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Review

Applications and Impacts of Edible Coatings on Food Quality

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Abstract: Edible coatings are emerging as a significant trend in the food industry, driven by growing consumer interest in environmental issues, mainly due to concerns about the excessive use of plastics. This study aimed to perform an integrative review to identify the materials used to produce edible films and characterize their applicability for food quality and conservation. For this, the descriptors "edible films" or "edible coatings" and "food quality" or "food preservation" or "food safety" were used in the Science Direct database, resulting in 48 articles selected. Fruits and vegetables are the two food groups most studied with coatings based on hydrocolloids, protein, composite films, and lipids, with a greater emphasis on the positive impacts on their quality and conservation. Animal products have a higher frequency of studied antimicrobial effects. There is a diversity of materials used in coatings: vegetable-based, such as algae, mucilages, and fibers, as well as those of animal origin, such as gelatin and protein hydrolysates. Few studies have addressed sustainability concepts as final characteristics of coatings. In conclusion, edible coatings show promise for the food industry, offering benefits for both food and the environment. However, more studies are needed to fully explore their potential as replacements for conventional plastics, while ensuring safety and regulatory compliance.

***Keywords*:** sustainable packaging, edible film, food preservation, sustainability, biofilm, shelf life

1. Introduction

Food packaging has essential attributes, from protection, storage, and delivery functions to aspects such as ease of use and providing information about the product. Packaging can retain the beneficial effects of processing, extend shelf life, delay food deterioration, and maintain and/or increase the quality and safety of products, which consequently offer protection against three main classes of external influences: chemical, biological, and physical [1, 2].

Among the different materials used in its composition, plastics are mainly derived from petrochemical sources [3] and are widely used in the food industry, as they present low production costs, durability, good mechanical properties, and resistance to oils and chemicals [4]. However, because of the prolonged decomposition time, plastic food and beverage packaging is the greatest contributing source of global plastic pollution [5].

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Plastics derived from fossil hydrocarbons accumulate in the environment (soil, waters, and coasts) and can become microplastics as well as accumulate in marine environments [6-8]. Furthermore, the use of plastics can cause harm to the health of humans and animals due to microplastics, the effects of which are not yet completely understood [9]. However, microplastics do exist in the air as well, resulting from plastic packaging and inadequate disposal, and have resulted in harmful effects on respiratory health [10]. However, conventional plastics generally have good elongation, high tensile strength and tensile failure, and relatively low elasticity [11]. Thus, there is a clear need to develop strategies that can replace the use of this material in food packaging to reduce its environmental impacts. Research that promotes the development of biofilms or edible coatings for direct application to food aims to achieve final products with good mechanical properties similar to plastics.

Additionally, the use of agri-food waste or even food waste, which could become co-products, is another relevant factor in minimizing damage caused to the environment. The fruit and vegetable processing industries contribute greatly to the production of these co-products. Approximately 50% of the waste generated consists of by-product, such as shells, almonds, and bagasse (immature or damaged) [12, 13]. These can be useful for new products or even be part of the constitution of food covering systems.

The growing concern from consumers about the environmental and health impact of synthetic plastics has driven the search for alternative, biodegradable, and renewable packaging. These materials preserve the freshness of products for longer and reduce degradation and methane emissions linked to food waste. However, many consumers are unaware of the beneficial potential of alternative forms of packaging. In the future, ideal packaging will maximize food utilization and minimize environmental impact [14, 15]. In this context, biodegradable materials, produced naturally or synthetically, are a promising alternative for the formation of coatings or biofilms, since they decompose after fulfilling their purpose, and become assimilated or mineralized in the environment by decomposition or even digestion, and even may be edible [16].

Edible films and coatings are layers of biomaterials that can be consumed with food [17], with elaborative differences. While the edible coating is formed directly on the food, the elaborated edible film is then adhered to the product [18]. In addition to being biodegradable, they can be from natural waste, in addition to promising results for application in food such as inhibition of microorganisms, prevention of oxidation, improvement of nutritional value, increase of shelf life, and even health promotion [19]. The improvement in food shelf life from films and coatings is due to protection against UV light, transport of solutes, water vapor, and organic vapors or gasses between the food and the atmosphere, in addition to other potential properties provided by bioactive components, antimicrobials, and healthy microorganisms incorporated into the biopolymer system [18]. Chitosan, for example, is a main biomaterial used for edible films and coatings for food due to its good film-forming properties and biological properties that include antimicrobial, antifungal, and antiviral, and low toxicity effects [20].

Despite the hydrophilic nature of edible coatings, which limits their mechanical and barrier properties compared to plastic, some technologies are used as multilayers, nanotechnology, or oils to minimize the moisture barrier [14, 21]. However, the toxicological data available regarding edible coatings is not yet well understood and needs to be evaluated for safe consumption [19, 21-23]. The development of these types of coatings is emerging and has been widely explored regarding their basic raw materials, application, and contribution to the quality of the coated food. Thus, this study aimes to identify and characterize the often materials used to produce edible coatings and their applicability to food quality and conservation.

2. Materials and methods

This study is an integrative descriptive review with defined data search criteria. The research was carried out from May to July 2023 on the Science Direct database using terms indexed in DeCS, with Boolean operators, such as “edible films” or “edible coatings” and “food quality” or “food preservation” or “food safety”, resulting in 1,087 results.

The search filters used were articles from the last five years (2018-2023), original research articles, and those with full open access to the database. The exclusion criteria were articles that included other types of films and coatings with functions outside of food application, or that were developed but not tested in food. With these criteria, the total number of articles used for the results was 55.

The data from the studies were described and evaluated regarding the type and composition of the coating used, whether it presented active or signaling (intelligent) action, the description of the food tested, whether the composition of the coating was from the reuse of waste/other foods or no, properties and impact on food, and when clarified, what were the mechanical properties of these coatings. The positive impacts of applying edible coatings to different food groups were categorized to assess the frequency of these effects.

3. Results

The coatings used in eligible studies and tested on specific foods were categorized as follows: hydrocolloids (18), proteinaceous (4), lipids (2), and composite films (23). The food groups evaluated in the studies were the following: fruits (19), vegetables (9), mushrooms (1), cheeses (8), sausages (4), meats (2), fish (2), sweets (2), seafood (1) and bread (1). It is notable the diversity with which edible coatings can currently be applied to various foods, from the vegetable group to those of animal origin and also preparations, for example, in baked goods.

Regarding the raw materials used as base ingredients in the formation of coatings (Table 1), there are diverse materials used from plant origin, such as algae, fibers, mucilages, and starches. Animal origin includes different gelatins, chitosan, and protein derivatives, such as hydrolysates. Regarding bioactive ingredients, plant extracts or essential oils are already recognized as having antioxidant and/or antimicrobial effects (such as cinnamon, clove, turmeric, acerola, thyme, oregano, jackfruit); synthetic preservatives already used in industry such as sodium metabisulfite, strains with probiotic recognition (*Lactobacillus*) and also the use of bacterial peptides, such as bacteriocins (nisin). In studies, these bioactive components contributed to positive effects on food quality, as well as the textural properties of coatings.

It is relevant to highlight that in some studies, besides raw materials and bioactive compounds, other procedures improved the positive effects on food safety and conservation. Packaging systems, such as modified atmosphere packaging (MAP), have been used along with compound and lemon dairy sweets [24, 25] and vacuum packaging of fresh curd cheese [26]. Other conservation technologies, such as ultraviolet (UV)-A light have been applied to cheeses [27], photodynamic therapy (PDT) in fresh cheeses [28], gamma radiation in tomatoes [29], and photodynamic inactivation of microorganisms (PDIM) in ricotta [30].

Ahmad et al. [31] demonstrated that chemical crosslinking in edible coatings is an easier and more cost effective option and can produce the much-needed improvement for membrane optimization. Table 2 shows a summary of the studies by Ahmed et al. [31] and Castro-Muñoz et al. [32] that evaluated different crosslinker agents and their effects on three polymers (6FDA-ODA, 6FDA-ODA:DABA, and poly (vinyl alcohol)/graphene oxide, respectively). Crosslinking agents produce polymers with a bonded network, which directly influences the density, permeability, and final properties of the coating material [31]. Depending on the type of crosslinker agent, there are significant differences in the permeability and selectivity to CO_2/CH_4 and in the stiffness and losses of the fractional free volume (FFV) of the membranes. A reduction in FFV occurs when the crosslinking agent is a short rigid compound or contains hydrogen bond donor/acceptor functional groups, as opposed to a bulkier crosslinker, which due to the compaction of the internal packing of its aromatic group, promotes a low reduction in FFV [31].

Regarding the positive impacts of coatings on food, the most frequent attributes were categorized as "shelf/shelf life"; "nutrient/antioxidant preservation"; "quality and appearance"; and "antimicrobial effect" which are shown in Figure 1.

In the "shelf life" category, positive results are included in the foods tested compared to control food, such as increased shelf life, conservation and delay in ripening, lower respiratory rate, and inhibition of ethylene synthesis. The "preservation of nutrients/antioxidants" category demonstrates studies that addressed the effects of which nutrients and antioxidants were preserved, such as ascorbic acid and phenolic compounds, among others, and that there was stability of lipid and/or protein oxidation. Regarding shelf life extension, many studies have evaluated the preservation of coated versus uncoated foods within an experimental test period that ranged from 21 days to 180 days. Some studies have identified an increase in the total shelf life of foods compared to control samples, with an average of 15.5 ± 8.0 days for fruits and vegetables (n = 12 studies), an average of 16.0 ± 7.0 days for cheeses (n = 2 studies) and an average of 21 days for meats (n = 1 study).

Table 1. Characteristics of edible coatings: composition, bioactive ingredients and tested foods

Food groups			Types of coatings	Raw material	Bioactives	Reference
Fruits, vegetables and Fungi	Fruits	strawberry (2), melon (2), lemon (2), grape (2), blackberry (2), pear, sapodilla, star fruit, tangerine, banana, apple, guava, umbu, mango, papaya and avocado.	HC, PT, CF	sodium alginate, chitosan, tuna shell gelatin, glycerol, agarose, neem gum, Chlorella sp biomass powder, locust bean gum, hydroxypropylmethylcellulose (HPMC), beeswax (BW), silk fibroin, pectin, whey protein, lemon bean starch, coconut oil, Nature Seal, potato starch, cashew gum, gelatin, zein, shellac, carboxymethylcellulose (CMC).	sodium metabisulfite, black tea extract, nanohydroxyapatite (nHA), curcumin, pomegranate seed oil, limonene liposome, sodium chloride, stearic acid, glacial acetic acid, bioactive whey protein peptides, lactic acid, essential oil cumin, thymol.	[22, 33-50]
	Vegetables and Mushroom	tomato (5) and cherry tomatoes, cucumber (2), carrot (2), lettuce, radish, yellow pepper, red pepper, pepper, Kapia pepper, potato and zucchini, fresh Agaricus bisporus.	HC, CF, LP	neutral glycerides, C16-18 fatty acids, chitosan, sodium alginate, glycerol, carnauba wax, starch, gelatin, zein, potato starch, pectin, whey protein isolate, xanthan gum, glycerol monostearate, dextrin.	oils essential oils (thyme, oregano), α-dl tocopherol acetate, *lactobacilli* (*Lactobacillus paracasei*), jackfruit extract, clove oil, olive oil, purified oleuropein.	[26, 51-58]
Cheeses	Traditional	fresh cheese (2), kalari cheese, coalho cheese (2), ricotta, mozzarella.	HC, CF, PT	alginate, carrageenan, ethanolic residue from the pulp of the Ziziphus joazeiro fruit (POLIJUA), whey protein, guar gum, alginate-maltodextrin-glycerol, hydroxyethylcellulose.	citric acid, *T. bellerica* extract 0.5%, juá, Chinese cinnamon bark, natamycin, *P. commune*.	[26, 28, 30, 59-62]
	Vegetarian	tofu	CF	furcellaran (algae) and soybean meal protein hydrolysates.	-	[63]
Meat products	Sausages	sausage, pork ham, meatball and beef burger.	HC, CF, PT	glycerol, bovine gelatin, cassava gelatin (hydrogel), chitosan/furcellaran, rice husk, chitosan, alginate.	curcumin, bacterial peptides (RW4 and LL-37), acerola pomace extract, erythrosine, liquid smoke.	[27, 64-66]
	Meats	slice of beef and chicken, and meatballs.	HC, CF	sodium alginate, κ-carrageenan/konjac glucomannan, chitosan.	cinnamon and nisin essential oil nanocapsules, bacteriophage (pbse40), liquid smoke.	[67, 68]
	Fishes	croaker, fish fillets, chikuwa fish.	HC, CF	sodium alginate, chitosan nanoparticles, collagen, liquid smoke from coconut shell + chitosan.	Cinnamon, perilla essential oil, liquid smoke.	[69-71]
	Seafoods	black tiger shrimp.	CF	chitosan-gelatin.	longkong pericarp extract.	[72]
Bakery and confectionery products	Sweets	kulfi ice cream and compound dairy sweets.	HC	carrageenan, corn starch, glycerol.	*Aloe vera*, nisin and natamycin.	[12, 73]
	Bread	Wheat bread.	CF	sodium caseinate + chia mucilage and glycerol.	probiotic (*Limosilactobacillus fermentum-NKN51* and *Lactobacillus brevis-NKN52*).	[74]

HC-hydrocolloids; PT-protein; CF-composite films; LP-lipids

Table 2. Effects of the crosslinking agents with different polymers in the membranes for edible coatings

Crosslinker agents	Polymer	Permeability		Selectivity	Thermal stability		Mechanical stability	
		CO_2	CH_4	$\alpha CO_2/CH_4$	Advantages	Disadvantages	Advantages	Disadvantages
-	6FDA-ODA	43.8	1.5	29.9	-	-	-	-
m-xylene diamine	-	10.6	0.2	58.8	Better effectiveness among crosslinkers. Lower FFV reduction.	-	large and rigid crosslinker.	-
n-ethylamine	-	7.8	0.2	37.5	Effective	High FFV reduction.	-	-
n-butylamine	-	8.8	0.2	42.9	Effective	High FFV reduction.	-	Short rigid compound.
-	6FDA-ODA: DABA	36.7	2.1	17.7	-	-	-	Short rigid compound.
EGmSal- ethylene glycol monosalicylate	-	10.7	0.2	43.0	Increased selectivity (143%).	-	-	limitation of movement due to rigidity of polymer chains.
EGAn- anhydrous ethylene glycol	-	-	-	-	-	brittleness and cracks in the membrane.	-	highly rigid and shorter component.
FeAc- thermally labile iron(III) acetylacetonate	-	47.2	1.2	40.0	Improved performance (126% and 29% increase in selectivity and permeability, respectively). Ideal separation at 2% by weight).	-	preservation of membrane integrity.	highly rigid and shorter component.
-	poly(vinyl alcohol) (PVA)	-	-	-	Effective	losses in selectivity.	Overall improvement (Young's modulus, tensile strength and elongation at break).	highly rigid and shorter component.
Graphene oxide (GO) 0.5%	-	-	-	-	Better performance (75% increase); acceptable separation factor (2.63 at 40 °C). Better water transport.	losses in selectivity.	Overall improvement (Young's modulus, tensile strength and elongation at break).	-
Graphene oxide (GO) 1%	-	-	-	-	-	losses in selectivity.	-	-
Graphene oxide (GO) 2%	-	-	-	-	-	-	-	no improvement in mechanical properties.

FFV: Fractional free volume. Data from Ahmad et al. [28] and Castro-Muñoz et al. [29]

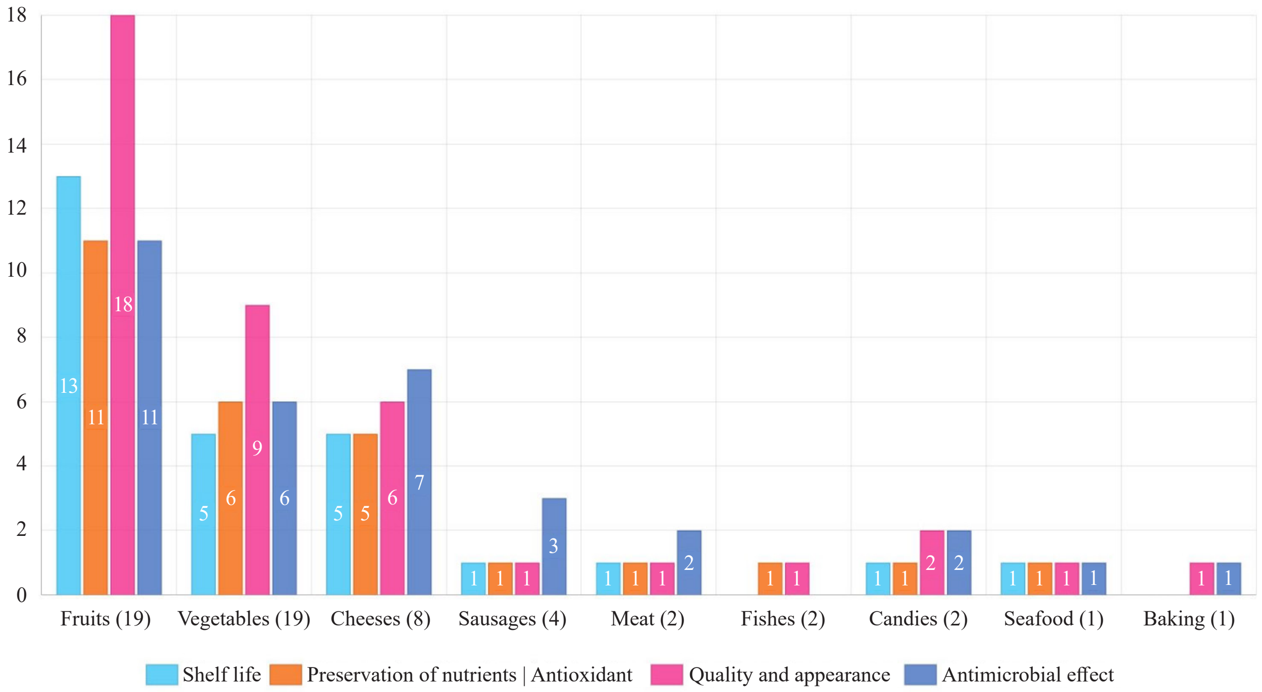

Figure 1. Frequency of positive impacts of coatings on different food groups

The "quality/appearance" category includes studies that presented positive aspects for food quality and conservation and foods with coatings that had good evaluations in sensory analysis tests, both aspects that were compared with the control group. In addition to these, studies also highlighted effects such as less weight or mass loss, acidity control, maintenance of texture, firmness and/or rigidity, reduction of enzymatic browning, improvement of appearance, less loss of total soluble solids, stability of color, brightness, and freshness, better sensory parameters, among others related to quality preservation. Regarding the "antimicrobial effect" category, the frequency of studies with results relating to food safety in general, with coatings with antimicrobial, antibacterial, antifungal action, with the presence of probiotics, and also with characteristic non-toxic according to current requirements for consumption and increased safety.

In Figure 1, there was a higher frequency of positive impact to improve the quality and appearance of fruits and vegetables (n = 27) and a higher frequency of antimicrobial effects evaluated in products of animal origin (n = 15). This result is compatible with the nature of these food matrices, given that, for fruits and vegetables, controlling the post-harvest respiratory rate is relevant to preserve quality and reduce breathing speed, and for dairy foods and meat, inhibiting the growth of pathogens leads to longer shelf life.

Although edible coatings have a composition of biodegradable raw materials or can be co-products and materials from agroindustry and food waste, few studies have highlighted this sustainability characteristic. The terms 'biodegradable' and 'profitable' were included in only five studies, one in 2021 and 2022, and three in 2023.

4. Discussion

The types of edible coatings can be classified according to the materials used in their preparation, such as hydrocolloids (cellulose, chitin, and chitosan, starch or gums), proteinaceous (gelatin, corn zein, collagen and casein), lipids (waxes, paraffins, fats and oils) or composite films (combination of hydrocolloids, proteins and/or lipids) [17]. The preference for composite films among the coatings used by different films obtain a final product with better permeability and mechanical properties for specific applications. The combination of types of films makes it possible to take advantage of each one, enhancing their functions and resulting in a more efficient coating to meet the technological needs of the foods used [17].

Signaling or “smart” edible coatings use an indicator to provide some signalization to the food and can perform intelligent functions, such as communication through thermal indicators, leak indicators, freshness indicators, pH indicators, sensors, and radio frequency identification tags, among other advanced technologies [19]. In edible coatings, indicators are polymers-based and incorporated with anthocyanins, which allow a visible colorimetric change to inform consumers about the quality and safety of foods available for consumption [3].

Furthermore, edible coatings can also perform active functions by incorporating bioactive compounds, such as antioxidants, micronutrients, antimicrobials, natural dyes, and pigmentation agents. Some coatings may even include live microorganisms, including probiotics, providing additional health benefits to the consumer [20]. This combination of intelligent and active properties makes edible coatings a versatile and innovative solution for the food industry.

One study demonstrated coatings applied to food had specific negative effects. This study used furcellaran (an algae-derived polysaccharide) and soybean meal protein hydrolysates as coatings for tofu [30]. However, the results showed a higher loss of mass, an unfavorable effect on color, ineffectiveness in inhibiting the growth of microorganisms, and a lack of efficiency in inhibiting lipid oxidation. Notwithstanding such consequences, further investigations are underway to mitigate the negative impacts of using coatings for tofu. Furthermore, certain coatings used on fruits and vegetables exclude co-products from animals in their composition, which is significant for vegans.

The sustainability findings are relevant to promote the use and supply of foods with edible coatings, as there is a tendency to change the packaging concept due to consumer concerns about plastic pollution and agri-food waste [5].

An example of a study about agri-food waste is tuna shells with chitosan, glycerol, and 15% black tea extract as a coating for minimally processed papaya. In this study, the coating was able to suppress microbial growth and extend the shelf life of papaya by ten days, in addition to reducing weight loss and preserving the texture and firmness of the fruit [34]. As well, 4% acerola pomace with bovine gelatin and glycerol had an antioxidant effect on the beef burger, delayed lipid and protein oxidation, increased shelf life, and reduced the formation of total carbonyl compounds and malonaldehydes by 23.58 and 60.14%, respectively [66].

Regarding food packaging, mechanical and barrier properties can be provided to improve food safety. These properties determine the behavior of a material when subjected to external forces. The mechanical properties analyzed in the studies were elongation, thickness, tensile rupture, tensile strength, and modulus of elasticity. Among these, some ingredients added to the formulations promoted texture improvements, such as citric acid [25] and aloe vera extract [73].

It is relevant to consider the characteristics and interactions of different base polymers used in the formulation of coatings and their crosslinking agents to improve membrane thermal and barrier properties (Table 2). The protonated (by sulfuric acid) 2-pyrrolidone-5-carboxylic acid crosslinker (deep eutectic solvents (DES)) has potential for application in hydrophilic pervaporation membranes for the removal of polar compounds-with high applicability in biorefinery [75]. Thus, crosslinkers can act to obtain membranes with better compound selectivity and permeability, such as in active packaging systems.

A study developed a coating that could eliminate 100% of the Escherichia coli population in fresh cheese, using alginate, citric acid, erythrosine, and photodynamic therapy (PDT), in which the addition of citric acid made the coating more rigid, with lower elongation and higher thickness, in addition to lower permeability to water vapor. Thus, it was possible to produce a resistant coating in the presence of this acid [25].

Aloe vera gel at 15% increased the density and thickness of the carrageenan coating applied to kulfi ice cream [73]. Thickness is a variable that allows the homogeneity of films to be assessed and affects barrier properties [76]. This application of the coating was stable for six months of storage.

Data from studies on the effects of applying edible coatings demonstrate that, when well polymerically established, these materials are versatile, can be used in all types of foods and preparations, and are promising for extending shelf life and promoting better food preservation. Bioactive compounds with antioxidant and antimicrobial action associated with the coating are the elements that effectively contribute to the reduction of oxidative reactions that can compromise the nutritional and sensory aspects of the food and the reduction of the growth of microorganism colonies to an increased food safety period. It is important to reduce food waste and save or even replace other industrial technological resources that would be used to extend the shelf life of foods.

It is necessary to perform additional research to replace the plastics and clarify future concerns. Some issues related to edible coatings are toxicological and sanitary safety, as well as controlling production costs.

Although many edible packaging uses natural ingredients, it is essential to investigate the toxicity and the possibility of allergies related to the components present in their formulations. Nanotechnology, a technology used in active coatings, is a promising area for edible coatings, however, there are still not enough studies on the toxic effects [11]. An example related to possible allergies concerns the use of whey and dairy products, which are considered allergenic for some people [77]. This investigation must follow packaging regulations.

An alternative in question for reducing costs in the production of edible coatings is the use of biopolymers extracted from agro-industrial waste, as well as encouraging the reduction of food waste and reducing environmental impact. Fruit and vegetable waste (skin, bark, bagasse, among others) constitute a source of bioactive compounds, phenolic compounds, proteins, and polysaccharides. However, due to the heterogeneity of each batch of food waste, standard procedures regarding composition, hygiene, and safety are necessary and must be conducted in a cost-effective manner [5]. Another important consideration regarding edible coatings is related to the protection of this coating against various sources of contamination, as it may be edible, and this level of security must correspond to other biodegradable packaging, such as materials such as cellulose, originating from reforestation.

5. Conclusions

Edible coatings have enormous potential and benefits in the food industry. In addition to increasing the shelf life of food and having antimicrobial and antioxidant effects, these coatings also promote the protection of the environment by reusing materials that contribute to the circular economy and reducing waste.

According to the articles studied, many materials can be used as a base for edible coatings, such as alginate, carrageenan, chitosan, fruit pulp residue, sodium caseinate, and chia mucilage, whey protein of milk, together with bioactive compounds, respectively, citric acid, aloe vera, essential oils of thyme or oregano, Chinese cinnamon bark, and probiotic bacteria. In addition to having antimicrobial and antioxidant effects, these coatings can preserve nutrients, increase shelf life, reduce losses, and even improve the sensorial quality of food.

From the data evaluated in these studies, there was a higher frequency of positive impact to improve the quality and appearance of fruits and vegetables, and a higher frequency of antimicrobial effects evaluated in products of animal origin. There are still limitations in the research that highlight issues of sustainability of coatings. Despite this characteristic, it is of fundamental importance for promoting studies to develop different edible coatings.

In conclusion, edible coatings show promise for the food industry, offering benefits for both products and the environment. However, more studies are needed to fully explore their potential as replacements for conventional plastics while ensuring safety and regulatory compliance.

Author contributions

The authors confirm contribution to the paper as follows: study conception and design: Le, S. S. F.; Matos Pinto, L. C. Fonseca, M. C. P.; Boa Morte, E. S.; data collection: Le, S. S. F. analysis and interpretation of results: Le, S. S. F.; Fonseca, M. C. P.; Andrade, L. L.; Matos, M. F. R.; Pinto, L. C.; draft manuscript preparation: Le, S. S. F.; Boa Morte, E. S.; Matos Pinto, L. C. English Review: Allahdadi K. J.

Conflict of interest

The authors declare that they have no conflict of interest.

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