**Recent Progress and Emerging Trends of**

**Antimicrobial Edible Food Packaging**

*1*

# ABSTRACT

Recent advancements in antimicrobial edible food packaging have revolutionized food safety and sustainability. With growing consumer awareness, there is an increasing demand for ecofriendly packaging materials that prevent microbial contamination, foodborne illnesses, and spoilage. To address this concern, scientists have developed novel edible packaging materials infused with antimicrobial agents. These innovations aim to extend shelf life while reducing reliance on non-biodegradable plastics.

Natural antimicrobial applications play a key role in these developments. The incorporation of essential oils, antimicrobial peptides, and plant extracts into biopolymers such as polysaccharides and proteins has garnered significant attention for their potential in antimicrobial edible films. Additionally, nanotechnology has enhanced the mechanical properties and antimicrobial efficacy of these biopolymers.

Future applications of these materials may be customized for specific food products, with improved sensory attributes through the integration of various flavors and aromas. Production processes are also expected to scale up for commercial viability. A promising emerging trend is the integration of smart technology with antimicrobial edible films, enabling real-time monitoring of product quality through freshness indicators, including microbiological contamination.

Furthermore, future research should focus on developing fully biodegradable films through nanotechnology-driven advancements. These innovations would not only reduce environmental impact but also shape the future of the packaging industry while meeting the evolving demands of modern consumers.

**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 human health and the environment. Nowadays, the food industry is not interested in packaging food in cheap and durable packages made of petroleum-based plastic. A paradigm shift has taken place in food packaging in the last few decades. As 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 traditional synthetic polymer-based packaging materials, the antimicrobial coat protects the food from microbial growth and extends the shelf life, but there are still concerns about the deleterious effect of plastics on the 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 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.

## 1.1 Significance 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, 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 longterm effects which will help in addressing potential side effects and consumer concerns and will provide a comprehensive understanding of 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).

**Edible**

**film/coating**

**components**

**Polysaccharides**

**Proteins**

**Lipids**

**Chitosan, Pectin, Alginate,**

**Starch,**

**Cellulose, Exudate gums**

**arabic, tragacanth, and karaya),**

**(**

**Seed gums (locust bean and**

**guar), and Microbial**

**fermentation gums (xanthan and**

**gellan).**

**Gelatine**

**Albumin**

**Cereals protein (soy protein,**

**corn zein, wheat protein, peanut**

**protein)**

**Milk protein (casein, whey**

**protein)**

**Fatty acids**

**Waxes**

**Resins**

**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 as shown in figure 2. 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. Nonvolatile 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  |

## 2.1 Natural Antimicrobial Agents

Various natural antimicrobial agents (figure 3), 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). Examples of Natural Antimicrobials are given in table 2.



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

### 2.1.1 Plant and animal-derived natural antimicrobial agents

Plant-based essential oils and extracts have been utilized for many years as additives in food, to enhance flavour, 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 protein can be used as films/coatings to safeguard against chemical or microbial damage, ultimately prolonging shelf life. The WP films show higher mechanical and barrier characteristics compared to polysaccharides and other films made from protein sources (Kandasamy et al., 2021). Lactoperoxidase can have bacteriostatic and/or bactericidal effects on microorganisms, including bacteria, fungi, and viruses (Bafort et al., 2014).

### 2.1.2 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 theLactoperoxidase 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/cm2 | (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 cellfree 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 microorganisms | (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) |

## 2.1.3 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 CO2 and O2 due to tightly packed hydrogen bonds. 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) (figure 4). 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)

|  |
| --- |
| **Pour the solution onto the mold or Teflon plate**  |

|  |
| --- |
| **Homogenization**  |

|  |
| --- |
|  **Heating**  |

|  |
| --- |
| **Film Forming Solution**  |

--

**Drying**

**Peel the dried film**

**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 (figure 5), 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 films and 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 (figure 6) is commonly used in conjunction with the extrusion method, where it is used to prepare the film-forming material before the thermoforming process. A compressionmoulded film may possess greater thickness and increased flexibility compared to a solvent-cast film (Krishna et al., 2012). Injection moulding, is 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 shows some applications of antimicrobial edible packaging.

# Table 3: Some applications of Antimicrobial Edible Packaging

**Edible film Antimicrobial Food Targeted micro- Result References matrix agents product organisms**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **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 (Raybaudimass shelf-life ilia et al., 2008) microbiologic al (up to 9.6 days) and physicochemi cal aspects (> 14 days)  |
| **Nanoemulsio n coatings**  | lemongrass essential oil  | fresh-cut Fuji apples  | *Escherichia Coli*  | inhibited (Salvia-Trujillo microorganis et al., 2015) ms for 2 weeks eliminated *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 (Abedi et al., and 0.23 log 2021) CFU/g total microbial and coliform counts respectively smallest reduction in chlorophyll content  |
| **Nanoemulsio n-based** **edible sodium caseinate coatings**  | ginger essential oil (GEO)  | refrigerat ed chicken fillets  | total microbial counts  | reduction in the total number of bacteria over a period of 12 days  | (Noori et al., 2018)  |
| **Gelatincarboxymeth****yl cellulose (Gel-CMC)**  | chitin nanofiber (CHNF) and Trachyspermumammi essential oil  | uncooked beef  | \_  |  prolonged (Azarifar et al.,  shelflife for 12 2020) days postponed lipid oxidation, breakdown of the proteins  |

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Gelatincarrageenan** **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)  |
| **Gelatinbased bionanocompos****ite films**  | chitosan nanofibers and zinc oxide (ZnO) nanoparticles  | chicken fillets  | *total bacterial* *countsStaphylococ cus aureus* and *Escherichia coli*  | increased (Amjadi et al., shelf-life up to 2019) 12 days lower overall bacterial counts inhibited harmful pathogens  |
| **Alginate, maltodextrin -based coating**  | *Lactococcus lactis L3A21M1* and *Lc. garvieae SJM17*  | fresh cheese  | *Listeria* *monocytogenes,* mesophilic bacteria  | inhibited mesophilic bacteria growth and *L. monocytogen es* decreases moisture and weight loss during storage  | (Silva et al., 2022)  |
| **Liquid acid whey protein concentrate, apple pectinbased coating**  | *Lactobacillus* *helveticus* MILH13 | 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** **alginatebased 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,* *Enterobacteriacea e, yeasts, and molds*  | inhibited microorganis ms’ 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 and 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 cinnamonbased nanoemulsio ns (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 film mechanical, thermal, optical and barrier properties. Antimicrobial films made with essential oils, bacteriocins, or metallic nanoparticles can enhance active packaging (Brandelli, 2024). Nanoemulsion 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 on the human body still need more research (M. Wang et al., 2024). Some applications of nanoparticles are given in Table 4. **Table 4: Some applications of Nanoparticles in Food Packaging**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Food packaging material**  | **Nanoparticles**  | **Food product**  | **Findings**  | **References**  |
| **Chitosan incorporated with essential oils**  | Silver nanoparticles  | Strawberri es  | Showed great antimicrobial activity against *E. coli, L. monocytogenes,* *Salmonella Typhimuri um,* 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, TiO2 nanoparticl es  | White shrimp  | Exhibited antimicrobial activity against Gramnegative bacteria  | (Azizi-Lalabadi et al., 2020)  |
| **Whey protein isolate/cellulose** **nanofibre//rosem ary essential oil**  | TiO2 nanoparticl e  | 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  | Vegetable s, 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. Applications of Microencapsulation technology are given in Table 5. However, more research on microcapsule stability during processing conditions and release mechanisms at 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 isolates 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 (Ocimumbasili cum L.) extracts  | Sodium alginate  | Cream cheese  | *S. aureus,* *Geobacillus stearothermophilus,* *B.cereus, Candida albicans, Enterococc**us 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). Some applications are given in Table 6.

# 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  | (Wang et al., 2022)  |
| **Biodegradable pH film**  | Pork  | pH monitoring  | (Zhang et al., 2019)  |
| **Enzymatic timetemperature** **colorimetric Indicator**  | Milk  | Enzymatic timetemperature 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 can tackle this problem by incorporating essential 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 option and 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 plays a 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 offer extensive 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 among researchers, 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 can reduce their environmental impact while also standing out in a crowded market.

# 7. CONCLUSION

Antimicrobial edible packaging is revolutionizing the food industry by tackling both safety and environmental sustainability issues. This innovation can prevent microbial growth, and increase shelf life 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 contributes to a 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.

COMPETING INTERESTS DISCLAIMER:

COMPETING INTERESTS

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Option 2:

Author(s) hereby declare that generative AI technologies such as Large Language Models, etc. have been used during the writing or editing of manuscripts. This explanation will include the name, version, model, and source of the generative AI technology and as well as all input prompts provided to the generative AI technology

Details of the AI usage are given below:

1.

2.

3.

**COMPETING INTERESTS**

The authors declare that they have no conflict of interest

# REFERENCES

Abedi, A., Lakzadeh, L., &Amouheydari, M. (2021). Effect of an edible coating composed of whey protein concentrate and rosemary essential oil on the shelf life of fresh spinach. *Journal of Food Processing and Preservation*, *45*(4). https://doi.org/10.1111/jfpp.15284

Abral, H., Basri, A., Muhammad, F., Fernando, Y., Hafizulhaq, F., Mahardika, M., Sugiarti, E., Sapuan, S. M., Ilyas, R. A., & Stephane, I. (2019). A simple method for improving the properties of the sago starch films prepared by using ultrasonication treatment. *Food Hydrocolloids*, *93*, 276–283. https://doi.org/10.1016/j.foodhyd.2019.02.012

Ali, A., Chen, Y., Liu, H., Yu, L., Baloch, Z., Khalid, S., Zhu, J., & Chen, L. (2019). Starch-based antimicrobial films functionalized by pomegranate peel. *International Journal of Biological Macromolecules*, *129*, 1120–1126. <https://doi.org/10.1016/j.ijbiomac.2018.09.068>

Alizadeh Sani, M., Ehsani, A., & Hashemi, M. (2017). Whey protein isolate/cellulose nanofibre/TiO 2 nanoparticle/rosemary essential oil nanocomposite film: Its effect on microbial and sensory quality of lamb meat and growth of common foodborne pathogenic bacteria during refrigeration.

*International Journal of Food Microbiology*, *251*, 8–14. https://doi.org/10.1016/j.ijfoodmicro.2017.03.018

Aloui, H., &Khwaldia, K. (2016). Natural Antimicrobial Edible Coatings for Microbial Safety and Food

Quality Enhancement. *Comprehensive Reviews in Food Science and Food Safety*, *15*(6), 1080– 1103. https://doi.org/10.1111/1541-4337.12226

Amjadi, S., Emaminia, S., Nazari, M., Davudian, S. H., Roufegarinejad, L., &Hamishehkar, H. (2019).

Application of Reinforced ZnO Nanoparticle-Incorporated GelatinBionanocomposite Film with

Chitosan Nanofiber for Packaging of Chicken Fillet and Cheese as Food Models. *Food and*

*Bioprocess Technology*, *12*(7), 1205–1219. https://doi.org/10.1007/s11947-019-02286-y

Appendini, P., & Hotchkiss, J. H. (2002). Review of antimicrobial food packaging. *Innovative Food*

*Science & Emerging Technologies*, *3*(2), 113–126. [https://doi.org/10.1016/S1466-8564(02)000127](https://doi.org/10.1016/S1466-8564%2802%2900012-7)

Arfat, Y. A., Ahmed, J., Hiremath, N., Auras, R., & Joseph, A. (2017). Thermo-mechanical, rheological, structural and antimicrobial properties of bionanocomposite films based on fish skin gelatin and silver-copper nanoparticles. *Food Hydrocolloids*, *62*, 191–202. https://doi.org/10.1016/j.foodhyd.2016.08.009

Argueta, I. G., Salazar, B. Q., & Lopez, A. D. (2016). Effect of Edible Coating Based on Whey, Inulin and Gelatine with Lactobacillus casei on the Textural and Sensorial Properties of a Cracker Cookie. *Journal of Probiotics & Health*, *04*(03). https://doi.org/10.4172/2329-8901.1000153

Arqués, J. L., Rodríguez, E., Nuñez, M., & Medina, M. (2011). Combined effect of reuterin and lactic acid bacteria bacteriocins on the inactivation of food-borne pathogens in milk. *Food Control*,

*22*(3–4), 457–461. https://doi.org/10.1016/j.foodcont.2010.09.027

Azarifar, M., Ghanbarzadeh, B., Sowtikhiabani, M., Akhondzadehbasti, A., &Abdulkhani, A. (2020). The effects of gelatin-CMC films incorporated with chitin nanofiber and Trachyspermumammi essential oil on the shelf life characteristics of refrigerated raw beef. *International Journal of Food Microbiology*, *318*, 108493. <https://doi.org/10.1016/j.ijfoodmicro.2019.108493>

Azizi-Lalabadi, M., Ehsani, A., Ghanbarzadeh, B., &Divband, B. (2020). Polyvinyl alcohol/gelatin nanocomposite containing ZnO, TiO2 or ZnO/TiO2 nanoparticles doped on 4A zeolite: Microbial and sensory qualities of packaged white shrimp during refrigeration. *International Journal of Food Microbiology*, *312*, 108375. https://doi.org/10.1016/j.ijfoodmicro.2019.108375

Bafort, F., Parisi, O., Perraudin, J.-P., &Jijakli, M. H. (2014). Mode of Action of Lactoperoxidase as Related to Its Antimicrobial Activity: A Review. *Enzyme Research*, *2014*, 1–13. https://doi.org/10.1155/2014/517164

Bahram, S., Rezaei, M., Soltani, M., Kamali, A., Ojagh, S. M., & Abdollahi, M. (2014). Whey protein concentrate edible film activated with cinnamon essential oil. *Journal of Food Processing and Preservation*, *38*(3), 1251–1258. https://doi.org/10.1111/jfpp.12086

Bartolozzo, J., Borneo, R., & Aguirre, A. (2016). Effect of triticale-based edible coating on muffin quality maintenance during storage. *Journal of Food Measurement and Characterization*, *10*(1), 88–95. https://doi.org/10.1007/s11694-015-9280-1

Beristain-Bauza, S. del C., Mani-López, E., Palou, E., & López-Malo, A. (2017). Antimicrobial activity of whey protein films supplemented with Lactobacillus sakei cell-free supernatant on fresh beef. *Food Microbiology*, *62*, 207–211. https://doi.org/10.1016/j.fm.2016.10.024

Boyacı, D., Korel, F., &Yemenicioğlu, A. (2016). Development of activate-at-home-type edible antimicrobial films: An example pH-triggering mechanism formed for smoked salmon slices using lysozyme in whey protein films. *Food Hydrocolloids*, *60*, 170–178. https://doi.org/10.1016/j.foodhyd.2016.03.032

Brown, C. A., Wang, B., & Oh, J.-H. (2008). Antimicrobial Activity of Lactoferrin against Foodborne

Pathogenic Bacteria Incorporated into Edible Chitosan Film. *Journal of Food Protection*, *71*(2),

319–324. https://doi.org/10.4315/0362-028X-71.2.319

Chawla, R., Sivakumar, S., & Kaur, H. (2021). Antimicrobial edible films in food packaging: Current scenario and recent nanotechnological advancements- a review. *Carbohydrate Polymer Technologies and Applications*, *2*, 100024. <https://doi.org/10.1016/j.carpta.2020.100024>

Chen, Q., Hui, Z., Zhao, J., & Ouyang, Q. (2014). Evaluation of chicken freshness using a low-cost colorimetric sensor array with AdaBoost–OLDA classification algorithm. *LWT - Food Science and Technology*, *57*(2), 502–507. <https://doi.org/10.1016/j.lwt.2014.02.031>

Chumee, J., Kumpun, S., Nimanong, N., Banditaubol, N., & Ohama, P. (2022). Colorimetric biofilm sensor with anthocyanin for monitoring fresh pork spoilage. *Materials Today: Proceedings*, *65*,

2467–2472. https://doi.org/10.1016/j.matpr.2022.07.103

Cunha, J. A., Heinzmann, B. M., &Baldisserotto, B. (2018). The effects of essential oils and their major compounds on fish bacterial pathogens – a review. *Journal of Applied Microbiology*, *125*(2), 328– 344. https://doi.org/10.1111/jam.13911

Dai, L., Yuan, Y., Song, Z., Qiu, Y., & Yue, T. (2018). Preparation and Characterization of LactobacilliLoaded Composite Films with Sustaining Antipathogenic Activity and Preservation Effect. *Journal of Food Science*, *83*(10), 2511–2519. https://doi.org/10.1111/1750-3841.14348

Deegan, L. H., Cotter, P. D., Hill, C., & Ross, P. (2006). Bacteriocins: Biological tools for bio-preservation and shelf-life extension. *International Dairy Journal*, *16*(9), 1058–1071. https://doi.org/10.1016/j.idairyj.2005.10.026

Dinika, I., Verma, D. K., Balia, R., Utama, G. L., & Patel, A. R. (2020). Potential of cheese whey bioactive proteins and peptides in the development of antimicrobial edible film composite: A review of recent trends. *Trends in Food Science & Technology*, *103*, 57–67. https://doi.org/10.1016/j.tifs.2020.06.017

El-Sayed, H. S., El-Sayed, S. M., Mabrouk, A. M. M., Nawwar, G. A., & Youssef, A. M. (2021).

Development of Eco-friendly Probiotic Edible Coatings Based on Chitosan, Alginate and Carboxymethyl Cellulose for Improving the Shelf Life of UF Soft Cheese. *Journal of Polymers and the Environment*, *29*(6), 1941–1953. https://doi.org/10.1007/s10924-020-02003-3

Freitas, P. A. V., Siiva, R. R. A., de Oiiveira, T. V., Soares, R. R. A., & Soares, N. F. F. (2020).

Biodegradable Film Development by Nisin Z Addition into Hydroxypropylmethylcellulose Matrix for Mozzarella Cheese Preservation. *International Journal of Food Studies*, *9*(2), 360–372. https://doi.org/10.7455/ijfs/9.2.2020.a8

Genskowsky, E., Puente, L. A., Pérez-Álvarez, J. A., Fernandez-Lopez, J., Muñoz, L. A., &Viuda-Martos, M. (2015). Assessment of antibacterial and antioxidant properties of chitosan edible films incorporated with maqui berry (Aristotelia chilensis). *LWT - Food Science and Technology*, *64*(2), 1057–1062. https://doi.org/10.1016/j.lwt.2015.07.026

Guitián, M. V., Ibarguren, C., Soria, M. C., Hovanyecz, P., Banchio, C., &Audisio, M. C. (2019). AntiListeria monocytogenes effect of bacteriocin-incorporated agar edible coatings applied on cheese. *International Dairy Journal*, *97*, 92–98. https://doi.org/10.1016/j.idairyj.2019.05.016

Gumienna, M., &Górna, B. (2021). Antimicrobial Food Packaging with Biodegradable Polymers and

Bacteriocins. *Molecules*, *26*(12), 3735. <https://doi.org/10.3390/molecules26123735>

Haseli, A., Pourahmad, R., Eshaghi, M. R., Rajaei, P., & Akbari-Adergani, B. (2023). Application of nanoencapsulatedMofarrah (Nepeta crispa) essential oil as a natural preservative in yogurt drink

(doogh). *LWT*, *186*, 115256. https://doi.org/10.1016/j.lwt.2023.115256

Hyldgaard, M., Mygind, T., & Meyer, R. L. (2012). Essential Oils in Food Preservation: Mode of Action, Synergies, and Interactions with Food Matrix Components. *Frontiers in Microbiology*, *3*. <https://doi.org/10.3389/fmicb.2012.00012>

Jayakumar, A., K.V., H., T.S., S., Joseph, M., Mathew, S., G., P., Nair, I. C., & E.K., R. (2019). Starch-PVA composite films with zinc-oxide nanoparticles and phytochemicals as intelligent pH sensing

wraps for food packaging application. *International Journal of Biological Macromolecules*, *136*,

395–403. https://doi.org/10.1016/j.ijbiomac.2019.06.018

Jin, T. (2010). Inactivation of *Listeria monocytogenes* in Skim Milk and Liquid Egg White by Antimicrobial Bottle Coating with Polylactic Acid and Nisin. *Journal of Food Science*, *75*(2). https://doi.org/10.1111/j.1750-3841.2009.01480.x

Juneja, V. K., Dwivedi, H. P., & Yan, X. (2012). Novel Natural Food Antimicrobials. *Annual Review of Food Science and Technology*, *3*(1), 381–403. https://doi.org/10.1146/annurev-food-022811101241

Kandasamy, S., Yoo, J., Yun, J., Kang, H.-B., Seol, K.-H., Kim, H.-W., & Ham, J.-S. (2021). Application of Whey Protein-Based Edible Films and Coatings in Food Industries: An Updated Overview. *Coatings*, *11*(9), 1056. https://doi.org/10.3390/coatings11091056

Khan, M. R., Sadiq, M. B., & Mehmood, Z. (2020). Development of edible gelatin composite films enriched with polyphenol loaded nanoemulsions as chicken meat packaging material. *CyTA - Journal of Food*, *18*(1), 137–146. https://doi.org/10.1080/19476337.2020.1720826

Krishna, M., Nindo, C. I., & Min, S. C. (2012). Development of fish gelatin edible films using extrusion and compression molding. *Journal of Food Engineering*, *108*(2), 337–344. https://doi.org/10.1016/j.jfoodeng.2011.08.002

Liu, X., Zhang, C., Liu, S., Gao, J., Cui, S. W., & Xia, W. (2020). Coating white shrimp

(Litopenaeusvannamei) with edible fully deacetylated chitosan incorporated with clove essential oil and kojic acid improves preservation during cold storage. *International Journal of Biological Macromolecules*, *162*, 1276–1282. https://doi.org/10.1016/j.ijbiomac.2020.06.248

Marta Henriques, David Gomes, & Carlos D. Pereira. (2016). *Emerging and Traditional Technologies for Safe, Healthy and Quality Food* (V. Nedović, P. Raspor, J. Lević, V. TumbasŠaponjac, & G. V.

Barbosa-Cánovas, Eds.). Springer International Publishing. https://doi.org/10.1007/978-3-31924040-4

Marta Henriques, Gustavo Santos, Ana Rodrigues, David Gomes, Carlos Pereira, & Maria Gil. (2013).

REPLACEMENT OF CONVENTIONAL CHEESE COATINGS BY NATURAL WHEY PROTEIN EDIBLE

COATINGS WITH ANTIMICROBIAL ACTIVITY. *Journal of Hygienic Engineering and Design*, *3*, 34–47.

Melo, A. M. de, Turola Barbi, R. C., Souza, W. F. C. de, Luna, L. C., Souza, H. J. B., Lucena, G. L., Quirino, M. R., & Sousa, S. (2020). Microencapsulated lemongrass ( *Cymbopogonflexuosus* ) essential oil:

A new source of natural additive applied to Coalho cheese. *Journal of Food Processing and Preservation*, *44*(10). https://doi.org/10.1111/jfpp.14783

Min, S., Harris, L. J., & Krochta, J. M. (2005). Antimicrobial Effects of Lactoferrin, Lysozyme, and the Lactoperoxidase System and Edible Whey Protein Films Incorporating the Lactoperoxidase System Against Salmonella enterica and Escherichia coli O157:H7. *Journal of Food Science*, *70*(7). https://doi.org/10.1111/j.1365-2621.2005.tb11476.x

Min, S., & Krochta, J. M. (2005). Inhibition of *Penicillium commune* by Edible Whey Protein Films Incorporating Lactoferrin, Lacto-ferrin Hydrolysate, and Lactoperoxidase Systems. *Journal of Food Science*, *70*(2), M87–M94. https://doi.org/10.1111/j.1365-2621.2005.tb07108.x

Molayi, R., Ehsani, A., & Yousefi, M. (2018). The antibacterial effect of whey protein–alginate coating incorporated with the lactoperoxidase system on chicken thigh meat. *Food Science & Nutrition*, *6*(4), 878–883. https://doi.org/10.1002/fsn3.634

Moreira, M. del R., Pereda, M., Marcovich, N. E., & Roura, S. I. (2011). Antimicrobial Effectiveness of

Bioactive Packaging Materials from Edible Chitosan and Casein Polymers: Assessment on Carrot, Cheese, and Salami. *Journal of Food Science*, *76*(1). https://doi.org/10.1111/j.17503841.2010.01910.x

Motelica, L., Ficai, D., Ficai, A., Oprea, O. C., Kaya, D. A., & Andronescu, E. (2020). Biodegradable Antimicrobial Food Packaging: Trends and Perspectives. *Foods*, *9*(10), 1438. https://doi.org/10.3390/foods9101438

Nair, S. S., Trafiałek, J., & Kolanowski, W. (2023). Edible Packaging: A Technological Update for the Sustainable Future of the Food Industry. *Applied Sciences*, *13*(14), 8234. https://doi.org/10.3390/app13148234

Noori, S., Zeynali, F., & Almasi, H. (2018). Antimicrobial and antioxidant efficiency of nanoemulsionbased edible coating containing ginger (Zingiber officinale) essential oil and its effect on safety and quality attributes of chicken breast fillets. *Food Control*, *84*, 312–320. https://doi.org/10.1016/j.foodcont.2017.08.015

Nussinovitch, A. (2009). Biopolymer Films and Composite Coatings. In *Modern Biopolymer Science* (pp.

295–326). Elsevier. https://doi.org/10.1016/B978-0-12-374195-0.00010-0

Oliveira, S. P. L. F., Bertan, L. C., De Rensis, C. M. V. B., Bilck, A. P., & Vianna, P. C. B. (2017). Whey protein-based films incorporated with oregano essential oil. *Polimeros*, *27*(2), 158–164. <https://doi.org/10.1590/0104-1428.02016>

Panjagari, N. R., Raman, R. K., Uma, K., Suwalka, R., & Thomas, E. (2021). Freshness indicators for realtime quality evaluation of packaged animal origin foods: A mini-review. *INDIAN JOURNAL OF ANIMAL HEALTH*, *60*(2-Spl). <https://doi.org/10.36062/ijah.2021.spl.02421>

Pérez-Soto, E., Cenobio-Galindo, A. de J., Espino-Manzano, S. O., Franco-Fernández, M. J., LudeñaUrquizo, F. E., Jiménez-Alvarado, R., Zepeda-Velázquez, A. P., & Campos-Montiel, R. G. (2021). The Addition of Microencapsulated or Nanoemulsified Bioactive Compounds Influences the Antioxidant and Antimicrobial Activities of a Fresh Cheese. *Molecules*, *26*(8), 2170. <https://doi.org/10.3390/molecules26082170>

Pinilla, C. M. B., &Brandelli, A. (2016). Antimicrobial activity of nanoliposomes co-encapsulating nisin and garlic extract against Gram-positive and Gram-negative bacteria in milk. *Innovative Food Science & Emerging Technologies*, *36*, 287–293. <https://doi.org/10.1016/j.ifset.2016.07.017>

Popescu, L., Cojocari, D., Lung, I., Kacso, I., Ciorîţă, A., Ghendov-Mosanu, A., Balan, G., Pintea, A., &

Sturza, R. (2023). Effect of Microencapsulated Basil Extract on Cream Cheese Quality and Stability. *Molecules*, *28*(8), 3305. https://doi.org/10.3390/molecules28083305

Prastuty, Kaur, G., & Singh, A. (2022). Shelf life extension of muffins coated with cinnamon and clove oil nanoemulsions. *Journal of Food Science and Technology*, *59*(5), 1878–1888. https://doi.org/10.1007/s13197-021-05202-5

Punia Bangar, S., Chaudhary, V., Thakur, N., Kajla, P., Kumar, M., & Trif, M. (2021). Natural

Antimicrobials as Additives for Edible Food Packaging Applications: A Review. *Foods*, *10*(10), 2282. https://doi.org/10.3390/foods10102282

Raju, A., & Sasikala, S. (2016). Natural antimicrobial edible film for preservation of paneer. *Biosciences*

*Biotechnology Research Asia*, *13*(2). https://doi.org/10.13005/bbra/2136

Raybaudi-Massilia, R. M., Rojas-Graü, M. A., Mosqueda-Melgar, J., & Martín-Belloso, O. (2008).

Comparative Study on Essential Oils Incorporated into an Alginate-Based Edible Coating To

Assure the Safety and Quality of Fresh-Cut Fuji Apples. *Journal of Food Protection*, *71*(6), 1150– 1161. https://doi.org/10.4315/0362-028X-71.6.1150

RAYBAUDIMASSILIA, R., MOSQUEDAMELGAR, J., & MARTINBELLOSO, O. (2008). Edible alginate-based coating as carrier of antimicrobials to improve shelf-life and safety of fresh-cut melon.

*International Journal of Food Microbiology*, *121*(3), 313–327. https://doi.org/10.1016/j.ijfoodmicro.2007.11.010

Ribeiro-Santos, R., de Melo, N. R., Andrade, M., Azevedo, G., Machado, A. V., Carvalho-Costa, D., & Sanches-Silva, A. (2018). Whey protein active films incorporated with a blend of essential oils: Characterization and effectiveness. *Packaging Technology and Science*, *31*(1), 27–40. https://doi.org/10.1002/pts.2352

Rodríguez, G. M., Sibaja, J. C., Espitia, P. J. P., & Otoni, C. G. (2020). Antioxidant active packaging based on papaya edible films incorporated with Moringa oleifera and ascorbic acid for food preservation. *Food Hydrocolloids*, *103*, 105630. https://doi.org/10.1016/j.foodhyd.2019.105630

Salvia-Trujillo, L., Rojas-Graü, M. A., Soliva-Fortuny, R., & Martín-Belloso, O. (2015). Use of antimicrobial nanoemulsions as edible coatings: Impact on safety and quality attributes of freshcut Fuji apples. *Postharvest Biology and Technology*, *105*, 8–16. https://doi.org/10.1016/j.postharvbio.2015.03.009

Senturk Parreidt, T., Müller, K., & Schmid, M. (2018). Alginate-Based Edible Films and Coatings for Food Packaging Applications. *Foods*, *7*(10), 170. <https://doi.org/10.3390/foods7100170>

Shah, B., Davidson, P. M., & Zhong, Q. (2013). Nanodispersed eugenol has improved antimicrobial activity against Escherichia coli O157:H7 and Listeria monocytogenes in bovine milk.

*International Journal of Food Microbiology*, *161*(1), 53–59. https://doi.org/10.1016/j.ijfoodmicro.2012.11.020

Shao, P., Liu, L., Yu, J., Lin, Y., Gao, H., Chen, H., & Sun, P. (2021). An overview of intelligent freshness indicator packaging for food quality and safety monitoring. *Trends in Food Science & Technology*, *118*, 285–296. <https://doi.org/10.1016/j.tifs.2021.10.012>

Shankar, S., Khodaei, D., & Lacroix, M. (2021). Effect of chitosan/essential oils/silver nanoparticles composite films packaging and gamma irradiation on shelf life of strawberries. *Food Hydrocolloids*, *117*, 106750. https://doi.org/10.1016/j.foodhyd.2021.106750

Shulga, О., Chorna, А., & Аrsenieva, L. (2016). Edible coating as factor of preserving freshness and increasing biological value of gingerbread cakes. *Food Science and Technology*, *10*(4). https://doi.org/10.15673/fst.v10i4.247

Silva, S. P. M., Ribeiro, S. C., Teixeira, J. A., & Silva, C. C. G. (2022). Application of an alginate-based edible coating with bacteriocin-producing Lactococcus strains in fresh cheese preservation. *LWT*, *153*. https://doi.org/10.1016/j.lwt.2021.112486

Silva, S. P. M., Teixeira, J. A., & Silva, C. C. G. (2023). Application of enterocin-whey films to reduce Listeria monocytogenes contamination on ripened cheese. *Food Microbiology*, *109*. https://doi.org/10.1016/j.fm.2022.104134

Tiwari, B. K., Valdramidis, V. P., O’ Donnell, C. P., Muthukumarappan, K., Bourke, P., & Cullen, P. J.

(2009). Application of Natural Antimicrobials for Food Preservation. *Journal of Agricultural and Food Chemistry*, *57*(14), 5987–6000. https://doi.org/10.1021/jf900668n

Trajkovska Petkoska, A., Daniloski, D., D’Cunha, N. M., Naumovski, N., & Broach, A. T. (2021). Edible packaging: Sustainable solutions and novel trends in food packaging. *Food Research International*, *140*, 109981. <https://doi.org/10.1016/j.foodres.2020.109981>

Tsai, T.-Y., Chen, S.-H., Chen, L.-C., Lin, S.-B., Lou, S.-N., Chen, Y.-H., & Chen, H.-H. (2021). Enzymatic

Time-Temperature Indicator Prototype Developed by Immobilizing Laccase on Electrospun Fibers

to Predict Lactic Acid Bacterial Growth in Milk during Storage. *Nanomaterials*, *11*(5), 1160. https://doi.org/10.3390/nano11051160

Valdés, A., Ramos, M., Beltrán, A., Jiménez, A., &Garrigós, M. (2017). State of the Art of Antimicrobial Edible Coatings for Food Packaging Applications. *Coatings*, *7*(4), 56. https://doi.org/10.3390/coatings7040056

Valencia-Chamorro, S. A., Palou, L., del Río, M. A., & Pérez-Gago, M. B. (2011). Antimicrobial Edible Films and Coatings for Fresh and Minimally Processed Fruits and Vegetables: A Review. *Critical Reviews in Food Science and Nutrition*, *51*(9), 872–900. https://doi.org/10.1080/10408398.2010.485705

Vasiliauskaite, A., Mileriene, J., Songisepp, E., Rud, I., Muizniece-Brasava, S., Ciprovica, I., Axelsson, L., Lutter, L., Aleksandrovas, E., Tammsaar, E., Salomskiene, J., Serniene, L., &Malakauskas, M. (2022). Application of Edible Coating Based on Liquid Acid Whey Protein Concentrate with Indigenous Lactobacillus helveticus for Acid-Curd Cheese Quality Improvement. *Foods*, *11*(21). https://doi.org/10.3390/foods11213353

Vedove, T. M. A. R. D., Maniglia, B. C., &Tadini, C. C. (2021). Production of sustainable smart packaging based on cassava starch and anthocyanin by an extrusion process. *Journal of Food Engineering*,

*289*, 110274. https://doi.org/10.1016/j.jfoodeng.2020.110274

Vinoth Kumar M, Neha Sharma, & Ranjith S. (2022). Trends in edible packaging of bakery products: A review. *The Pharma Innovation Journal*, *11*(12), 182–193.

Wang, B., Leng, J., Wang, X., & Zhao, W. (2022). Reversible AIE-active fluorescent probe with a large emission peak shift for ratiometric detection of food freshness indicator H2S. *Food Chemistry*,

*386*, 132768. https://doi.org/10.1016/j.foodchem.2022.132768

Wang, M., Wei, Z., & Zhang, Z. (2024). Antimicrobial Edible Films for Food Preservation: Recent Advances and Future Trends. *Food and Bioprocess Technology*, *17*(6), 1391–1411. <https://doi.org/10.1007/s11947-023-03178-y>

Wen, Y.-H., Tsou, C.-H., de Guzman, M. R., Huang, D., Yu, Y.-Q., Gao, C., Zhang, X.-M., Du, J., Zheng, Y.T., Zhu, H., & Wang, Z.-H. (2022). Antibacterial nanocomposite films of poly(vinyl alcohol) modified with zinc oxide-doped multiwalled carbon nanotubes as food packaging. *Polymer Bulletin*, *79*(6), 3847–3866. <https://doi.org/10.1007/s00289-021-03666-1>

Weston, M., Kuchel, R. P., Ciftci, M., Boyer, C., & Chandrawati, R. (2020). A polydiacetylene-based colorimetric sensor as an active use-by date indicator for milk. *Journal of Colloid and Interface Science*, *572*, 31–38. <https://doi.org/10.1016/j.jcis.2020.03.040>

Zhang, J., Zou, X., Zhai, X., Huang, X., Jiang, C., & Holmes, M. (2019). Preparation of an intelligent pH film based on biodegradable polymers and roselle anthocyanins for monitoring pork freshness. *Food Chemistry*, *272*, 306–312. https://doi.org/10.1016/j.foodchem.2018.08.041