items mass production, and it can also create edible films through filling, packing, and cooling(Nussinovitch, 2009). Pre-injection pressure temperature, injection pressure, and moulding temperature are crucial factors.

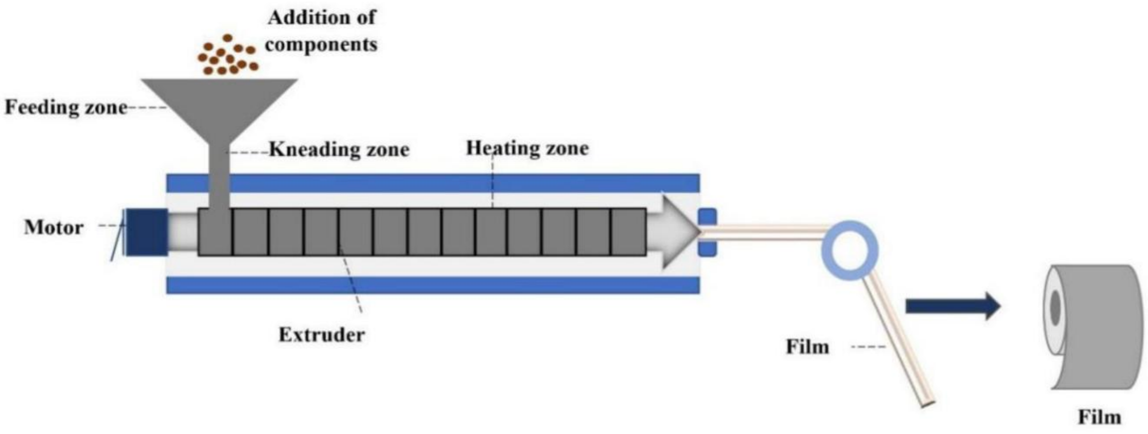

Figure 5. Schematic representation of extrusion technique of edible film(Nair et al., 2023)

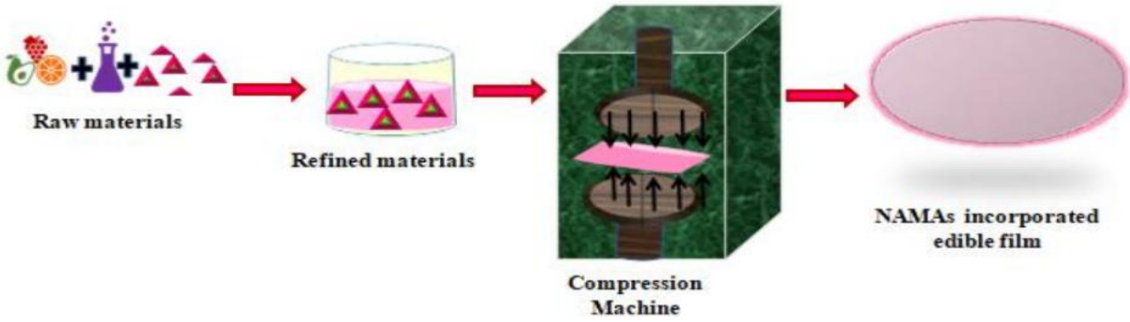

Figure 6. Compression molding technique(Punia Bangar et al., 2021)

4. Applications of Antimicrobial Edible Packaging

4.1. Fruits and vegetables

Creating new natural edible films and coatings with added antimicrobial compounds to protect fresh and minimally processed fruits and vegetables is a significant technological obstacle for the industry and is a highly researched area globally. Antibacterial substances have been effectively incorporated into edible films and coatings made from polysaccharides or proteins like starch, cellulose derivatives, chitosan, alginate, fruit puree, whey protein isolate, soy protein, egg white, wheat gluten, or sodium caseinate(Valencia-Chamorro et al., 2011).

4.2. Meat and Poultry Products

The meat industry experiences spoilage during storage due to enzymatic activity.Most human consumption of animal protein comes from meat, including fresh and cured products, but is prone to rapid decay from microbial contamination, mainly from pathogens such as *Listeria monocytogenes*(Valdés et al., 2017).To combat this, biodegradable biopolymer packaging materials are used to maintain the quality and safety of meat products.

4.3. Dairy Products

Dairy products like milk, fermented milk, cheese, cream, and more are nutritionally valuable, but highly prone to spoilage due to moisture, oxygen, microorganisms, and light.Innovative packaging can improve the functionality of dairy products and enhance their mechanical and barrier properties.Milk can be preserved at refrigeration temperature using the synergistic combination of reuterin and nisin, which demonstrated antimicrobial activity against *L. monocytogenes* and *S. aureus*.(Arqués et al., 2011)

4.4. Bakery and Confectionery Items

In bakery products, fungi are the primary microorganisms responsible for spoilage.Fungi can produce off-flavours, mycotoxins and allergens.(Vinoth Kumar M et al., 2022). Okra mucilage edible coating for biscuits proved more effective before baking at creating a moisture barrier than post-baking, under various atmospheric conditions. The use of an edible covering can preserve gingerbread cakes' quality while stored, without impacting their flavour, consistency, or measured physical and chemical characteristics. This pre-baking process greatly decreased moisture absorption while storing the item (Shulga et al., 2016).

Table 3: Some applications of Antimicrobial Edible Packaging

Edible film matrix	Antimicrobial agents	Food product	Targeted micro-organisms	Result	References
Alginate based coating	cinnamaldehyde, eugenol, and citral Eos	Fresh-cut Fuji apples	*Escherichia coli O157:H7*	reduction of *E. coli O157:H7* by over 4 log CFU/g. increased shelf life by over 30 days	(Raybaudi-Massilia et al., 2008)
Alginate based coating	cinnamon, palmarosa, and lemongrass Eos	fresh-cut "Piel de Sapo" melon (Cucumis melo L.)	—	extended the shelf-life microbiological (up to 9.6 days) and physicochemical aspects (> 14 days)	(RAYBAUDIMASSILIA et al., 2008)
Nanoemulsion coatings	lemongrass essential oil	fresh-cut Fuji apples	*Escherichiacoli*	inhibited microorganisms for 2 weeks eliminated	(Salvia-Trujillo et al., 2015)

				*E.coli*over time higher LEO showed browning after sometime	
Whey protein concentrate (WPC)	rosemary essential oil (REO)	spinach	total microbial and coliform counts	reduced 0.57 and 0.23 log CFU/g total microbial and coliform counts respectively smallest reduction in chlorophyll content	(Abedi et al., 2021)
Nanoemulsion-based edible sodium caseinate coatings	ginger essential oil (GEO)	refrigerated chicken fillets	total microbial counts	reduction in the total number of bacteria over a period of 12 days	(Noori et al., 2018)
Gelatin-carboxymethyl cellulose (Gel-CMC)	chitin nanofiber (CHNF) and Trachyspermum ammi essential oil	uncooked beef	–	prolonged shelflife for 12 days postponed lipid oxidation, breakdown of the proteins	(Azarifar et al., 2020)
Gelatin-carrageenan film	curcumin, gallic acid, and quercetin polyphenols nanoemulsion	fresh broiler meat	*Salmonella typhimurium* and *Escherichia coli*	displayed antimicrobial properties against *S. typhimurium* and *E. coli* prolonged freshness of fresh broiler meat to 17 days	(Khan et al., 2020)

Gelatin-based bio-nanocomposite films	chitosan nanofibers and zinc oxide (ZnO) nanoparticles	chicken fillets	*total bacterial countsStaphylococcus aureus* and *Escherichia coli*	increased shelf-life up to 12 days lower overall bacterial counts inhibited harmful pathogens	(Amjadi et al., 2019)
Alginate, maltodextrin-based coating	*Lactococcus lactis L3A21M1* and *Lc. garvieae SJM17*	fresh cheese	*Listeria monocytogenes*, mesophilic bacteria	inhibited mesophilic bacteria growth and *L. monocytogenes* decreases moisture and weight loss during storage	(Silva et al., 2022)
Liquid acid whey protein concentrate, apple pectin-based coating	*Lactobacillus helveticus* MI-LH13	fresh acid-curd cheese	Meast and mould	decreased discoloration of cheese, improved flavour reduced 1 log cfu/g after 14 days and inhibited mold for 21 days	(Vasiliauskaite et al., 2022)
Sodium alginate-based coating	cinnamon essential oil	paneer	—	increased shelf life of the paneer to 13 days preserved quality of paneer	(Raju &Sasikala, 2016)
Ovine whey protein concentrate	lactic acid, and natamycin	cheese	*Staphylococcus, Pseudomonas, Enterobacteriaceae, yeasts, and molds*	inhibited microorganisms' highest microbial reduction seen in HD+UV treatment	(Marta Henriques et al., 2013)

PLA/nisin coatings	nisin	liquid egg white and skim milk	*Listeria monocytogenes*	inactivated *Listeria* after 3 days at both 10°C and 4°C, maintained for 42 days	(Jin, 2010)
Triticale flour edible coating	—	muffins	Mould	prevented muffins from becoming stale maintained freshness for up to 10 days of storage	(Bartolozzo et al., 2016)
Inulin, Gelatine based coating	*Lactobacillus casei*	cracker cookies	Mould	uphold freshness of cracker cookies at 25°C for a period of 20 days	(Argueta et al., 2016)
Clove and cinnamon-based nanoemulsions (NE) coating	—	muffins	—	prolonged shelflife for upto 6 days without sacrificing quality increased antioxidant potential	(Prastuty et al., 2022)

5. Recent advancements in antimicrobial packaging

Nanotechnology in food packaging

Nanotechnology has gained attention in the food industry. Nanocomposite films can be developed by incorporating nanofillers like Nanoclays, nanosilica, carbon nanotubes, nanocellulose, and chitosan/chitin nanoparticles, these materials can enhance filmmechanical, thermal, optical and barrier properties. Antimicrobial films made with essential oils, bacteriocins, or metallic nanoparticles can enhance active packaging (Brandelli, 2024Nanoemulsion can encapsulate antimicrobials and other bioactive compounds from changes and environmental stress without altering their properties. This technology helps prevent microbial contamination and spoilage and increases the shelf-life of food products, however, their behaviour, interaction and toxicological effect in the human body still need more research (M. Wang et al., 2024).

Table 4: Some applications of Nanoparticles in Food Packaging

Food packaging material	Nanoparticles	Food product	Findings	References
Chitosan incorporated with essential oils	Silver nanoparticles	Strawberries	Showed great antimicrobial activity against *E. coli*, *L. monocytogenes*, *Salmonella Typhimurium*, and *Aspergillus niger*.	(Shankar et al., 2021)
Fish skin gelatin (FSG)	Silver-copper nanoparticles	NA	Improved mechanical and thermal properties. exhibited strong antimicrobial activity.	(Arfat et al., 2017)
Polyvinyl alcohol/gelatin (PVA/G)	ZnO, TiO_2 nanoparticles	White shrimp	Exhibited antimicrobial activity against Gram-negative bacteria	(Azizi-Lalabadi et al., 2020)
Whey protein isolate/cellulose nanofibre//rosemary essential oil	TiO_2 nanoparticle	Lamb meat	Higher inhibition effect on Gram-positive bacteria. Increased shelf life of meat by 15 days	(Alizadeh Sani et al., 2017)
Starch-Poly Vinyl Alcohol	Zinc oxide nanoparticles	NA	Enhanced water barrier, mechanical and antimicrobial properties.	(Jayakumar et al., 2019)
Polyvinyl alcohol (PVA)	Carbon nanotubes	Vegetables, chicken meat	Increased thermal stability, tensile strength WVTR, hydrophobicity, and antibacterial activity	(Wen et al., 2022)

Microencapsulation technology

Microencapsulation technology encloses the tiny materials in a protective layer. This technology works as a protective layer for bioactive compounds by protecting their biological activity from light, oxygen and water. They also help in the controlled release of active substances. However, more research on microcapsule stability during processing conditions and release mechanismsat specific locations and rates is needed for their effective performance in antimicrobial packaging (M. Wang et al., 2024).

Table 5: Some applications of Microencapsulation technology in Food Packaging

Antimicrobial agent	Encapsulating material	Food material	Target microorganisms	Results	References
Nepeta crispa	Pectin, whey protein concentrate	Yogurt (doogh)	E. coli and S. aureus	Inhibited E.coli and S.aureus, increased the shelf life of phenolic compounds in doogh	(Haseli et al., 2023)
Opuntia oligacantha (Xoconostle)	Microcapsules: maltodextrin and gum arabic; nanoemulsion: soy lecithin and orange essential oil	Fresh cheese	Aerobic mesophilic bacteria, moulds and yeasts, and total coliforms	Decreased total coliforms, yeast and molds and aerobic mesophiles during storage	(Pérez-Soto et al., 2021)
Eugenol	Whey protein isolate and maltodextrin	Milk	Escherichia coli and Listeria monocytogenes	Nanodispersed eugenol was more effective than free eugenol, effective against E.coli and Listeria	(Shah et al., 2013)
Basil (Ocimumbasilicum L.) extracts	Sodium alginate	Cream cheese	S. aureus, Geobacillus stearothermophilus, B.cereus, Candida albicans, Enterococcus faecalis, E. coli, and Salmonella Abony	Increased the shelf life of the product by 7 days. Improved degree of water retention	(Popescu et al., 2023)

Nisin and garlic	Liposomes	Milk	L.monocytogenes, S almonella enteritidis, S.aureus, and E. coli	Inhibited L. monocytogenes, S. aureus, E. coli and S. Enteriti dis	(Pinilla &Brandelli, 2016)
Lemongrass essential oil	Arabic gum and maltodextrin	Coelho cheese	Aerobic bacteria, coliform	Inhibited the growth of coliforms in cheese for 21 days	(Melo et al., 2020)

Freshness indicators

Freshness indicators, a type of intelligent packaging, help in monitoring the quality of food by detecting the growth of microorganisms or chemical changes in the food. FIs work on the principle of colourimetric changes. They change colour in response to volatile compounds in food. They provide qualitative and semi-qualitative insights into food quality changes caused by microbial growth or physiological changes without opening the packaging. They are useful in perishable foods like seafood, dairy, meat, etc(Shao et al., 2021). They can be classified according to their sensitivity into the following types; 1. pH-sensitive indicators, 2. Volatile nitrogen compounds sensitive indicators, 3. Hydrogen sulphide sensitive indicators, 4. mixed microbial metabolites sensitive indicators, 5. indicators based on the release of specific nutrients, 6. Other headspace volatile compounds are sensitive indicators(Panjagari et al., 2021).

Table 6: Some applications of Freshness indicators in Food Packaging

Freshness indicators	Food product	Principle function	References
Colorimetric biofilm sensor	Pork	pH monitoring	(Chumee et al., 2022)
Reversible AIE-active fluorescent probe	Beef and shrimp	H2S level monitoring	(B. Wang et al., 2022)
Biodegradable pH film	Pork	pH monitoring	(Zhang et al., 2019)
Enzymatic time-temperature colorimetric Indicator	Milk	Enzymatic time-temperature colorimetric Indicator	(Tsai et al., 2021)

Colorimetric sensor array with classification algorithm	Chicken breast fillet	Volatile compounds detection	(Chen et al., 2014)
PDA/ZnO colorimetric sensor	Milk	pH and lactic acid level monitoring	(Weston et al., 2020)

6. Future Aspects of Antimicrobial Edible Packaging

As the food industry looks for new ways to address contamination, spoilage, and environmental impact, incorporating antimicrobial agents into edible packaging materials offers a promising solution**.**

Enhanced Food Safety

Foodborne diseases are a major issue for public health, and conventional packaging often fails to stop harmful microbes. Antimicrobial edible packaging cantackle this problem by incorporatingessential oils (such as thyme, and oregano), enzymes (like lysozyme), and bioactive peptides (such as nisin) into the packaging material as natural antimicrobial agents to combat bacteria, fungi, and viruses, prolonging the storage of food items and improving safety. Future advancements will enhance the antimicrobials delivery methods to ensure lasting effectiveness during the product's storage period.

Sustainability and Environmental Impact

The growing need for sustainable packaging solutions is spurred by the environmental crisis resulting from plastic waste. Edible packaging made from proteins, polysaccharides and lipids provides a biodegradable optionand will help in reducing landfills and environmental pollution. Future research can improve the functional properties of these materials for a wider range of uses, potentially exceeding those of traditional plastics.

Consumer Convenience and Acceptance

Edible packaging success relies heavily on consumer approval. Taste, texture, and appearance must be designed carefully. The food packaging future will require thorough consumer testing and sensory evaluation as well as education initiatives to introduce consumers to the idea and advantages of edible packaging to alleviate worries regarding safety and cleanliness.

Technological Advancements

Nanotechnology playsa crucial role in antimicrobial edible packaging by adding nanoparticles to edible, which improves mechanical strength, barrier properties, and antimicrobial effectiveness. For instance,silver nanoparticles can offerextensive protection against pathogens which when incorporated into edible films. Future research can create affordable and expandable nanotechnology applications that are safe for humans to consume and meet regulatory requirements.

Regulatory and Market Challenges

The widespread use of antimicrobial edible packaging depends on both regulatory hurdles and gaining market approval. Entities like the FDA and EFSA need to set precise rules and safety criteria for these fresh substances. the safety and effectiveness of antimicrobial agents and edible materials against pathogens is crucial, along with high manufacturing costs. Exploring affordable manufacturing methods, scalability, and possible financial support will be essential in addressing these obstacles.

Industry Collaboration and Innovation

Effective implementation of antimicrobial edible packaging in the food industry requires collaboration amongresearchers, material scientists, food manufacturers, and retailers. Joint efforts and open innovation platforms can accelerate advancements. Businesses that choose to invest in eco-friendly and secure packaging canreduce their environmentalimpact while also standing out in a crowded market.

6. Conclusion

Antimicrobial edible packaging is revolutionizing the food industry by tackling both safety and environmental sustainability issues. This innovation can prevent from microbial growth, increase shelflife by incorporating natural antimicrobial substances. Antimicrobial edible packaging offers significant ecological advantages but can be more expensive than traditional packaging. Future research on the manufacturing process could address this problem. Edible packaging helps decrease waste and contribute to circular economy by using renewable materials.

Creating edible packaging can be pricier to make compared to traditional plastics, and including antimicrobial substances further adds to the expense. Studying efficient manufacturing methods and taking advantage of economies of scale is crucial to ensure the economic feasibility of this technology. Despite these difficulties, there are promising solutions provided by technological advancements. The mechanical strength, barrier properties, and antimicrobial effectiveness of edible films can be improved with nanotechnology, whereas biopolymer blends can enhance material properties by balancing strength, flexibility, and biodegradability.

Consumer education is vital to encourage market adoption. Effective communication regarding the positive environmental and health impacts of antimicrobial edible packaging can assist in overcoming opposition. Collaboration within the food sector is equally important. Collaboration among researchers, material scientists, food manufacturers, and retailers is necessary to develop and bring these technologies to the market. Open innovation platforms and collaborative research efforts can speed up advancement and result in stronger, more widely embraced solutions.

There is great potential for antimicrobial edible packaging to improve food safety, lessen environmental harm, and offer convenience to consumers in the future. As regulations change and technology advances, antimicrobial food packaging made to be eaten could become common in the food sector. This technology pledges to help create a safer, more sustainable, and convenient food system for future generations, representing a major advancement in tackling global food safety and environmental issues. Through continuous developments and teamwork, antimicrobial edible packaging has the potential to revolutionize the food packaging industry, providing a hopeful resolution to current challenges in the food sector.

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