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Techno-functional characteristics, and potential applications of edible coatings: A comprehensive review

Vaishnavi Patil [a], Rafeeya Shams [a,**], Kshirod Kumar Dash [b,*]

[a] Department of Food Technology and Nutrition, Lovely Professional University, Phagwara, Punjab, India
[b] Department of Food Processing Technology, Ghani Khan Choudhury Institute of Engineering and Technology, Malda, West Bengal, India

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ABSTRACT

This review emphasizes the growing technical and functional properties of edible coatings, as well as their numerous prospective applications. Edible coatings were developed using proteins, carbohydrates, lipids, and natural polymers. These ingredients could be altered and blended to create coatings with distinct properties. Food products were coated with edible coatings in a number of ways, including dipping, spraying, brushing, rolling, or twirling the food in the coating material. The application strategy applied is dependent on the distinctive food product and the desired outcome. These coatings are at the cutting-edge of innovation and sustainability, employing organic and biodegradable components to efficiently address major environmental challenges. This study additionally investigates the many technical and practical advantages that these coatings have, such as better barrier qualities, precise release mechanisms, and integration with cutting-edge sensor technologies for continuous quality monitoring. It also emphasizes the wide variety of applications, which vary from increasing product shelf life and decreasing food waste to addressing various nutritional demands and improving food aesthetic appeal. The advancements created in the edible coatings industry highlight their crucial role in redefining accepted paradigms of food packaging, preservation, and consumption by fusing scientific advancement with culinary inventiveness are also been discussed. Innovative materials, bioactive compounds for health benefits, and packaging and coatings with less environmental impact are being researched to produce edible coatings with better functionality and sustainability.

1. Introduction

Fruits and vegetables have seen a major rise in demand in recent years as people have begun to realize how important they are to a balanced diet. They provide important nutrients such as vitamins, minerals, dietary fiber, antioxidants, bio-flavonoids, and flavorings. These healthy commodities are susceptible to a variety of both biotic and abiotic dangers. After harvest, fruits and vegetables experience significant losses due to variables like respiration, transpiration, respiration, and microbial activity. These foods also have a limited shelf life [1]. Based on the method of maturation, fruits can be divided into two; non-climacteric and climacteric groups. Contrary to non-climacteric perishable fruits, climacteric fruit continues to ripen once the harvest is completed, increasing its susceptibility to microbial infection and degradation [2]. Thus, climacteric fruits go through natural maturity as a result of biochemical changes, rendering them only momentarily fit for ingestion. Additionally, fruits and vegetables can pick up contaminants from their skins, speeding up the rotting process and causing biochemical deterioration. Browning, disagreeable flavors, and texture degradation are just a few examples of how this deterioration shows up, and it eventually degrades the quality of perishable commodities. In addition, customers are at risk when pathogenic germs are present [3]. To protect the skin of the fruits as mentioned above, edible coating technology comes into the limelight.

The important quality factors of fresh produce contributing to the marketability are color, flavor, microbial safety, appearance, nutritional value, and texture Thus, edible coating ensures all the factors to preserve the commodity [4]. The term “edible coating” refers to a substance used to cover the food’s surface and is acceptable to consume [5]. Coatings can be employed to provide safeguards against physical harm, exposure to light, and contamination. Edible coatings are primarily developed using biopolymers such as lipids, proteins, polysaccharides, or a mixture

* Corresponding author.
** Corresponding author.
E-mail addresses: rafiya.shams@gmail.com (R. Shams), kshirod@tezu.ernet.in (K.K. Dash).

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of both [6]. Typically, coatings containing fat exhibit reduced water-transfer capabilities, while Polysaccharide-sourced coatings have lower gas permeability. On the other hand, protein-based coatings tend to possess superior mechanical characteristics. To achieve desired properties in edible coatings, the use of resins, solvents, and plasticizers is common. Solvents enhance tensile strength, resins restrict water vapor permeability, and plasticizers contribute flexibility and permeability to edible coatings [7]. Additionally, coating adhesion is a crucial characteristic that relies on a variety of factors, including food surface attributes, intended coating objectives along with application methods [8]. Depending on the type of fruit, coating agents may have varying degrees of effectiveness. It is critical to emphasize that coatings are used commercially with the goals of maintaining the quality of the product for consumers, ensuring nutritional benefits, and lowering production and packaging costs [9].

The objective of edible coatings is to act as a barrier, regulating the movement of a number of chemicals such as carbon dioxide, oxygen, flavorings, lipids, moisture, along with other dissolved compounds [10]. Consequently, the application of edible coatings leads to a lowered rate of respiration and reduced weight loss in food commodities. Additionally, edible coatings have a noteworthy capacity for incorporating antimicrobial compounds, making them efficient transporters for these chemicals. As per the findings of Shafiei and Mostaghim, the inclusion of antimicrobial chemicals in the coating matrix has a significant impact on reducing fruit-related illnesses and microbial contamination [11]. By actively preventing the production of ethylene, edible coatings significantly increase the shelf life of perishable items. The ripening and degradation of fruits and vegetables are accelerated by the natural plant hormone ethylene [12]. In order to mitigate the effects of ethylene, edible coatings work as a shield, using a variety of strategies. They serve as a gas barrier, reducing the amount of ethylene that is exchanged between the produce and its surroundings thus, delaying the ripening process [13]. These coatings frequently contain anti-oxidants like ascorbic acid and tocopherols, which work to mitigate the oxidative effects of ethylene and maintain the aesthetic attractiveness of the food [14]. Furthermore, by maintaining temperature and moisture loss, these coatings reduce the stress response that results in ethylene synthesis [15]. Antimicrobial substances are sometimes added to coatings to prevent the growth of microorganisms that produce ethylene [16]. Additionally, edible coatings can act as physical barriers to keep the products separate from other products that release ethylene during storage and transit [17]. Even ethylene scavengers, which collect and neutralize the gas inside the packing or storage environment, may be present in some coating formulations [18]. Edible coatings actively reduce the impact of ethylene in this complex manner, significantly prolonging the shelf life of perishable foods, reducing food waste, and ensuring consumers have access to fresh and higher-quality produce [19].

These films and coatings are user-friendly, eco-conscious, highly secure, and cost-effective, presenting a promising solution for food preservation [20]. A number of studies have been conducted to analyze the influence of edible coatings on the microbiological and physiological stability of diverse types of fresh commodities. It has been demonstrated by Li et al. [21], using cinnamon-aldehyde as an edible coating on bananas that dramatically slowed down both weight loss and fruit ripening. Similar results were seen when protein isolate and organo-clay were applied to less processed papaya slices that had been cut into slices [22]. The surge in interest in edible films and coatings can be attributed to consumers growing awareness of the importance of making healthy food choices and their worries about the negative environmental effects of synthetic, non-biodegradable packaging materials. Based on this objective of this review is to discuss several polysaccharide-based edible coatings, starch-based edible coatings, pectin-based edible coatings, and aloe vera-based edible coatings. It discusses edible coating preparation methods such as dipping, spraying, and edible coating 3-D food printing technology. The techno-functional features of edible coatings as well as their characterization, such as thickness, microstructure, water-vapor resistance, and gas permeability, were discussed.

2. Classes of edible coating

2.1. Polysaccharide-source based edible coating

Ingredients frequently utilized in the development of edible coatings include polysaccharides, lipids, and proteins like collagen, zein, and casein [23]. Polysaccharides encompass a range of materials such as alginate, pectin, cellulose, chitosan, starch, and among others. These polymeric carbohydrates offer several notable advantages when used in edible coatings. They are bio-compatible, bio-degradable, and non-toxic to living individuals [24]. For example, edible films derived from chitosan, obtained from crickets and shrimp, have been shown to exhibit mechanical strength, water resistance, and light-barrier properties, this characteristic makes them promising candidates for bio-based packaging materials in food and medicinal applications [25]. Gums (such as gum-arabic and guar-gum), cellulose, starch, alginate, and carrageenan are polysaccharides that have garnered widespread attention for their safety (GRAS) by the United States Food and Drug Administration [26]. These polysaccharides have received acceptance and approval for their use in various food packaging applications.

Cegrí et al [27], reported a study on polysaccharide-based edible coating using Zucchini fruit. By reducing weight loss, chilling injury, and oxidative stress, the results showed that coating zucchini fruit with dextrin at lower temperatures retained its quality. Another similar study using polysaccharide-based edible coating was reported by [28] using Dashehri Mango as an experimental commodity. Gum and Carboxymethyl-cellulose (CMC) were used for coating treatment. After being kept at ambient temperature for nine days, sensory evaluations demonstrated that CMC-coated samples had increased fruit appeal. An alternative research was presented by Guerreiro et al. [29], At storage intervals of 0, 7, and 14 days, color measurements were made using the CIE (L*, a*, b*, h*, and C*) system, as well as evaluations of microbial growth observation, weight loss, firmness, Trolox equivalent antioxidant capacity (TEAC) analysis, soluble solids content (SSC), and taste panel evaluations. They observed changes in weight loss, reduced microbial growth and extended shelf life was there in coated commodities.

2.2. Starch-based edible coating

Carbohydrates are extensively utilized as biopolymers in the production of coatings and films, primarily because of cost-effectiveness and wide availability. Their abundance and affordability make them a preferred choice for various applications in the food and packaging industry [30]. Plant-based carbohydrates have the benefit of being simple to alter to fit particular needs. For instance, hydrolysis of starch and cellulose can produce simpler carbohydrates like maltose and glucose. These simpler complex carbohydrates act as the basic building blocks for the synthesis of edible polymers. Due to their cheap and wide availability, carbohydrates are especially advantageous for the production of edible polymers [31]. Zhang et al. also reported that due to their affordability and accessibility, carbohydrates are the most frequently studied and used biopolymer for these materials, which are primarily made from carbohydrates, proteins, lipids, or a mix of these. To summarize, carbohydrates, specifically starch, are the most practical and widely studied materials for producing edible polymers. Starch, a naturally produced carbohydrate found in an array of plant parts, is significant as an important source of energy for both people and animals. It consists of two polysaccharides, amylose, and amylopectin, which are insoluble in water [32]. Through the application of shear pressures, heat energy, and plasticizers, the semi-crystalline structure of starch granules can be irreversibly disrupted, transforming it into a continuous matrix. Many investigations have looked into the utilization of starch from various sources to create films and surface coatings with an array of qualities.

The unique capability of starch to form films with heat sealability, isotropy, and extended shelf life can be attributed to its component, amylose [33]. Starch is often used in the development of edible coatings and films due to its ability to generate transparent, flavorless, and colorless layers that possess similar properties to synthetic polymers [5]. Dai et al. [34] Conducted a study using starch-sourced edible coating on graded Huangguan pears. The development of a film or coating made of nanocomposites based on starch was successful. Starch nanocrystals (SNCs) and cross-linked cassava starch were used to make this substance. An analysis of the physical and chemical properties of the pears revealed that the grading procedure had a negative impact on pear preservation. Conversely, using a coating treatment to extend the shelf life of pear has shown to be very beneficial. The results showed that the film performing the best overall was the one having 6 % SNCs. A similar study in the field of starch-sourced edible coating was reported by Thakur et al. [6]. The study examined the feasibility of prolonging the preservation time of plum fruit by utilizing a composite coating consisting of rice starch-ι-carrageenan (RS-ι-car) combined with sucrose fatty acid esters (FAEs). When contrasted with uncoated control fruits stored at room temperature, the composite coating comprising rice starch showed efficacy in reducing weight loss (WL), and respiration rate and reducing the generation of natural ethylene (p 0.05). The results of this study show that the RS-car-FAEs coating increases the shelf life and preserves the overall quality of plum fruit while it is being stored. This coating may one day be made available for sale as a new edible covering for the plum fruit industry. Thakur et al. [35], also reported a similar study using Apple. Measurements were taken for fruit weight loss, total soluble solids (TSS), firmness, titratable acidity (TA), respiration rate, greasiness, and alterations in fruit skin color. The results of this study showed that lower temperatures and the optimized combination, which included 1.5 % -carrageenan, 2.5 % rice starch, 1.5 % glycerol, and 2 % sucrose fatty acid ester, were beneficial in preventing weight loss and maintaining tissue stiffness. Additionally, these benefits were attained during storage after harvesting without affecting titratable acidity (TA), total soluble solids (TSS), or the bioactive makeup of the apple fruit. Furthermore, coated fruit samples exhibited a notable postponement in skin color alteration and a decrease in fruit greasiness ($p < 0.05$). These results highlight the potential of a coating formulation based on starch to improve visual appeal without degrading the nutritional qualities and interior quality of apple fruit over the course of storage.

2.3. Pectin-based edible coating

Apples, currants, and other mature fruits contain pectin, a white, colloidal carbohydrate with a high molecular weight. It is utilized in medications, fruit jellies, and cosmetics because of its emulsifying and thickening qualities, additionally to its capacity to change into a gel [36]. Pectin has entered the market of bio-polymers with scope and opportunities in future development as a result of all these characteristics and uses. Pectin is useful in a wide variety of applications since it is categorized according to its Degree of Methyl-esterification (DE) [37]. The intermediate lamellae and primary cell walls of numerous plants and fruits frequently contain pectic compounds. The cellulose, hemicellulose, and lignin structures are frequently linked to them [38]. These substances play a number of crucial tasks in the cell, such as improving cell-to-cell adhesion, aiding in the mechanical resilience of the cell wall, creating stabilizing gels, and having a big impact on plant cell proliferation. These substances play a number of crucial tasks in the cell, such as improving cell-to-cell adhesion, aiding in the mechanical resilience of the cell wall, creating stabilizing gels, and having a big impact on plant cell proliferation [39]. Pectin, which is predominantly made up of acidic structural polysaccharides with a variety of structures and is distinguished by high molecular weight, and heterogeneous groups of glycan galacturonans, is the most complex category of polysaccharides. The pectin backbone is made up of molecules of (14)-linked D-galacturonic acid that is linked to a number of rhamnose residues in the main chain and to galactose arabinose, and xylose in the side chains [40]. Pectin polysaccharides are divided by some authors into three groups. Pectin-based edible coatings that incorporate functional substances improve the physical and structural integrity of food products, reinforce their mechanical characteristics, boost their resistance capabilities, and help to reduce microbial contamination [41].

Many studies were reported using pectin-based edible coating, one of them was reported by [42]. Apple pectin edible coating was used on fresh “Rojo Brillante” persimmon. Lower a* values were seen in samples coated with the antioxidant solution and those dipped in it compared to the control samples, demonstrating successful browning suppression. Slices of persimmon coated with a coating containing sodium benzoate and potassium sorbate were still sellable after up to seven days of storage. The foundational categorization of pectic polysaccharides centered around D-galacturonic acid. These polysaccharides are primarily grouped based on their structural composition and functional roles in plant cell walls. The key divisions include homogalacturonans, which consist of linear chains of D-galacturonic acid; rhamnogalacturonans characterized by their branching and the presence of additional sugar residues. The overall fruit flavor was rated favorably and within acceptable limits by the conclusion of the storage time. The coatings with the highest effectiveness at preventing the spread of mesophilic aerobic bacteria were those containing sodium benzoate and nisin. Molds, yeasts, or psychrophilic aerobic bacteria did not grow during storage. A similar study on pectin-based edible coating was conducted by Maftoonazad & Ramaswamy [43]. The objective of this study, which implemented a predefined coating process, was to evaluate the effect of a pectin-based coating on the rate of quality changes in preserved lime fruits (*Citrus aurantifolium*). Maftoonazad & Ramaswamy [43] observed that the coated sample has extended shelf life, preserved color, and less microbial load.

2.4. Aloe vera-based edible coating

Aloe vera is a widely recognized plant renowned for its remarkable therapeutic properties. It is typically found in both tropical and subtropical regions. The gel obtained from aloe vera lacks any flavor, color, or odor. It is regarded as a natural substance that serves as an environmentally friendly and safe substitute for artificial preservatives like sulfur dioxide. The gel, according to researchers, works through a variety of processes. [44], through its different antibacterial and antifungal components, preventing the action of microorganisms that cause food-borne diseases and developing a shield against both oxygen and moisture. Aloe vera gel has demonstrated the ability to effectively postpone oxidative browning, limit microbial development, control respiration rate, retain moisture, maintain fruit firmness, and regulate the maturation process when applied as an edible coating ([45]; [46]).

Habeeb et al. [47], reported that both gram-negative and gram-positive bacteria were suppressed by Aloe vera gel. It was reported that through the inhibition of solute transport in membranes, anthraquinones demonstrated antimicrobial activity against strains of *S. aureus* and *E. coli* [48].

Aloe vera gel-based coatings have drawn greater interest in recent years as a practical and secure way to significantly increase the shelf life of harvested horticulture. Due to its environmental friendliness, edible coating is attracting attention in the food business [49]. It can be considered a sustainable substitute for artificial coatings and other post-harvest chemical treatments. Fresh fruits, vegetables, and their cut equivalents can all be kept fresh longer with the Aloe vera gel coating. It also aids in retaining more nutrients by improving storage conditions. As a result, the Aloe vera gel coating gives an opportunity for future fruit and vegetable post-harvest preservation [50].

In recent years, Consumers have globally accepted aloe vera-based edible coating and numerous studies have been conducted in the field of packaging for this purpose. Recently, [51] reported a study using aloe vera coating on Button mushrooms (*Agaricus bisporous*) at a temperature of 4 °C over a storage period of 16 days. The results showed that the edible coating made from aloe vera gel at a 50 % concentration, without the inclusion of essential oil, displayed noticeably improved properties, including a higher and more stable zeta potential than formulations made from aloe vera gel at other concentrations. Additionally, this formulation showed the greatest potential for keeping the postharvest qualitative characteristics of mushrooms over the course of storage. A similar study was reported by Ebrahimi & Rastegar [52]. Guar gum (GG), an edible coating sourced from Aloe-vera gel, along with alcohol-water-based Spirulina platensis extracts were investigated on the physico-chemical characteristics of mangoes (Mangifera indica L.) kept at ambient temperature (25 ± 2 °C) for a duration of three weeks. According to the investigation, the coatings enabled the mangoes to shed less weight and respire at a lower rate. Compared to the control group, mangoes coated with GG + SPE exhibited noticeably increased firmness. Additionally, the amount of fruit weight loss was dramatically reduced after applying GG + AL coatings. According to the study's findings, mangoes might have had their shelf life greatly increased by GG-edible coatings augmented with Spirulina platensis, particularly the alcoholic extract.

2.5. Nano-emulsions based coating

Nano-emulsion coatings are a specific subset of edible coatings, utilizing nano-emulsion technology to provide specialized functionalities and benefits to food products. Nano-emulsion forms a thin film around the food product that is composed of ecologically friendly and digestible ingredients that protects the food from gases, microorganisms and moisture [53]. Nano-emulsions can also be termed ultrafine-emulsions or submicron-emulsions [54]. The heterogeneous colloidal systems known as nano-emulsions are made up of two liquids that do not mix properly. An aqueous liquid must be used while the other liquid must be unctuous as stated by Lago et al. [55]. The stability, optical properties, and droplet size influence the rheology of the emulsion. Due to the much smaller size of its particles, nano-emulsions are more suitable than microemulsions in a number of applications [56]. This microscopic particle size has numerous significant advantages over other formulations. Improved physicochemical qualities and increased stability are made possible by nano-emulsions. Nano-emulsions can be used to slow down the physiological processes in fruits and vegetables that cause them to deteriorate over time, such as respiration and ripening. Nano-emulsions can be applied in a uniform and sparse manner to fruits and vegetables as coatings in order to protect them against variables like dust, humidity, and microbial contamination [57]. The shelf life of fruits and vegetables can be greatly increased by using nano-emulsions as a preservation technology, minimizing food waste and raising the general safety and quality of the produce [54]. Nano-emulsions play a pivotal role in delivering flavors, nutrients, and bioactive compounds, enhancing bioavailability, and improving the overall quality and shelf life of food products [55]. These benefits, including reduced fat content and extended product freshness, make nano-emulsions a valuable tool for developing health-conscious and appealing food offerings.

3. Technologies for the preparation of edible coating

The food sector is presently encountering novel challenges concerning the sustainability and health implications of packaging and processing methods. With shifting lifestyles and consumer inclinations towards novel and organic items, individuals are seeking food products that demand minimal processing yet possess extended shelf lives, all the while retaining their nutritional and sensory attributes [58]. It can be difficult to achieve these requirements when working with extremely perishable goods like fruits and vegetables. As a result, there has been a noticeable increase in the study and creation of edible coatings recently [59]. These coatings have drawn a lot of interest because they have the potential to improve the performance, safety, lifespan, and quality of food products that have been coated [60]. Edible coatings can be administered through a range of methods, including dipping, spraying, or coating (as depicted in Fig. 1), with the goal of controlling gas exchange, moisture transfer, and oxidative reactions. Additionally, beneficial elements can be added to edible matrices and applied to food surfaces to increase safety and perhaps even improve nutritional and sensory aspects [61]. Specific quality parameters, such as color, weight loss, firmness, decay rate, sensory qualities, microbiological contamination, and nutritional attributes, need to be carefully evaluated when it comes to coated fruits and vegetables. These variables are strongly influenced by the kind of items and how they are stored [62].

3.1. Dipping method

The dipping method comprises dipping the commodity into a coating emulsion that is kept in a container. This method works especially well for foods with complex or uneven surfaces that require extensive coatings (with antibacterial, antioxidant, nutritious qualities, etc.). After the food has been dipped and the extra coating has been scraped off, it is allowed to dry either naturally (air drying) or with the help of a specialized drier [63]. The process of using this method to apply an edible coating to food items involves three key steps: immersion, deposition, and solvent evaporation [9]. The immersion method is widely used to apply edible coatings to fresh produce. Usually, the edible coating mixture is used on fruits and vegetables for 5–30 s. In general, this technique is simple, especially when working with the majority of fruits [64].

The immersion method is typically used in laboratory settings to apply coatings since it is straightforward and affordable [65]. The dipping method of applying anti-microbial agents directly to food surfaces has demonstrated decreased efficacy, primarily as a result of the antimicrobial agents' diminished efficacy as a result of leaching into the food, enzymatic activities, and interactions with other food components [9]. Occasionally, using this procedure results in a thick coating, which could obstruct the food product's capacity to breathe and have an impact on how well it stores [9].

The dipping procedure is fraught with difficulties, including the possibility of coating dilution, the build-up of waste or pollutants, and the potential for microbe growth in the dipping solution. Additional drawbacks of the dipping procedure include the disintegration of the food product's outer layer and a potential reduction in its functionality [66]. For example, fruits and vegetables' natural wax coating may fall

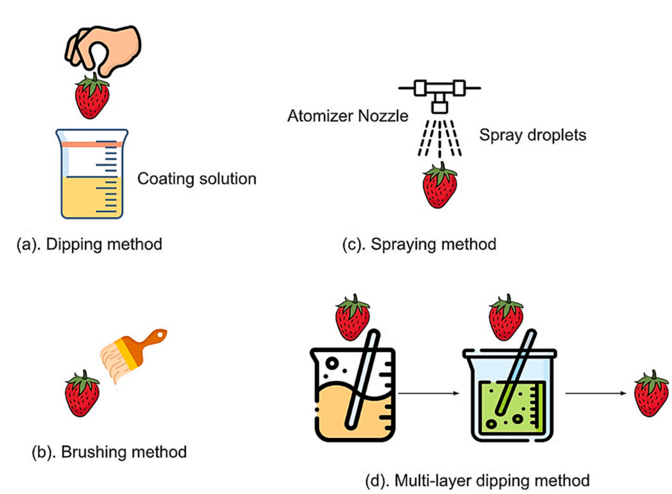

Fig. 1. Illustration of Various methods involved in forming coating of different foods.

off after dipping.

3.2. Spraying method

The most widely used method to apply emulsions or coatings to food products is spraying [8]. This technique entails creating droplets of the coating solution using a variety of nozzles, which are then evenly distributed throughout the food's surface. Three different spraying techniques have been used in industrial settings to apply edible coatings to food items: pressure atomization, air spray atomization, and air-assisted airless atomization [67]. Strong inertial forces and negligible viscous forces cause coating solution droplets to develop [9]. The pressure used for atomization during the spraying process is crucial to take into account. The pressure must be kept below 3.5 bars in order to protect the film-forming process. Additionally, it has been demonstrated that a thickness of 30 m is the best for achieving the appropriate mechanical and water vapor properties. Therefore, it is imperative to carefully monitor this parameter [68].

This method guarantees a consistent and even coating thickness while also allowing for the application of multiple layers, including alternating solutions like sodium and calcium chloride [66]. Spraying technologies also provide control over the temperature of the coating solution, guarantee the maintenance of the layer's integrity, and enable self-sustaining and uninterrupted manufacturing [9]. High-viscosity solutions, on the other hand, are frequently applied to food products by dipping rather than spraying, which leaves a thicker coating layer on the food's surface [69]. Due to the need for a 4-step process (2 sprays and 2 dryings) in industrial settings, emulsified formulations are preferred over bilayer applications since they are more advantageous [70].

3.3. Edible coating 3-D food printing

Applications for 3-D printing have been identified in a number of fields, including environmental research, medical innovation, and military use. Notably, the global market for 3D food printers has had a strong rate of annual growth and has developed into a sizable business with a projected value of over one billion dollars [71]. The process of building goods layer by layer using three-dimensional stacking of plastic material is known as 3-D printing, sometimes known as rapid prototyping or additive manufacturing [72]. This technique creates objects by cutting them into a series of cross-sections [73].

The 3D food printing procedure begins with the edible ink-filled cartridges being preheated to 5° Celsius and kept there throughout. A silicone base is sprayed with edible ink using a nozzle with a 1.5 mm diameter. Each ink is automatically modified by the printer to match the printing conditions in order to guarantee the appropriateness of edible inks for food printing, improve printability, and evaluate the accuracy of the printed structure. A single-layer square form with dimensions of 54 mm on each side and 6 mm in thickness is chosen to assess the fidelity of 2D printing (line resolution). A three-layer disc with a diameter of 41 mm is selected for the evaluation of 3D printing, and the desired shape is scaled for printing using CBM (Cell-based meat analog) [74]. Currently, no established guidelines exist for assessing the accuracy of 3D-printed food. Therefore, dimensions are chosen in a manner that minimizes the influence of the nozzle diameter on the final printed product's dimensions. For each ink type, a single sample is printed, followed by a visual inspection and measurements using a digital caliper. For the 2D square's side lengths, measurements are taken six times: three times along the full length and evenly spaced in a direction parallel to the square's sides. The side thickness is measured at the center of each square's side. Regarding the 3D discs, measurements include the height nearest to the edge of the silicone base on which the structure is printed, as well as the two-way perpendicular diameter [75]. The amount of lipids (triglycerides) present is a key element in controlling the pore morphology, and it can be done to expand the range of pore sizes created with this edible ink composition by accelerating the freezing and drying of meat. Additionally, there is a trade-off between the effects of SL and Canola oil in terms of managing printability while also providing exact pore morphology as compared to rheological characterization [76]. A variety of food ingredients are simultaneously extruded in extrusion-based printing to produce a whole meal [74]. Nevertheless, a material capable of being easily extruded from the nozzle tip and capable of bearing the weight of subsequent printed layers without distorting is required [73].

4. Techno-functional properties of edible coating

Synthetic polymers have been widely used since the 20th century due to their easy manufacturing and ability to achieve desired functional qualities. Today's consumers are increasingly aware of the repercussions because the disposal of these materials has negatively impacted the environment [77]. As a result, support for biobased alternatives and an increasing emphasis on sustainability are present in industrial breakthroughs. Scientists are working hard to develop composite materials made of biodegradable polymers like proteins, lipids, and polysaccharides. When compared to synthetic polymers, these materials have unique qualities including being non-toxic, biodegradable, and widely accessible [78]. Selecting the suitable polymer to mix with can help overcome any restrictions in a polymer's potential hydrophilicity, water solubility, or mechanical strength. It is feasible to maximize the desired characteristics in the resultant structure by combining polymers [79]. A useful method for changing qualities as needed is polymer blending, which makes use of established and affordable technologies. However, rather than drastically changing a material's properties, polymer blending's main goal is to increase the material's performance capacity [80].

In addition to playing a prominent role among other biodegradable materials, starch polymer offers an important substitute for synthetic polymers. It finds widespread application across food and non-food sectors, serving various purposes like edible packaging, adhesives, textile sizing, and cosmetic products [81]. Its widespread use, low cost, easy accessibility, biodegradability, and biocompatibility are all factors contributing to its appeal (as outlined in Table 1). Linear amylose and branched amylopectin make up the majority of starch, with the quantities varied depending on the plant source. For instance, corn flour contains 70 % amylopectin and 30 % amylose [82]. By heating starch granules combined with a plasticizer like water or glycerol, thermoplastic starch (TPS), a polymer formed from starch, can be developed [78]. Although starch-based films offer desired qualities including transparency, odorlessness, and oxygen impermeability, their use in several applications has been constrained by their brittleness and hydrophilic character. To overcome these limitations, a feasible approach is to mix the films with other natural polymers that exhibit favorable interactions with starch [83].

Recent emphasis has been focused a lot on bio-sourced materials from the marine ecosystem, mostly seaweed, to meet the growing need for natural and renewable resources. Due to its abundance of polysaccharides, which provide it with a wide range of useful features like excellent gel-forming properties, recycling potential, thermal resilience, and effectiveness in addressing health issues, seaweed may be a promising choice as a biopolymer [92]. Carrageenan, agar, and alginate are three examples of seaweed-derived compounds that create films. These substances have drawn a lot of interest from a variety of industries, such as functional meals, medicine delivery, tissue engineering, and textile sizing [25]. These polysaccharides are frequently used because of their special characteristics. However, because the extraction of these polysaccharides requires the utilization of a significant amount of energy and chemicals, it is now regarded as being both environmentally and economically unfriendly. The fact that seaweed itself contains additional non-polysaccharide elements including proteins and lipids that support its capacity to form films should also be taken into consideration [25].

Table 1
Techno-functional properties of the edible coating and their mechanism.

Techno-functional property	Description	Mechanism	Potential benefits	References
Biodegradability	Natural Degradation into Environmentally Safe Elements	Incorporating Biodegradable Materials and Additives	Minimizing Packaging Waste and Advancing Sustainability	[84]
Enhancing Texture	Changes Surface Texture	Tailoring Coating Matrix for Desired Texture	Elevating Sensory Experience and Enhancing Appeal	[85]
Protection and Preservation	Protection Against Microbes, Oxidation, and Light	Developing Antimicrobial and Antioxidative Barriers	Minimizing Spoilage and Preserving Quality	[86]
Barrier Properties	Prevents moisture, gas, and aroma transfer	Constructing a Physical Barrier, Decreasing Permeability	Prolonging Shelf Life and Retaining Freshness	[87]
Flavor Retention	Preventing Flavor Loss and Aroma Degradation	Encasing and Safeguarding Volatile Flavor Compounds	Preserving Product Taste and Aroma	[88]
Innovative Approaches	Customizing Coatings for Specific Requirements	Integrating Various Additives for Intended Outcomes	Crafting Distinctive Textures, Flavors, and Appearances	[88]
Adhesion and Uniformity	Guaranteeing Uniform and Reliable Coating Application	Improving Adhesion Via Formulation Optimization	Enhancing Attachment and Aesthetic Excellence	[89]
Controlled Release	Controlled Release of Additives or Compounds	Managing Diffusion and Release Kinetics	Offering Prolonged Flavor, Nutrient, or Color Release	[90]
Aesthetic Improvement	Elevates Appearance and Visual Allure	Crafting Consistent and Visually Pleasing Coatings	Enhancing Consumer Attractiveness	[91]

To make the hydrocolloid kappa-carrageenan (k-carrageenan), a species of red seaweed called *kappaphycus alvarezii* is widely cultivated. Recent research has indicated that natural K. alvarezii seaweed, both with or without additional fillers, can be used to create films. These films have demonstrated notable functional qualities and mechanical strength required for numerous industrial applications [93].

4.1. Role of edible coatings in food quality and food safety

The use of edible coatings has a big impact on improving food quality and food safety. These coatings can be used as a protective barrier to cover a variety of food products, and they have a noticeable effect on these elements of food [94]. Edible coatings have a crucial role to play in maintaining the sensory qualities of food, which include aspects like texture, look, flavour, and scent [95]. These coatings can efficiently prevent moisture loss from fruits and vegetables, preventing wilting and maintaining their crispness [96]. Additionally, they can slow down the ripening process, extending the shelf life of food.

Fan et al. [97] reported an innovative approach involving the use of alginate edible film infused with *Cryptococcus laurentii* to coat strawberries. The study revealed that the microorganism retained its viability within the film, and, notably, the application of these edible films led to a substantial reduction in mold growth. Additionally, the coated strawberries exhibited improved overall quality, sensory attributes and a more appealing physical appearance. This innovative technique showed the potential for preserving freshness and extending the shelf life of fruits using edible films with the aid of beneficial microorganisms.

In another study, Lago et al. [98] highlighted the practical application of edible coatings, specifically using cassava starch and native or modified maize, in preserving carotene and overall quality of pumpkin during the drying process. The results indicated a significant preservation effect ($P < 0.05$) on carotenoids in pumpkin when the edible coating was applied. This study underscores the potential of edible coatings to enhance food safety and quality by preventing the degradation of essential nutrients like carotenoids. Edible coatings can efficiently preserve the crispness of the crust in baked goods and stop moisture from escaping the crumb, preserving the ideal texture [99]. Additionally, by preventing browning, discolouration, and surface cracking, the coatings can protect the aesthetic appeal of various food products. Edible coatings significantly improve consumer pleasure and the marketability of food products by preserving these essential qualities [100].

Edible coatings operate as a barrier to protect food from external pollutants like microbes and pathogens when it comes to food safety [101]. Foods that are ready to eat or other goods that are prone to contamination during storage and transportation require more protection [102]. Edible coatings effectively reduce the risk of microbial proliferation and the occurrence of foodborne diseases by adding an extra line of defence [103]. Additionally, the ability of these coatings to control gas exchange and oxygen transport can successfully delay the oxidation of food ingredients, preventing the development of unfavourable flavours and the spread of spoiling germs [104]. Thus, edible coatings improve food safety by lowering the risk of contamination and lengthening the product's shelf life, which in turn lowers food waste and the risks connected with it [105].

4.2. Role of edible coatings in circular economy

The circular economy, which attempts to reduce waste and improve resource efficiency, can be significantly influenced by edible coatings. By minimizing food waste, edible coatings help to achieve this goal in an effective manner [106]. Edible coatings reduce the premature spoiling of perishable commodities, such as fruits, vegetables, and baked goods, so avoid their wastage [107]. This reduction in food waste reduces the environmental impact associated with food production and disposal while also conserving precious resources.

Edible coatings support this reduction by typically using natural and edible materials, which is another important aspect of the circular economy [106]. For instance, coatings made from proteins or polymers derived from plants, both of which can be obtained in environmentally friendly and inexpensive ways [108]. By maximising the use of easily available raw materials and reducing reliance on non-renewable resources, this practice encourages resource efficiency [109]. Additionally, biodegradable edible coatings can be created, in line with the circular economy's emphasis on products that can degrade naturally in the environment and promote regeneration [110]. Edible coatings are environmentally beneficial solutions as they are recyclable and biodegradable (illustrated in Fig. 2) [111]. Even though they might not always

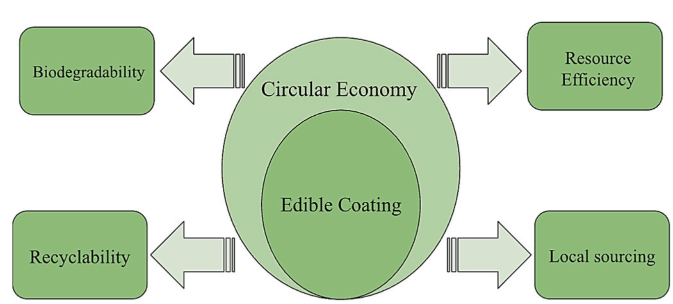

Fig. 2. Role of edible coatings within the circular economy.

be compatible with traditional recycling systems, they can be added to composting methods, enabling the ethical disposal and recycling of organic waste [112]. This is consistent with the tenets of the circular economy, which places a focus on reusing materials and avoiding their disposal in landfills in order to manage waste more sustainably [113].

Furthermore, the usage of edible coatings can aid in the circular economy's support of local sourcing and production. These coatings can be produced easily using locally available materials, hence lowering the transportation-related carbon impact [114].

Due to their role in completing the food supply chain, edible coatings also support the circular economy. By enabling the use of leftovers and underutilised foods, like fruit peels, which can be turned into coatings, it helps the food sector become more circular and reduce waste [35]. In addition, some edible coatings are simple to remove or consume with the food, which eliminates the need for additional packaging materials and promotes the usage of all food product components efficiently [23]. Edible coatings are a useful instrument in promoting the objectives of the circular economy, especially within the food business, as they are in line with sustainability and responsible resource management [115].

5. Characterization of edible coatings

Assessing edible coatings is a crucial step in verifying its appropriateness and effectiveness in preserving food product quality and safety [116]. This process includes the evaluation of various aspects of the coatings, such as their ability to act as good barriers, mechanical strength, microstructure, thickness, evenness, and their adhesion to the food surface (as depicted in Fig. 3). Assessing th barrier properties of coatings such as its resistance to water vapor and oxygen transmission, is essential for gauging its capacity to protect against moisture loss and oxygen exposure [117]. In a study, Nasirifar et al. [118] reported the effect of a carnauba wax coating and 2 % montmorillonite nano-clay on the shelf life and freshness of blood oranges. The fruit was stored at 7 °C for 100 days and showed improved total acidity, antioxidant activity, firmness, and color characteristics after coating application.

The mechanical properties, such as tensile strength, flexibility, and resistance to puncture, help determine how effectively the coatings can endure handling and safeguard the food product [119]. Analyzing the microstructure through techniques like scanning electron microscopy (SEM) and atomic force microscopy (AFM) provides insights into the inner structure of the coating [120]. Moreover, measuring the thickness and uniformity of the coating ensures consistent performance and adhesion testing assesses how efficiently the coating sticks to the food surface [121]. Through the characterization of edible coatings, manufacturers can modify their formulations and application techniques to suit the specific requirements of different food products, ultimately enhancing their shelf life and quality [122]. Ongoing research continually improves these characterization methods, optimizing the performance of edible coatings in the food industry [12].

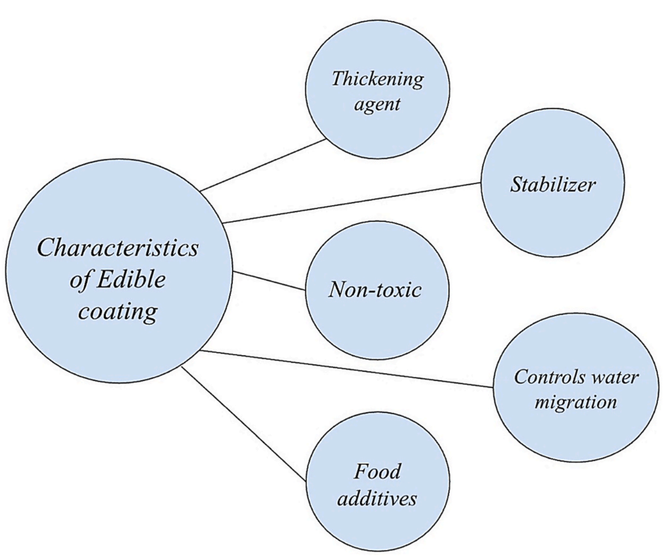

Fig. 3. Characteristics of the edible coating as thickening agent, stabilizer, non toxic, control of water permeation, and as food additive.

5.1. Thickness of edible coating

Key characteristics like gas permeability are directly influenced by edible coating thickness. Peeling coatings that have been cast and cured on flat plates allow for convenient micro-meter measuring. However, it can be difficult to gauge the thickness of the fruit after treatment. Measuring post-application thickness on fruit is challenging. In such instances, an estimation can be derived via surface solid density (SSD) quantification [123] [124]. The mathematical expression for surface solid density is presented in Eqn. (1).

$$SSD = \frac{(MFa)\ (Xs)}{As} \tag{1}$$

In equation (1); The solid-mass fraction (Xs) of each film-forming solution is essential for computing SSD and MFa for the edible coatings. The MFa value is calculated by comparing the fruit's quality before and after the coating has been applied. Calculating the average sample area (As) may need image analysis or measurements of volume/surface area as fruit forms get increasingly complex and irregular. As an alternative, the coating solution's viscosity, density, drying time, and solid concentration can be used to describe the film's thickness.

A cutting-edge technique with high potential for measuring coating thickness is spectroscopic ellipsometry. Although it has been used to characterize film and multilayer structure [125], as far as we are aware, its use in edible coatings has not been investigated. By comparing the actual experimental results to the predicted ellipsometric response of an optical model that represents the expected surface structure, spectroscopic ellipsometry data are analyzed. A least-squares regression analysis is used to carry out this fitting process [77]. The measurements are made across the whole visible spectrum, As a result, the results are contrasted using a mathematical model to calculate the film's thickness and coating's refractive index. However, a number of microscopy methods, including confocal microscopy, scanning electron microscopy (SEM), and atomic force microscopy (AFM), may also be used to measure the topography, coating thickness, and roughness of the surface of treated fruits [126].

Soares et al. [127] examined the effects of several factors such as fish temperature, coating temperature and dipping time on the thickness of edible coatings (water and 1.5 % chitosan) applied to frozen Atlantic salmon, including fish and coating temperatures as well as dipping time. Chitosan produced thicker coats when the temperatures of the fish and coating solution were reduced. To keep salmon temperatures from rising to dangerous levels for the growth of harmful microorganisms, safe dipping intervals have been established. Compared to water, chitosan had better freezing characteristics. Furthermore, understanding essential characteristics, such as gas permeability and resistance to water vapor transport, is greatly aided by analyzing the coating microstructure.

5.2. Barrier efficiency

The effectiveness of edible coatings in creating a protective barrier relies on several factors, encompassing the choice of coating material, its thickness, the microstructure of the coating, environmental elements like temperature and humidity, as well as the particular needs of the food product [13]. These all parameters come under the umbrella of barrier efficiency. The efficiency of the barrier properties in an edible coating is crucial for maintaining the quality and safety of the food product [95]. According to Garcia et al. [128], edible cassava starch coating along with the plasticizer potassium sorbate improves strawberry fruit quality during the storage period by increasing water vapor resistance and lowering the rate of respiration. Similarly, Ma et al. [129], also used gelatin and olive oil in combination to create a composite film using a microfluidic emulsification process. The study was done to increase the hydrophobic nature and the effect of oil content on the distribution of lipid droplets in suspensions that form films. It was concluded that gelatin and olive oil can be used to produce films or coatings for a variety of culinary products. It was also stated that adding olive reduces the tensile strength and water vapor permeability of the gelatin film and gives it a lustrous appearance. For instance, in the case of fresh strawberries, it is essential for the edible coating to possess strong moisture-blocking capabilities to safeguard against dehydration and preserve their crisp texture [28]. Conversely, when coating a baked product, the primary concern is to inhibit moisture movement from the interior to the surface [130].

5.2.1. Water-vapor resistance

The characteristics of edible films and coatings are influenced by various factors, including the composition of the material, preparation conditions such as solvent type, pH of the medium, temperature, and the type and concentration of additives like plasticizers, antimicrobials, antioxidants, cross-linking agents, or emulsifiers [131]. When compared to plastic films, hydrocolloid films derived from proteins and polysaccharides showcase enhanced gas barrier properties. They effectively impede the permeation of carbon dioxide and oxygen. Additionally, these films display satisfactory barrier capabilities against lipids. However, they are less effective in preventing the passage of water vapor [61].

On the contrary, lipid-sourced edible films and coatings like resins and waxes are very effective at creating films and coatings that stop both moisture gain and loss. They are good moisture barriers due to their hydrophobicity and low water vapor penetration [78]. However, these films frequently have an opaque look when utilized as packing materials. Despite their advantages in terms of functionality, their aesthetic appeal could be a disadvantage in some situations [77].

The water vapor resistance (WVR) of coated fruits can be assessed by tracking sample weight loss under controlled temperature and relative humidity conditions. Water vapor resistance is expressed using Equation (2) [132].

$$WVR = \frac{aw - \%R\,H100\cdot\,Pwv}{R} \times \frac{T.As}{J} \tag{2}$$

Here, J signifies the slope of the weight loss curve during stable conditions, As represents the sample area, aw indicates the water activity of samples, Pwv stands for the saturated vapor pressure, T denotes the absolute temperature, and R signifies the universal gas constant.

An alternative approach to ascertain the water vapor permeability of coated fruits is to create a coating through casting and drying on a plate. Subsequently, the water vapor permeability of this coating can be gauged using established methods grounded in gravimetric techniques [133]. This technique has been used widely in numerous research to assess the permeability properties of a variety of edible coatings [134].

Nevertheless, it's important to emphasize that while these measurements are valuable for comparing different formulations, the permeability attributes of coatings can alter when they are applied to an actual fruit surface [135]. Changes in these properties can be caused by elements like the fruit partially absorbing the barrier layer or uneven lipid distribution in emulsified coatings because of surface imperfections [12].

5.2.2. Gas permeability

By analyzing the internal makeup of coated fruits, often in relation to levels of O2 and CO2 as well as significant volatile chemicals like ethanol and acetaldehyde, one can determine the gas permeability of coatings. These compounds are essential to the metabolism of the fruit. Using a syringe, samples are taken from the fruit core to undertake the analysis. These samples are then exposed to gas chromatography for in-depth analysis [136]. This procedure is done to measure the internal atmosphere. Alternately, the respiration rate of covered fruits can be used to gauge changes in their interior makeup. Fruits are maintained in a glass container that is well sealed in order to accomplish this, and headspace is collected at various time intervals for gas chromatography examination of the CO2 and O2 levels [132].

Mathematically, the process of permeation can be expressed using Fick's first law. The flux (J), which correlates with the concentration gradient, can be defined in a specific direction as shown in Eqn. (3).

$$J = -D\frac{(\partial C)}{(\partial X)} \tag{3}$$

J here stands for the flux, which is the total amount of solute that diffuses through a given area in a given amount of time (measured in units like g/m2s or ml/m2s). The diffusivity constant, D, is expressed as the square meters per second (m2/s) rate of diffusion. The letters C and X represent the diffusing substance's concentration gradient and meters (m) stand for the film's thickness [126].

The flux (J) is provided under the two assumptions that the diffusion is in a steady state and that there is a linear gradient through the film and hence the flux J can be presented as shown in Eqn. (4).

$$J = D\frac{(C2 - C1)}{(X)} = \frac{Q}{A.t} \tag{4}$$

Where A is the area of the film (m2), Q is the amount of gas diffusing through the film (g or ml), and t is the time (s). The driving force is represented after Henry's law is applied in terms of the partial pressure difference of gas, and rearranging the terms results the equation in terms of permeability as mentioned in Eqn. (5) ([137],

$$\frac{Q}{A.t} = D.S.\frac{(p2 - p1)}{(X)} = \frac{P.\Delta p}{X} \tag{5}$$

p is the partial pressure difference of the gas across the film (Pa), S is the Henry's law solubility coefficient (mole/atm), and P is the permeability ((ml or g) m/m2.s.Pa). The permeabilities of O_2, CO_2, and water vapor can be determined using Equation (6) [138,139].

$$P = \frac{(Q.X)}{(A.t.\Delta p)} \tag{6}$$

5.2.3. Sensorial and textural properties

The fundamental essential characteristics of coated fruits and vegetables include the increase in shelf life as well as the enhancement of texture and appearance (as outlined in Table 2). Understanding wettability-related parameters is essential for coating applications. According to Choi et al. [140], The surface-free energy, the interfacial tension between the coating solution and the fruit's surface, and the contact angle are all significant factors to consider, are examples of this. These factors mainly influence the extent to which liquid adheres to the surface, subsequently impacting the eventual thickness of the coating that covers the fruit. In this context, Fama et al. [141]. found that the viscosity, draining time, the density of biopolymer solutions, the surface tension of both the fruit and the liquid, and the fruit's surface roughness all had an impact on the mean liquid film thickness on coated apples. Maintaining the basic flavors (bitter, sour, and sweetness), aroma, firmness, color, gloss, and other sensory qualities of coated fruits throughout the coating application is essential. To evaluate the sensory qualities of coated fruits, techniques like descriptive analysis or consumer and free-choice profiling panels are frequently used [142]. Customers might reject samples in some cases because of their synthetic color and waxy look, especially when lipids are integrated into coatings

Table 2
Various properties of coated fruits and vegetables.

Sr. No	Property	Description	References
1.	Extension of Shelf Life	Fruits and vegetables with coatings have a longer shelf life because they retain more moisture, resist microbial growth, and take longer to ripen.	[145]
2.	Texture maintenance	By forming a layer that lessens physical damage and water loss, coatings can help maintain the firmness and texture of fruits and vegetables.	[146]
3.	Appearance	Coatings increase the visual appeal of produce by giving it a shiny or glossy surface, which can appeal to consumers more.	[147]
4.	Preservation of Flavour	By minimizing the loss of volatile components and shielding the product from outside odors, coatings can help preserve the flavor of fruits and vegetables.	[116]
5.	Retention of nutrients	By reducing the amount of time that fruits and vegetables are exposed to air and light, which can cause nutrient breakdown, coatings can help maintain the nutritious value of produce.	[148]
6.	Safety	To ensure that they do not pose any health concerns to customers, coatings must be food-safe and chemically free.	[149]

[142]. In addition, it's important to keep in mind that modifications to the internal environment of coated fruits and the ensuing metabolic slowdown might also affect their mechanical characteristics [143]. To assess these properties, compression studies employing a Texture Analyzer or an Instron Universal Testing Machine are frequently utilized. The most frequently reported measures when assessing the quality of preserved coated fruits are firmness or fracture resistance [144].

Due to their various applications, edible coatings are becoming more popular across numerous industries. They are essential in the food industry as they help protect fresh produce from oxidation, moisture loss, and microbial growth by forming a barrier [17]. This improves the quality and safety of fruits and vegetables in addition to reducing food waste.

According to Jiang et al. [150], chitosan coatings (both low molecular weight and high molecular weight) increased the storage period of blueberry fruits, demonstrating the significant potential for chitosan-based edible/biodegradable films in the food industry to extend the shelf life of fresh cut fruits and vegetable. The shorter storage time is caused by the decrease of antioxidant capability.

Additionally, pharmaceutical industries use edible coatings to encapsulate medicines for controlled release, enhancing drug absorption and efficacy [94]. These coatings can be used in the agriculture sector to alter seed surfaces for higher germination rates and defence against soil-borne diseases [151]. Additionally, edible coatings are explored in the cosmetics industry for innovative skincare products, and they hold promise in reducing the environmental impact of traditional packaging materials [152]. Edible coatings are a sustainable and promising solution for a variety of applications dueto their biodegradability and functional properties, which are in line with the expanding demand for environmentally friendly and effective solutions in today's industrial landscape [153].

6. Current and future trends

The increasing value given to sustainability and natural elements is an interesting trend. Due to their ability to break down naturally, plant-derived biodegradable polymers like chitosan and cellulose are becoming more and more popular [154]. Additionally, functional components are being added to coatings to improve the durability of items as well as their nutritional value. As smart packaging and sensors are being investigated, nanotechnology is helping to develop coatings with improved barrier qualities. This will allow for in-the-moment quality monitoring [155]. These changes align with the general objectives of decreasing food waste, accommodating personal preferences, and responding to the expanding popularity of alternative proteins [156].

These tendencies may be further developed in the years to come, with a stronger emphasis on customization and individualized nutrition. The development of precise nutrient delivery into edible coatings could provide consumers who are concerned about their health with customized experiences [154]. Edible coatings and smart packaging may be more seamlessly integrated as technology develops, bringing with it a new level of convenience and transparency in food safety. The future of food preservation and enhancement will be shaped by the development of sophisticated edible coverings that address both environmental issues and personal dietary needs [157]. The newest development entails an edible coating that may completely eliminate all signs of viscous fluids. A Colorado State University research team [158] recently created a super-hydrophobic coating, a water-repellent, extremely thin surface layer. Given that it is made of beeswax and carnauba wax, two naturally occurring materials that may be consumed and are allowed by the FDA, this unique coating falls under the category of edible coatings.

7. Conclusion

Edible coatings are a potential new food protection technology, however, the best coating base for a given application may vary depending on the type of food being protected and the required qualities. For instance, polysaccharide coatings like chitosan and alginate, which effectively lower moisture loss and microbial development, are frequently used to preserve fruits and vegetables. Because they can act as a barrier to oxygen and moisture, coatings comprised of lipids, such as waxes and fatty acids, are frequently employed to preserve meat and poultry. Additionally, coatings consisting of proteins like gelatin and casein can be utilized to enhance the appearance and texture of food products. There are various particular instances of edible coatings that have been proven to be efficient for food protection of numerous foods including fruits and vegetables such as strawberries, apples, and tomatoes coated with chitosan and alginate-based coatings, a polysaccharide with antibacterial and antioxidant properties. The shelf stability of cheese and other dairy products can be potentially increased with wax coats as wax coats can stop moisture evaporation and microbiological development. To develop and optimise edible coatings for particular food products and applications, more study is required. However, edible coatings can contribute to the development of a more equitable and sustainable food system by lowering food waste and enhancing food quality and food safety.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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