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***Correspondence**

Muhammad Jabbar
Email:
zoologistofficial@gmail.com

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A Comprehensive Review on Antimicrobial Activity of Edible Biofilms

Muhammad Jabbar[1]*, Hamna Shahid[2], Hasooba Hira[3], Hafsa Kanwal[4]

[1]Department of Zoology, Faculty of Bioscience, Cholistan University of Veterinary and Animal Sciences, Bahawalpur, Pakistan.
[2]Department of Biotechnology, Virtual University Lahore, Pakistan.
[3]University of Agriculture, Faisalabad, Pakistan.
[4]Allama Iqbal Open University, Islamabad, Pakistan.

Abstract:
Latest trends are emerging for food packaging, which is beneficial for human health and overcoming environmental issues. Edible biofilms are protective coverings made up of polysaccharides, proteins, and lipid-based natural edible polymers and then applied outside the food product as an alternative solution to conventional packaging. Biodegradable edible biofilms extend the shelf life of foods, protect food from different food-borne pathogens, minimize the harmful impact of synthetic preservatives, provide better moisture and gas barrier properties, and improve nutritional values. Natural antimicrobial agents are used to enhance the antimicrobial activity of packaging. Here, we review the incorporation of natural polymers into the edible biofilm and how they affect specific food quality characteristics. About different types of edible biofilms and their applications on food while describing advantages and drawbacks. Limitations, use of nanoparticles in edible biofilms, and safety concerns.

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1. INTRODUCTION

There is a difference even if edible coatings and films have a similar meaning. Typically, edible coatings are created directly onto the food surfaces, as opposed to edible films, which are made separately and applied to the food surface (Vali and Joe, 2017). Due to the crucial role they play in the prevention of cardiovascular problems, cancer, and diabetes, biodegradable films are widely used in a variety of industries, including packaging, storage, and even in medicine, to replace non-biodegradable plastic (Linares-Bravo *et al.,* 2022).

The purpose of the edible film is to manage moisture loss and reduce the rate of unfavorable chemical reactions to raise the quality and safety of a variety of refined and fresh meals (Kumar *et al.,* 2022). By slowing down the drought, giving selective barriers to moisture, breathing suppression, gases like oxygen and carbon dioxide, upgrading texture, maintaining volatile compounds, and averting microbial growth on food surfaces, edible films preserve comestible products from degeneration (Atta *et al.,* 2021).

Edible coatings or films are not a modern method of food preservation. They have used it since ancient times to keep food from spoiling. For example, they frequently reported cellulose coatings on meat products and waxes on fruits and vegetables cases. Since the 12th century, they have employed edible coatings in China. (Bizymis and Tzia, 2021). Nowadays, a diversity of foods is used with edible films, and their combined yearly profit reaches $100 million US dollars (Vali and Joe, 2017).

Traditionally, edible films and coatings were created translucent and tasteless to protect food's sensory qualities. However, new research results suggested that certain sensory attributes would be required for some applications, such as sushi wraps and toppings for pizza. Additionally, antioxidant edible coatings may be safe against food oxidation and nutritional losses, while antimicrobials may prevent bacterial food spoilage and organoleptic deterioration (Dubey and Dubey, 2020).

Due to their advantages over artificial films and their promising outcomes in food preservation, edible films and coatings have achieved a noticeable interest in recent years (Hassan *et al.,* 2018). However, the most often used methods of food preservation include the use of chemical preservatives, which have several negative side effects, including a change in the nutritional value of the food and hazardous effects on human health. Therefore, in recent years, there has been a major increase in interest in the demand for natural or bio preservatives to replace these chemical compounds (Sidhu and Nehra, 2019). In the food industry, many preservation procedures, such as heat treatment, acidification, salting, and drying, have been employed to stop the growth of spoilage and pathogenic microorganisms in foods (Benbettaïeb *et al.,* 2019). Additionally, bacterial cells that produce biofilm are harder to get rid of than planktonic bacteria because they are more resistant to environmental stresses like antimicrobials and detergents. This leads to the development of food-borne illnesses (Das *et al.,* 2020).

Conventional packaging is frequently a single-use item that is thrown away once it has reached the consumer or after the packaged material has been used. Paper, plastic, glass, steel, aluminum, and other alloys are a few of the materials most frequently used in traditional food packaging. Therefore, while relatively high recycling rates for some materials (above 20% recycling rate for specific paper and paperboard), while others, like various plastics, are frequently recycled at low recycling rates (less than 20%), conventional packaging creates a significant environmental burden (Petkoska *et al.,* 2021). Due to technical and financial challenges, only a small percentage of the plastic trash produced worldwide is recycled—less than 3%. Additionally, incinerating them might cause the production of harmful substances like dioxins and furans from burning polyvinyl chloride (PVC) (Otoni *et al.,* 2017). Plastic is therefore examined as the greatest threat to eradicating global pollution (Kumar *et al.,* 2022).

To overcome these problems, biodegradable and/or renewable polymers have attracted a lot of attention (Espitia and Otoni, 2018). The two main types of active packaging are antioxidant and antibacterial packaging, which are promising for increasing the shelf life of food items, whereas the use of natural antioxidants and antimicrobial components is an alternative to chemical products in food preservation. Edible plants, particularly those rich in secondary metabolites (such as essential oils and polyphenols), are gaining interest due to their high quantities of bioactive components with antioxidant and/or antibacterial action (Bonilla and Sobral, 2016). Chitin and its derivatives were designated as useful food additives by the Japanese department of health in 1992. More recently (in 2001), the US FDA allowed chitosan at the GRAS level. Chitosan is an intriguing polymer for the production of films as an antimicrobial delivery system because of its ability to generate films with outstanding mechanical and physicochemical qualities and to inhibit a wide variety of microorganisms. (Benabbou *et al.,* 2018). To replace traditional plastic packaging, biopolymers made of polysaccharides, including pectin, carrageenan, alginate, starch, and xanthan gum have been used to generate coatings and edible films (Mohammed *et al.,* 2020).

An edible polymer with built-in antioxidants was used in the development of edible active packaging. The mechanical properties and resistance to oxygen/water vapor transport via the packaging films are improved by adding natural antioxidants and nanofillers to the biopolymer matrix. This improves the food product's resistance to oxidation and prevents the growth of food-borne microorganisms on it (Rangaraj *et al.,* 2021) which gives extra safety features to the food items even in the lack of cold storage environment.

The common practice for incorporating antimicrobials into food products is through a direct introduction. However, the effectiveness of antimicrobial compounds against bacteria is decreased by their interactions with different food ingredients. Therefore, using alternate techniques to minimize these interactions could enhance the compound's activity and stability in complicated food systems (Ibarguren *et al.,* 2015). It is necessary to choose the appropriate antimicrobial agent that is tailored specifically for food and to package it in a manner that takes into account the minimum inhibitory concentration of the target organisms. The packaging industry has given substantial attention to antimicrobial packaging because of its great alternative method for decreasing, preventing, or inhibiting the growth of pathogenic and spoilage microorganisms in food products as well as extending shelf life.Antimicrobial packaging films are created by combining the antimicrobial agents in a polymer matrix to inhibit the growth of specific microorganisms whose activity would otherwise contaminate food (Chawla *et al.,* 2021).

Though, their mechanical characteristics and permeability are typically weaker than those of synthetic films. The hydrophilic nature of edible polymers restricts their capacity to give desired edible film functions to certain applications. For this reason, when evaluating its uses, the relative humidity, which significantly affects the majority of attributes, must be taken into account. Due to this, creating composite films with hydrophobic compounds as edible fatty acids and waxes is typically required for their usage as moisture barriers (Murrieta-Martínez *et al.,* 2018).

The current study initially aims to review the effective edible biofilm by comparing the antimicrobial activity of commonly known compounds and the way of their application to food.

2. Different materials used for edible film formation

2.1 Polysaccharide-based edible biofilms

Polysaccharides can be mixed with other biomaterials to produce composite film-basedmethods with enhanced characteristics (Pandey, 2021). In sustainable food packaging, polysaccharides like starch, cellulose, pectin, alginate, carrageenan, and chitosan are frequently utilized. These polymers are often derived from organic materials like algae and plants. Gums are an alternative to these polysaccharides. For edible films and coatings, many types of exudate gums (such as gum arabic and mesquite gum), seed gums (such as locust bean and guar gum), and microbial fermentation gums (such as kefiran, pullulan, gellan, and xanthan gum) are utilized (Jiménez *et al.,* 2015).

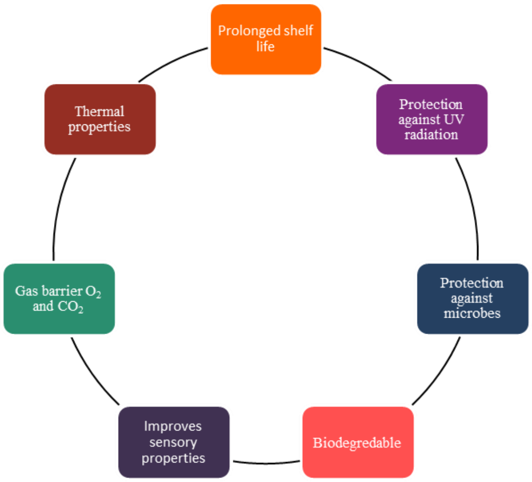

Fig. 1. Edible biofilms/coatings.

The primary particles must initially be dissolved or dispersed using such a solvent as water, alcohol, a solution of water and alcohol, or a combination of various solvents before being used in the creation of films. In this technique, plasticizers, antimicrobials, coloring agents, or flavoring compounds might be added. To enhance the soluble properties of some biopolymers, the pH may need to be changed, and/or the solutions may have to be heated. To create free-standing films, the film-forming solution is then cast and dried under the required temperature and relative humidity conditions.Film-forming solutions can be used to cover food as packaging material using a range of techniques, such as dipping, spraying, brushing, panning, and finishing by drying (Cazón *et al.,* 2017).

2.1.1 Cellulose and its derivatives

It is found in aquatic organisms, and the cell walls of vascular plants and even microbial biosynthesis produce it (algae, fungi, bacteria).It is a linear polymer glucan, comprised of glucose units that are connected by β-(1-4)-glycosidic linkages (Liu *et al.,* 2021; Yadav *et al.,* 2019). Due to its particular properties like low density, high mechanical strength, inexpensive, long-lasting, harmless, reusability, and biodegradability, as well as good film-forming capabilities, chemical stability, and simplicity in the production of chemical derivatives.Even though they have good properties but because of their hydrophilic nature, insolubility in water, and limpid, they are challenging to use for industrial applications (Ferreira *et al.,* 2016). Several physicochemical characteristics of plant nanocellulose, such as high aspect ratio, nanometer size, superior mechanical strength, harmless, and strong biocompatibility, are also shared by bacterial cellulose. It is thought to be superior to plant nanocellulose in some ways, such as high purity and limpid, ultrafine fiber network structure, and no use of harsh chemicals. Due to these characteristics, researchers and communities are interested in discovering its promising use in a variety of fields (Cheng *et al.,* 2021). However, they provide a good medium for moisture and the development of microbes so, adjustments must be made to give this natural polymer antimicrobial qualities. To achieve this, as well as in the case of polysaccharides, three main strategies have been used: modifying cellulose and cellulose derivatives (functionalization or grafting); combining with cationic molecules, essential oils, or antimicrobial polymers; and incorporating antimicrobial metal nanoparticles (silver, gold, etc.) (Muñoz-Bonilla *et al.,* 2019).

2.1.2 Starch-based edible biofilms

Starch is a polysaccharide, amylose is a linear chain of glucose molecules linked by α-l,4 glycosidic bonds and amylopectin is highly branched molecules, with α(1–4)-linked glucose linear chains and α(1–6)-linked branch points (Roy *et al.,* 2020). Starch is inexpensive and in plants, glucose is stored as starch, which is then used as a source of energy for the plant to reproduce. Starch-based biofilms are clear, inodorous, and flavorless just like synthetic polymers. Corn, wheat, potatoes, and rice are the main sources of starch for biofilms, other sources like grains, tubers, and Andean roots also present (Lescano *et al.,* 2021). They have high tensile strength, and the qualities of the obtained films are enhanced by the addition of high amylose corn starch.Chemical substitution and acid hydrolysis of starches containing amylose enhance the transparency and pliability of coatings (Sandoval *et al.,* 2021). Though, it shows various benefits, has several drawbacks, including weak mechanical qualities and a high hydrophilic character when compared to traditional synthetic polymers, which render it unsuitable for packing (Sandhu *et al.,* 2020).

2.1.3 Chitosan/chitin

Chitosan is a natural polysaccharide obtained by the enzymatic or chemical deacetylation of chitin and has many characteristics: antibacterial, unharmful, decomposable, and film-forming ability (Guo *et al.,* 2019). Due to these properties, it is Generally Recognized as Safe (GRAS) by the United States Food and Drug Administration (USFDA) and is used for food to increase the shelf life of food (Amarillas *et al.,* 2018). Even though that chitosan has natural antibacterial capabilities because of active amino groups, its applicability for active packaging is limited because the restriction of bacteria becomes imperceptible in an insoluble form. Numerous active substances, including bacteriocins, essential oils, plant extracts, and antimicrobial nanoparticles, have been added to the chitosan films to control these deficiencies (Nguyen *et al.,* 2020). Chitosan films have been cross-linked using a variety of physical and chemical techniques. Additionally, hydrophobic compounds and plant essential oils were used to enhance the efficiency of films (Xu *et al.,* 2020).

2.1.4 Alginate

According to Mahcene et al. (2020), alginate is a decomposable linear polysaccharide obtained from brown algae. The alginate comprises 1,4-β-D-mannuronic acid and 1,4 α-L-guluronic acid.Alginic acid and its salts (E400-E404) are approved as a food additive by the European Commission (EC). Alginate isbroadly employed as a thickening agent, stabilizer, emulsifier, chelating agent, encapsulating agent, suspending agent, or utilized to make gels, membranes, and films in different sectors, including food, beverage, textile, printing, and in medicine.Sodium alginate makes up the majority of the alginate currently used in foods (Senturk Parreidt *et al.,* 2018). Two adjacent, diaxially connected guluronic residues create a cavity that serves as a calcium ion binding site when creating alginate gels.This configuration is represented as the "eggbox" model, and the mechanical properties of films are linked with the amount of “eggbox” sites. Due to this film’s properties such as mechanical and water resistance problems, barrier properties, cohesion, and inflexibility can be upgraded (Tavassoli-Kafrani *et al.,* 2016).

2.1.5 Pectin

Due to its widespread access in citrus peels, reduced extraction cost, high solubility, excellent gelling qualities, exceptional biocompatibility, and ease of modification by chemical and biological procedures, pectin is a polysaccharide that is extensively utilized in the food market. Moreover, pectin has tremendous opportunities to be used in the manufacture of biofilms, and even as food and drug coatings (Lopes *et al.,* 2017). Pectin’s in-solution activity (gels or dispersions) performance the structure of which has been initially mentioned is related primarily to its texturizing benefits in food and comparable systems such as gelling, fluidity augmentation, and colloid stabilization. Pectin is used in the pharmaceutical and food industries for drug delivery as well as in the dairy, confectionery, nutraceutical, and functional food manufacturers (Adetunji *et al.,* 2017). Because pectin-based active packaging films have very poor natural antimicrobial properties, their antibacterial potential can be increased by combing them with various functional substances such as essential oils, phenolic compounds, nanomaterials, free fatty acids, and other bioactive substances (Kumar *et al.,* 2020).

2.2 Polypeptide/protein-based biofilms

Proteins are large biomolecules composed of 20 different types of amino acids and their classification is based on their composition, geometric shape, molecular weight, solubility, sedimentation behavior, and polarity of the amino acid. Proteins are either fibrous or globular in their natural state and these two are different from each other in size, structure, appearance, solubility, and functionality (Milani and Tirgarian, 2020). Both plant-based (soy protein, corn zein, and wheat) and animal-derived protein origins, such as collagen, gelatin, fish myofibrillar protein (FMP), and whey protein, have been employed (Kaewprachu *et al.,* 2016). Furthermore, when compared to films made from lipids and polysaccharides, protein-based films have greater mechanical and gas-barrier qualities.Additionally, protein-based films can be transporter for active substances because of their amphiphilic nature, which could maintain the nutritional value of foods (Calva-Estrada *et al.,* 2019).

2.2.1 Gelatin

The partial or complete hydrolysis of collagen results in the production of gelatin, a flavorless, colorless, water-soluble protein. Depending on the method of extraction, gelatin is divided into two categories. Acid extraction is used to produce type A gelatin, while alkaline extraction is used to produce type B gelatin (Luo *et al.,* 2022). Edible gelatin films have limited oxygen permeability and can be made to have antioxidant and antibacterial effects by adding substances such as citrus essential oils, carvacrol, and so on (Chen *et al.,* 2019). Gelatin, for example, is delicate and has little flexibility when dry; however, its mechanical quality can be increased by combining it with various types of cellulose, such as microfiber cellulose and dialdehyde carboxyl methylcellulose.The compatibility of the composite materials in this situation has a significant impact on their mechanical, physical, and chemical properties (Ibrahim *et al.,* 2021).

2.2.2 Wheat gluten protein

Wheat and other related cereals like rye and barley are sources of the specific protein as gluten. Two proteins, gliadin, and glutenin merge with starch in the endosperm of several forage grains to generate the gluten structure. A protein, glutenin makes up roughly 80% of the protein in wheat grains, along with gliadin (Chavoshizadeh *et al.,* 2020). The distinctive mass transfer qualities of wheat gluten have been the subject of extensive research for its gas properties. Wheat gluten has strong input to achieve the highest (ratio of carbon dioxide permeability to oxygen permeability), which makes it a desirable material for fresh fruit and vegetable packing due to its high permeability to carbon dioxide and (to a lesser extent) oxygen. In addition to these qualities, wheat gluten has many types of bonding, including hydrogen bonds and electrostatic interactions,which interrelate with the matrix (Bibi *et al.,* 2017). Due to the high concentration of hydrogen bonds in WG films, it has previously been shown that they have poor oxygen permeability under dry conditions. However, wheat gluten is a hydrophilic biopolymer and has high water permeability; there are some restrictions on how it can be used. Introducing additional material into the film matrix is one of the most efficient ways to change and develop the characteristics of a biopolymer film (Khashayary and Aarabi, 2021).

2.2.3 Soy protein

A copious by-product of the soybean oil industry, soy protein is frequently added to food as a nutritional supplement. Soy protein isolate (SPI), a natural biomaterial, has a higher protein content than any other soy protein product, which improves its capability to form films (Nandane and Jain, 2018). With the addition of plasticizer and auxiliary components, soybean separation uses soybean protein isolate as the main constituent and presses it into a film form. The cost of soybean separation is inexpensive, it can be extracted from an array of materials, and when compared to other materials, it has stronger film-forming qualities. But the soybean protein isolate membrane has a weak extension property and is unable to efficiently block water molecules. After film formation, the soybean protein isolate membrane needs to be further improved to increase its elongation, toughness, and antibacterial properties (Niu and Jiang, 2022).

In packaging, the use of natural antioxidant material is necessary because oxidation has harmful effects on food quality. Additionally, the food industry is looking for other waysto reduce the use of synthetic antioxidants(butylatedhydroxyanisole (BHA), butyl hydroxytoluene (BHT), tertiary butylhydroxyquinone (TBHQ), trihydroxy butyl phenone (THBP), and propyl gallate (PG)), because there are chances that these are injurious to human health confirmed by toxicological studies (de Souza *et al.,* 2020).

2.2.4 Corn zein

Zein is an industrially derived corn component known as prolamine protein that has numerous commercial and food applications.Corn zein is a water-insoluble protein with a molecular weight of about 40 kDa that, when dissolved in an adequate solvent, produces a yellowish translucent, bright, and elastic solution. (Barkhordari and Bazargani-Gilani, 2021). Pure zein films have weak mechanical properties, but great water resistance performance due to the high level of non-polar amino acids, and low gas permeability that make them good for the production of composite edible biofilms (Wang *et al.,* 2017). To increase the industrial applicability and meet consumer needs, it is anticipated that the secondary zein layer to the starch films will have synergistic effects and result in the creation of bilayer films with superior mechanical properties and oxidative security (Zuo *et al.,* 2019). However, using different plasticizers to increase the pliability of zein, numerous composites forming techniques were created to use zein as an oxygen barrier material.These include covering polyolefin surfaces with corn zein and laminating zein with other proteins and lipids, as well as mixing zein with biopolymers or synthetic polymers (Bayer, 2021).

2.2.5 Whey protein/milk protein

Bovine milk comprises two main types of protein, casein (80%) and whey protein (20%). An αs1-, αs2-, β-, κ-casein (CN) are the four main casein components, andγ-CN is a small component. These caseins are distributed as follows: 38, 10, 36, 13, and 3%, respectively. Whey proteins are made up of five fractions:α-lactalbumin (α-LA), β-lactoglobulin (β-LG), Bovine Serum Albumin (BSA), Immunoglobulin (Ig), and Protease peptone (PP). Theoretically, these fractions are distributed in proportions of 20, 52, 7, 12, and 9%, respectively. At pH 4.6, whey proteins are globular and soluble (Shendurse *et al.,* 2018). Whey protein films have good mechanical properties, operate as a good gas barrier at low relative humidity, and are very effective at blocking oil and aromatic components. However, it is hydrophilic these films provide an average barrier to moisture (Galus and Kadzińska, 2016). Without the addition of any plasticizers, dairy whey protein films are extremely brittle, however, adding plasticizers gives the films flexibility while also increasing their water vapor permeability (WVP).

Additionally, a higher plasticizer content reduced the tensile strength and increased the elongation of dairy whey protein films by raising Young's modulus. Increased glycerol concentration in plasticizers has been shown to improve the water vapor permeability and solubility of dairy whey films, lowering their apparent Young modulus, mechanical resistance, and glass transition temperature (di Pierro *et al.,* 2018).

2.3 Lipid-based edible biofilms

Lipids and waxes are used to minimize the water vapor permeability of starch-based edible biofilms, due to the composite material hydrophobicity. As a hydrophobic substance, beeswax is made up of a combination of esters, hydrocarbons, fatty acids, alcohol, and other substances. The incorporation of beeswax lowers the water vapor permeability and improves the mechanical abilities of corn starch-based edible biofilms. The addition of beeswax in the Hydroxypropyl methylcellulose (HPMC) based biofilms lower the weight loss in plums reported by Navarro- Tarazaga (Pérez-Vergara, *et al.,* 2020). As coating materials, lipids can be utilized such as waxes (paraffin wax, beeswax, carnauba wax, candelilla wax, etc.), vegetable oil, mineral oil, acetylated monoglycerides, and sucrose esters of fatty acids (SenturkParreidt *et al.,* 2018).

Catalytic polymerization of ethylene results in a mixture of hydrocarbons, including crude oil. Paraffin wax is derived from crude petroleum after going through numerous distillation processes.Most often, paraffin waxes are used in the fruit and vegetable sector as well as the dairy industry (cheese). Carnauba wax, which was derived from Copoernica Cerifera, is an example of paraffin wax (palm tree leaves). Bee wax is also produced by honeybees. From candelilla plants, we gathered candelilla wax (Walait *et al.,* 2022). Carnauba wax was added to chitosan and cashew tree gum films to boost opacity while lowering WVP and water solubility (Zhang *et al.,* 2018).

According to reports, using carnauba wax can minimize the post-harvest deterioration of apples by 70%. *Monilinia fructicola* and *Rhizopus stolonifer* occurrences in nectarines and plums were greatly reduced by the protective application of 4.5% and 9% carnauba wax, but not enough to properly prevent the postharvest growth of these two diseases. It is essential to combine other antimicrobial agents into carnauba wax coating to give protection against microbes and upgrade fruit quality (Chen *et al.,* 2019).

2.4 Poly (lactic acid) PLA-based edible films

Because of its mechanical, physicochemical, and biodegradable qualities, polylactic acid (PLA) is regarded as an efficient packaging material. Before being used in food packaging, PLA's poor barrier property, minimum heat distortion temperature, and low melting viscosity all need to be improved. To prevent contact between food and the packaging material, active nanometals like ZnO-NPs in the packaging material minimize the oxygen interaction of food components (Batool *et al.,* 2022). Additionally, it belongs to the GRAS (Generally Recognized as Safe) category if it is employed especially as a package of lactic acid food (PLA), protecting it against the migration of toxic components from packing (Agusnar *et al.,* 2019). It is an economical, mechanically robust, hydrophobic, and edible biopolymer. Additionally, because of its high stress, has a high molecular weight, and is resistant to high water solubility (Gürler *et al.,* 2020). Previous studies claimed that combining PLA with Thermoplastic starch could make a less brittle and more affordable final PLA/TPS blend (Chotiprayon *et al.,* 2020).

2.5 Nanomaterial/nanoparticle-based edible biofilms

Nanocomposites have been created using a variety of nanoparticles, including silver, copper, titanium dioxide, and zinc. In addition, cyclodextrin, starch, shellac, kefiran, and chitosan are among the matrices utilized to create edible coatings and films comprising nanoparticles (Paidari *et al.,* 2021). Under UV light, TiO_2 nanoparticles can kill foodborne pathogens like Listeria monocytogenes, *Vibrio parahaemolyticus*, and *Salmonella choleraesuis* (Hoffmann *et al.,* 2019). Currently, there is a lot of research being done on the use of nano cellulose for bio-derived food packaging from the viewpoint of performance, food safety, sustainability, end-of-life disposal issues, and environmental protection (Kocabaş *et al.,* 2021). According to numerous reports, these nanoparticles can successfully increase food safety by increasing the effectiveness of food packaging, shelf-life, and nutritional value as additives without altering the flavor and physical properties of food products (Bajpai *et al.,* 2018). Since the antimicrobial properties of nanoparticles are directly proportional to the surface area accessible for interaction with biological substances, the change in the geometry of nanomaterials is useful for antimicrobial applications. Consequently, antimicrobial nanomaterials, also known as “nanoantibioticsare viewed as one of the most potent methods for avoiding or reducing microbial development and infections (Ahari *et al.,* 2021).

3. Application of edible films and coatings

The food industry and producers have created bio-based packaging, such as edible coatings, with great gas barrier capabilities, long shelf life, economic viability, and the ability to carry antibacterial and antioxidant compounds, in response to the harmful environmental effects of synthetic packaging (Ozma *et al.,* 2022). In addition to having appropriate mechanical qualities, edible films based on polysaccharides have excellent barrier capabilities against oxygen, odors, and lipids.

To create edible films with functional features, recent research focused on the creation of active and biodegradable packaging through the addition of antioxidants and antimicrobials in its formulation (Bojorges *et al.,* 2020). Specific features, such as sensory, physicochemical, and nutritional aspects, in coated products, can be improved depending on the biomaterials employed and the kinds of biologically active substances (Díaz-Montes and Castro-Muñoz, 2021).

3.1 Meat and seafood

Meat is extremely decomposable as a meat product. Therefore, it has become quite crucial to be concerned about extending the shelf life of raw beef in retail packaging. Although numerous sophisticated packaging technologies exist, their price makes them unsuitable for beef retail marketing (Mohan *et al.,* 2019). In recent times, titanium dioxide (1% TiO_2) particles were added to a cellulose nanofiber/whey protein matrix with rosemary essential oil (2%), which was utilized in packaging or encapsulated form. With an improvement in life span from 6 to 15 days, this packaging was able to considerably lower the growth of microorganisms and lipid oxidation in sheep meat during chilled storage.It was reported that adding clove essential oil to edible gelatin-chitosan films inhibited bacteria from growing and prevented the generation of total volatile nitrogen in chilled cod fillets.

Active packaging films made of poly lactic acid that also contain 1.5% ZnO nanoparticles, Mentha piperita, and Zataria multiflora essential oils (carvacrol and menthone). The active films dramatically increased the otolith ruber fillet's storage life, going from 8 to 16 days (Šimat *et al.,* 2021). When stored in the refrigerator, the prepared sausages of the mortadella variety had a betterlife span thanks to chitosan (CH) film that included grape seed and its extract as an antioxidant and antibacterial agent.

Table 1. Application of edible biofilms on meat and seafood to control the food-borne pathogens.

Meat and seafood	Edible biofilms	Inhibition of food-borne pathogen	Reference
Bigeye snapper and tiger prawn	LAE-Gelatin-TPS/PBAT and Nisin-LAE-Gelatin-TPS/PBAT	*V. parahaemolyticus* *S. typhimurium*	(Pattanayaiying *et al.,* 2019)
Beef meat	Chitosan films (CH) are incorporated with oregano oil and thyme oil.	*E. coli* O157:H7, *S. aureus*, and *S. typhimurium*	(Gaba *et al.,* 2022)
Sliced bolognas	pectin coating made with essential oils and/or extracts of Thymus vulgaris (thyme) and Thymbra spicata (thymbra)	*Salmonella typhimurium* count by 1.73 logs CFU/g	(Gedikoğlu, 2022).
Chicken wingettes	Gum Arabic (GA) and chitosan (CH) based coating fortified with carvacrol (CR).	*Campylobacter jejuni*	(Shrestha *et al.,* 2019)
Nile tilapia fillets	Nanoemulsified clove essential oils and fish gelatin (NCEO-FG).	Pseudomonas	(Hai *et al.,* 2022)

TPS/PBAT (thermoplastic starch/polybutylene adipate terephthalate); LAE (lauric arginate).

Furthermore, it was mentioned that the usage of GSE in CH films helped to maintain the freshness of chicken flesh (Sogut and Seydim, 2019). Current findings have shown that the antibacterial and antioxidant benefits of apple peel extract (APE) and *Ziziphora clinopodioides* essential oil (ZEO) can assist the industry to satisfy consumer demands for fresher seafood products (Rezaei and Shahbazi, 2018). The microbial burden is reduced when processing is done in a sterile environment. However, processing and constant handling may still introduce hazardous germs. These bacteria multiply and develop, altering the physical, chemical, and sensory environments. Thus, a promising strategy for the environmentally friendly storage of meat, fish, and related products has emerged: introducing functional agents that can stop, prevent, avoid, or decrease deteriorative processes in packaging (Umaraw *et al.,* 2020).

3.2 Fruits and vegetables

Consumers today seek high-quality fruits and vegetables that are packed with substances that are good for their health. The agricultural and horticulture sectors now faced the challenges of developing effective preservation techniques in dealing with the growing demand. Additionally, this has created a sense of urgency among scientists and the food processing sector to assess various strategies for enhancing food quality, hygiene, freshness, and shelf-life by using organic, eatable, and biodegradable polymers (Nair *et al.,* 2020). Implementing minimal preparation is one technique to keep fruits and vegetables closer to their natural state while extending shelf life. Vegetables that have gone through minimal processing are those that only experience physical changes, preserving their condition of freshness. This outlines the methods like picking, washing, disinfecting, peeling, cutting, and removingimpurities, packaging, and cryogenic preservation. Even if it ensures that the food is more organic, less processing still doesn't provide the product with a prolonged shelf life. Still, there are certain opportunities for gentle treatments that can prolong the storage life of less processed fruit and vegetables. Among these, bleaching, different kinds of freezing, the use of food-safe chemicals, edible coatings or biofilms, and so on, can be emphasized (Thode Filho *et al.,* 2021).

The process of development of film needs film-forming material, solvent, plasticizer, and emulsifier. Antioxidants and antibacterial agents are two additives that are occasionally used to improve the quality of the films. The source material needed for the film's development will influence the solvent that is used. For instance, sodium alginate issoluble in distilled water, but chitosan is dissolvable in glacial acetic acid. Glycerol, sorbitol, and other plasticizers are utilized to make films more elastic by lowering the intermolecular tensions inside them. Tween 20 and Tween 80 are the two most used emulsifiers, and they are used to produce stable emulsions. Mangoes have been coated with cellulose acetate and antimicrobials like nisin (Saxena *et al.,* 2020).

3.3 Dairy products

The formation of packaging materials currently uses natural lipids, waxes, and biopolymers as an alternative source. These materials are used to create edible films and coatings that serve as a semi-permeable barrier to water vapor, carbon dioxide, and oxygen vapors and guarantee the safety of the meal. These edible coatings and films prevent unwanted growth on the surface of the cheese by acting as antimicrobial agents (Iqbal *et al.,* 2021). The organoleptic and nutritional qualities of cheese can be improved, either because of the film/coating composition, which may have valuable properties by itself, or because they can incorporate components like flavoring, dyeing, or sweetener agents. They also have other advantageous characteristics, including the ability to be consumed along with the cheese, which reduces waste generation (Costa *et al.,* 2018).

Table 2. Use of various edible materials for the packaging of fruits and vegetables.

Fruits and vegetable	**Edible materials**	**Overall result**	**Reference**
Carrots	Protein, polyalcohol, and polysaccharide coatings.	Shelf-life prolongation.	(Villafañe, 2017)
Fresh cucumber	Corn starch and mint (*Mentha viridis* L.) extract herbal edible coating.	Prolonged shelf life and quality stored at room temperature (25°C) and low temperature (10 °C).	(Raghav and Saini, 2018)
Freshcut apples	Pectin emulsion and nanoemulsion edible coating carrying cinnamon essential oil.	Keeping the microbial load under acceptable limits, enabling its shelf-life extension, better texture, color, and odor.	(Naqash *et al.,* 2022)
Blueberries and raspberries	Film-forming dispersions (FFD) based on κ−, ι− and λ− carrageenans-based coatings with green tea.	Antiviral effects against murine norovirus (MNV) and hepatitis A virus (HAV) at both refrigerated and ambient temperatures also promote better appearance.	(Falcó *et al.,* 2019)
Kiwifruit slices	Opuntia ficus-indica mucilage edible coating	Significantly higher firmness and lower weight loss than untreated slices.	(Allegra *et al.,* 2017)
Okra	Alginate coating containing nano-emulsified basil (*Ocimum basilicum* L.) oil with Sapindus extract	Effective against spoilage fungi *Penicillium chrysogenum* and *Aspergillus flavus*. In comparison to uncoated samples, the texture, color, and general attractiveness were substantially better maintained.	(Gundewadi *et al.,* 2018)
Tomatoes	Pectin, cornflour, and beetroot powder-based coating	Retained maximum glossiness and improved the shelf life of tomatoes.	(Chaturvedi *et al.,* 2019)
Banana	A rice starch edible coating blended with sucrose esters.	Extended postharvest quality during ripening (at 20 ± 2 ◦C); effective in delaying ethylene biosynthesis and reducing respiration rate. Shelf life prolonged for 12 days.	(Thakur *et al.,* 2019)
Green beans	Antimicrobial coating formulation consisting of modified chitosan containing a nanoemulsion of mandarin essential oil.	Reduction of *L. innocua* over the storage time, owing to synergistic antimicrobial effects. A strong impact on green beans' color or firmness.	(Donsì *et al.,* 2015)
Fresh cut melons	Tilapia protein isolate-based coating	Coatings T2 and T3, based on Tilapia protein isolate, were efficient in reducing mass loss, maintaining firmness and color, and controlling psychrotrophic microorganisms, molds and yeasts during the 12 days of storage.	(Chevalier *et al.,* 2018)
Mango	Chitosan lactoperoxidase systems coatings	Effective against microbial contamination and enabled a delay in fruit ripening without altering the quality.	(Cissé *et al.,* 2015)

The FDA has designated the antimicrobial peptide known as nisin, which can be used up to 250 ppm in cheese, as GRAS. Nisin shows antimicrobial activity towards gram-positive bacteria (Berti *et al.,* 2019). Using an active edible coating with natural essential oils (EOs) that have greater sensory qualities can significantly improve the storage durability of soft cheese and butter. The storage stability of soft cheese and butter is positively associated with the essential oil concentration in the edible coating; as the essential oil concentration increase, the product's storage stability is also increased.However, the sensory qualities of soft cheese and butter are negatively impacted by increased essential oil concentrations in the edible coating (Arshad *et al.,* 2020).

3.4 Bakery products

Due to the hydrocolloids' natural origin, impact on dough rheology, and bread quality, there has been an increase in interest in them in recent years. The use of hydrocolloids as antistaling agents has been successful as well.Additionally, modern technologies like BOT (baking off technologies) can exploit these enhancements to make up for the damage done by freezing (Ferrero, 2017). To pack bread prepared without preservatives, antimicrobial active films have been designed. These packaging systems are composed of polymeric substances that contain antimicrobial elements that release slowly over time (Pasqualone, 2019). As a result, some essential oils with high antibacterial component concentrations, including thymol and carvacrol, may successfully extend the shelf life of bakery products whereas other essential oils might be viewed as less effective preservatives. Some research has been done to determine whether it is possible to use natural essential oils in place of synthetic preservatives in bakery goods like bread and cake (Gavahian *et al.,* 2020). Bakery foods (crackers) with low moisture levels were given an edible coating comprised of corn starch, methylcellulose, and soybean oil, which increased their shelf life under all testing conditions.The shelf-life of the cheese-based dessert mustafakemalpasa was found to be extended by 3 to 10 days by coatings comprising whey protein concentrate and corn zein. Additionally, the potential of using an edible film as a carrier for cinnamon oil to improve the quality and preserve the shelf-life of the cake was studied (De Pilli, 2020).

4. Limitations and future perspective in edible biofilms

Because edible biofilms are sensitive to various conditions, it is essential to handle them properly during storage and transportation. The effectiveness of edible plastics is also impacted by their moisture content. The effect of the oxygen barrier is decreased as the water content rises, but the antioxidant activity of the plastic is increased. Furthermore, biofilms need an outer covering to keep them safe for intake and to protect them from toxins. Because the films are made of biopolymers, they have low mechanical strength. Plasticizers and hydrophobic materials (e.g., oils and beeswax) can be added to the film formulation to improve mechanical and barrier properties, respectively.These properties are critical in the protection of packaged foods and may impede their commercialization (Ribeiro *et al.,* 2021).

Table 3. Limitations of edible biofilms and coating.

Type of edible biofilm/coating	Limitations	References
Protein-based edible biofilm	They have a higher water vapor permeability but are less flexible.	(Chiralt *et al.,* 2018)
Polysaccharide-based edible biofilm	Because of their hydrophilic nature, they are poor moisture barriers.	(Galus and Kadzińska, 2015)
Lipid-based edible biofilm	Brittle network with very low water vapor permeability due to its high hydrophilic nature.	(Gahruie *et al.,* 2020)

There is a great interest in nanotechnology in the food industry. Multiple applications in different dimensions have been reported, including the targeted delivery of nutrients and/or bioactive molecules via nanoencapsulation, the use of biosensors to identify and evaluate pathogens and change food composition, as well as fruit and vegetable protection via edible films. Food formulation, storage, quality control, and packaging are some potential uses of nanotechnology in the food chain (Shafiq *et al.,* 2020). Previous research showed that nanosized materials can effectively improve the mechanical and barrier properties as well as the antimicrobial activities of edible films. These materials include clays (such as montmorillonite), fibers (including cellulose), and metals (like silver and titanium) (Abdollahzadeh *et al.,* 2021). As a result, some examples include edible, biodegradable, and antimicrobial packaging that uses biopolymers like carboxymethyl cellulose, chitosan, or polysaccharides modified with various natural extracts or inorganic nanoparticles with inherent antimicrobial properties that are effective against *Escherichia coli*, *Vibrio parahaemoliticus*, *Staphylococcus aureus*, *Diaporthe actinide*, *Salmonella choleraesius*, *Penicillium expansum*, etc. (Isopencu and Mocanu, 2022).

Despite the advantages that nanotechnology brings to the food packaging industry, there are still questions that need to be answered. More research is needed in this area to determine how nanoparticles migrate from nanocomposite to packaged food and what impact that has on consumer health. Additionally, the sustainability and recycling of nano packages must be taken into account. The creation of standardized methodologies to assess the effects of nanoparticles on human health, as well as further guidelines and regulatory information to assess the safety of nanocomposites applied to food packaging, should be provided by regulatory agencies like the FDA and EFSA (Hernández-Muñoz *et al.,* 2019).

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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