Chapter 9
Biopolymer Nanocomposites in Edible Food Packaging: Opportunity and Applications

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9.1 Introduction

The biopolymer nanocomposite is recognized as a green material, consisting of a biopolymeric matrix reinforced with inorganic or organic nanofillers (having one dimension in the size ranges of 10–100 nm), which gives an opportunity to replace the existing packaging materials. However, composite film as a group of hybrid material generally consists of two or more different materials exhibiting distinct attributes in terms of chemical or physical property, where the composite films offer superior characteristic properties in comparison with the individual one. By going with the current trends toward a sustainable future, the fabrication of biopolymeric nanocomposites has been considered as one of the most researched materials to replace synthetic plastic materials in food packaging applications. Interestingly, the use of polymer nanocomposites has gained an extreme enthrallment in the area of edible films and coatings for the improved shelf life of high perishable food products [1, 2]. In this regard, the selection of materials in the form of composites, blends, and individual use should have a biodegradable nature similar to the food materials. Interestingly, biopolymeric composite materials and nanohybrids are an industrially viable candidate with wide availability to be used in developing edible food packaging materials with excellent attributes and can be fortified with nutritional components such as fiber enrichment, mineral enrichment, and vitamin enrichment, and further other nutraceuticals can also be added through nanostructured materials. Additionally, the functionality in edible packaging can be attained using several components such as (1) nanofillers, (2) plasticizers, (3) functional additives, (4) binding agents, (5) purees, juice and extract of fruits, and vegetables, and (6) others. Based on this, the current chapter discusses the several biopolymer

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nanocomposite-based packaging properties in terms of physical property, barrier property, surface property, mechanical property, thermal property, and others. Additionally, the recent advances of biopolymer composite in developing edible films and coatings with the multifunctional attributes have been detailed in the present chapter. The synthesis strategies for attaining improved properties of biopolymer composite including the use of binding agents, cross-linkers, plasticizers, functional additives, compatibilizers, and others have been addressed in the current chapter. Interestingly, the effective properties of biopolymer composite include metal ion releasing property, defensive mechanism, and other benefits.

9.2 Overview of Biopolymer Nanocomposite in Edible Food Packaging

The plastic packaging is easily processable and has received a great attention for the last 50 years for several noteworthy benefits. However, the waste management and utilization are a serious problem from the past few years; thus, the use of synthetic plastic is getting reduced tremendously, and several innovative eco-friendly packaging solutions are researched and developed for greener future. The focused packaging attributes for developing edible food packaging include barrier properties, mechanical properties, thermal properties, antimicrobial properties, functionality, and other health benefits. The incorporation of nanomaterials in packaging systems modifies the packaging attributes to offer noteworthy properties and an improved product life of perishable food products such as fruits and vegetables, meat and meat products, fish and fish products, and dairy products. Interestingly, the nanocomposites have received a great interest in research and developments and for wide commercial packaging applications for being the solution of several socio-environmental issues. In this regard, the polysaccharide and lipid-based composite films are developed with the aim to reduce moisture migration with improved water barrier properties. The edible polymers-based composites are used as the alternatives to the existing synthetic polymers. The polymer composite films of hydrocolloids and lipids provide a barrier against gaseous components. The several polymer composites used in edible films and coatings include hydroxypropyl methylcellulose (HPMC)–lipid composites for *mandarins* cv. fortune [3], gelatin–chitosan composite for fresh-cut melon [4], gum arabic and chitosan composites, etc. However, to combat the current need for developing sustainable packaging materials, the organic and inorganic nanofillers have been mostly utilized to develop biopolymeric nanocomposite-based edible food packaging. As mentioned in the earlier chapters, the most investigated polysaccharide-based bio-nanomaterial includes nanocellulose, nanochitosan, nanostarch, and others. The inclusion of several categories of nanomaterials influences the composite properties in terms of physicochemical and structural properties and also provides versatility in nature. However, the higher production cost and longer processing time for the fabrication of nanostructured materials and their nanocomposites may put limitations in developing edible food packaging materials for highly perishable food products, minimally processed food products, and others. The polymer nanocomposite can be tailor-made in terms of diverse surface functionality and packaging properties to be used in the edible food packaging sector. However, the noteworthy properties of nanofiller materials such as surface area, surface functionality, and aspect ratio make it a potential candidate in edible films and coatings. The edible food packaging includes use of mineral nanoparticles, metal nanostructures, bionanostructures for developing edible food packaging. Additionally, in Fig. 9.1, the several aspects of biopolymer composite in edible food packaging in terms of eco-friendly nature, packaging properties, active functions, delivery system, improved food properties with the focused application have been displayed. The existing versatility of biopolymer composites such as functionality, concentration-dependent properties, nanofiller-dependent, and others provides a boom in industry and edible packaging sector. The biocomposite materials are focused to use as a high-performance edible food packaging materials such as (1) strong films, (2) edible active packaging, (3) drug-loaded edible packages, (4) lightweight materials, (5) ready-to-eat edible packaged food, (6) water-soluble edible packaging, and (7) others. The biopolymers have some disadvantages of brittleness, poor moisture barrier properties, and low processing ability and others [5]. Further, the main aim toward developing nanocomposite-based edible films and coatings is gas impermeable property, mechanical strength, thermal stability, structural property, etc., obtained due to the nanometer size dispersion of reinforced materials in matrix. Further, the biocomposite-based edible films and coatings can be a source to supply nutraceutical rich and fresh, good-quality ready-to-eat fruits for beneficial human health.

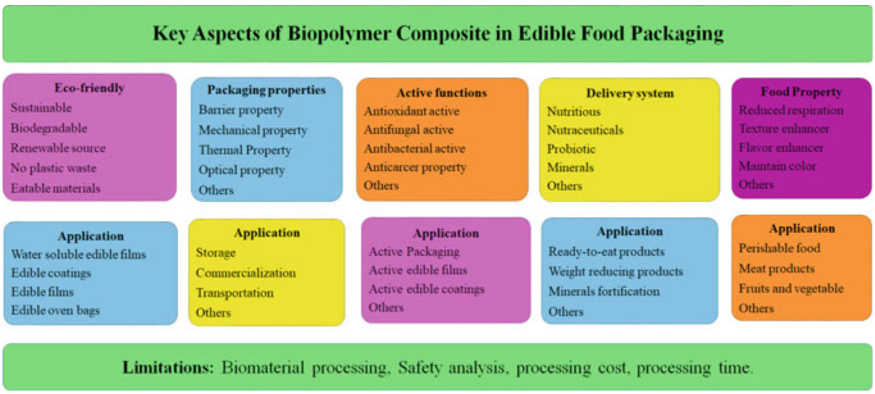

Fig. 9.1 Key aspects of biopolymer composite in edible food packaging

9.3 Application of Biopolymer Composite in Food Sectors and Others

From the last few decades, the use and availability of polymeric composites have increased in several fields including both edible and non-edible food packaging. In food sectors, biopolymer composites are used in (1) nutrition: nutrient delivery system, nutraceuticals, vitamin fortification, mineral fortification, improved sensory of food products, food rheology, etc., (2) protection in food products: antimicrobial delivery, high barrier, edible sensors, UV protection, etc., (3) food processing: nanoencapsulation, nanoemulsions, viscosifying agents, nanoadditives, gelation agents, etc., and (4) packaging sector: edible and non-edible food packaging. However, the multifaceted application of polymer biocomposite includes food packaging, biomedical application, textile industry, construction materials, electronics materials, and other high advanced applications [6–12]. The biomedical application of polymer composite includes scaffolds for tissue engineering, bone repair and fixation device, drug delivery, industrial application, hard tissue replacement, paper coating, textile, green adhesive and structural application, water filtration, etc. The various bioplastics for non-edible packaging are polylactic acid (PLA), polyhydroxybutyrate (PHB), polybutylene succinate (PBS), and their derivatives.

9.4 Biopolymer Nanocomposite Systems in Edible Food Packaging

The biopolymer composites for targeted edible films and coatings are functionalized for improved compatibility and better interaction between matrix and filler materials. The several attributes of nanofiller, matrix, and biocomposites are represented in Fig. 9.2. The multifunctional properties in edible packaging are obtained using versatile nanomaterials such as mechanical property, thermal property, antibacterial property, and barrier property. The effectiveness of nanostructured materials is

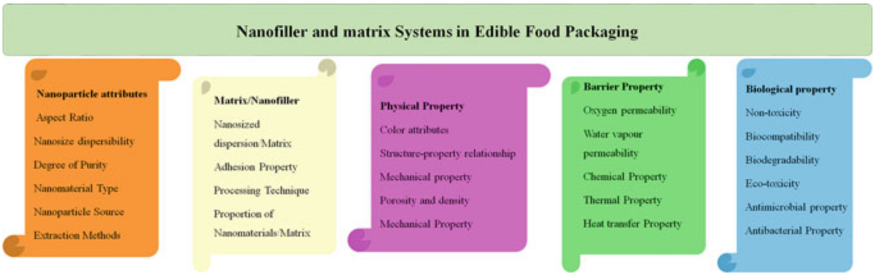

Fig. 9.2 Biopolymer nanocomposite in edible packaging

aspect ratio, nanosized dispersion/matrix adhesion property, degree of purity, moisture content, nanomaterial type, nanoparticle source, dimensions, extraction methods, processing technique, proportion of nanomaterials and matrix, etc. However, the important consideration in designing and application of polymer biocomposite includes concepts, materials, processing, and others. In this regard, the nanomaterials with antimicrobial active property have attracted a great interest and an emerging field of application in edible food packaging sectors. Besides, polymeric nanocomposites in different forms such as films, coatings, and foams are utilized to develop edible packaging materials. The usability of polymeric nanocomposite in the field of edible food packaging acts as a promising candidate to improve the product attributes, reduces the synthetic packaging waste, preserves food products, and also increases the storage life. In this regard, the fabrication of biopolymeric nanocomposites and nanohybrids provides a great consideration for developing edible packaging with high performance in terms of several packaging attributes including barrier property, mechanical property, physical property, antimicrobial property, and others. The several polymorphs of polymeric nanostructured materials also influence the composite properties, such as the crystal structures, morphology, degree of hydrogen bonding, and others. In this regard, cellulose nanocrystal (CNC) polymorphs influence the properties of biocomposite-based polymer properties such as barrier property, mechanical property, thermal property, and structural attributes [13]. The different dimensions of nanofiller materials such as spheres, fibers, particulates, and flakes influence the packaging attributes. The worldwide status of preparing nanosystem-assisted edible food packaging provides a motivating way to develop new polymeric composite materials for targeted edible food packaging materials. The several disadvantages of polymer nanocomposites for improper reinforcement include poor dispersion, non-optimum proportion, weak interface, random structure, and others. The benefits of developing polymer nanocomposites for targeted edible food packaging are aligned structure, well-dispersed composite, better surface interaction, etc. The use of biopolymeric nanofibers, nanocrystals, and nanoparticles has the capability to create a percolation network within the matrix and help to increase the stability of the film. The polymer nanocomposite involves the use of nanometer size dispersion which delivers biofunctional attributes to the composite materials for developing edible food packaging. The use of hydrophobic agents in biopolymeric nanocomposites such as glycerol and other antimicrobial agents improves the edible packaging attributes in terms of physical, mechanical, barrier, and other functional properties. The inorganic nanomaterials in developing biopolymer composites are generally used as additives in biopolymer matrix to improve the shortcomings of biopolymer composites. The other important attributes of biopolymer which are obtained by reinforcing nanofillers are dimensional stability, gas resistance property, tunable surface property, transparency, etc. However, the main aspects of developing bionanocomposites are biodegradability, renewable resources, acts as a carrier of antimicrobial agents, enhanced shelf life, reduced volume, weight and waste of packaging, etc [14].

9.4.1 Physical Properties

The physical properties of polymer nanobiocomposites-based packaging materials include molecular weight, crystallinity, degree of polymerization, density, molar volume, and others. Further, the binary films for developing edible films and coatings are polysaccharide–protein, protein–protein, polysaccharide–polysaccharide, lipid-added polymeric nanocomposite, and others. In this context, polymeric complex-based films have attained a great effectiveness in developing bilayer films to improve the property of perishable food products and others. The use of plasticizers in the fabrication of biopolymer nanocomposite also provides tunable properties in developing edible food packaging. The inclusion of biopolymeric nanofibers in fabricating polymeric nanocomposites provides improved mechanical properties such as tensile strength, thermal properties, optical properties, and others [1]. The gelatin-based edible films have poor mechanical properties, where the incorporation of nanofillers such as cellulose nanocrystal (CNC) and bacterial cellulose nanocrystal (BCNC) to develop biocomposite can improve the mechanical property such as tensile strength and tensile modulus. The improved mechanical property of the gelatin biocomposite films is attributed due to the high crystallinity of cellulose nanomaterials. As discussed in Chap. 3, the noteworthy properties of nanocellulose in terms of dimension, mechanical strength, functionality make it a potential nanofiller to be used in developing biocomposite-based edible films. The tensile strength of BCNC-reinforced gelatin films is $\sim 83.7 \pm 3.2$, $\sim 88.7 \pm 4.8$, $\sim 95.1 \pm 3.9$, $\sim 103 \pm 4.7$, and $\sim 108.6 \pm 5.1$ MPa, respectively, for 0, 1, 2, 3, and 4% BCNC content. Additionally, the tensile modulus of BCNC-reinforced gelatin films is $\sim 2189.5 \pm 50$, $\sim 2225.3 \pm 63$, $\sim 2272.8 \pm 68$, $\sim 2335.1 \pm 59$, and $\sim 2350.4 \pm 65$ MPa, respectively, for 0, 1, 2, 3, and 4% BCNC content [15]. Further, the mechanical performance of some polysaccharide-based films such as pullulan can be tailored using functional agents, essential oils, metal nanoparticles, and others. The physicochemical attributes of biopolymers can be improved using nanoclays (montmorillonite), where the dispersion of this kind of nanofillers can be improved by applying sonication. Further, the application of sonication in some nanofiller dispersion helps to avoid the agglomeration property of nanoreinforcements in matrix for developing edible films and coatings.

9.4.2 Barrier Properties

The water barrier properties of polysaccharides are commonly enhanced by developing composites with hydrophobic compounds such as fatty acids and mixture of lipids. The alginate is used to develop film where the film properties are associated with the formation of strong gel, when multivalent metal cations (such as calcium ions) are present. Interestingly, the interactions between carboxylic group of alginate and calcium ions help to form a cross-linked network. The alginate-based coating materials are found to have low oxygen permeability and can be added to other biopolymers having poor oxygen barrier properties. Further, the water vapor permeability of polysaccharide-based nanocomposites can be tailored using nanomaterials such as cellulose nanomaterials and others. The fruit puree-based films can also provide improved barrier properties when nanofillers are incorporated to develop polymer nanocomposite films. The fish protein has the ability to form networks which provide improved packaging properties such as good oxygen barrier properties, whereas the poor water vapor permeability of fish protein can be tailored with the aid of nanofiller materials.

9.4.3 Functional Attributes

The functional attributes of polymer biocomposite-based edible films and coatings can be improved using metal oxide-based nanofillers. The metal oxides are commonly used to provide antimicrobial, antiradiation, antibacterial, and other properties. The matrix and filler interaction can be tailored via electrostatic interaction, hydrogen bonding, and others. However, the metal oxide should be used in optimum concentration; otherwise, there may be an agglomeration within the matrix, which may result in discontinuity in films and coating properties and film network structure. The bioactivity of some polysaccharide films can be improved using several functional agents. Additionally, the several proteins such as gelatin, lysozyme, casein, and soy proteins are used as a blend or nanocomposite to provide functional packaging. The various biological activities of edible films and coatings are antioxidant, antimicrobial, antibacterial, anti-inflammatory, antihydrolytic activity, antiviral, antitumor, and others.

9.4.4 Antimicrobial Properties

The different types of antimicrobial agents widely used in nanocomposite-based edible films and coating include fatty acid esters, organic acids, polypeptides, bacteriocins, plant essential oils, and sulfites. The antimicrobial properties of polymer nanocomposite for targeted edible food packaging commonly involve the use of inorganic nanofiller materials such as titanium dioxide, zinc oxide, iron oxide, silver nanoparticles, and others. However, the inorganic nanofillers for developing edible packaging should be within permissible limits. The metal oxides are extensively used to deliver antimicrobial attributes to edible films and coatings. Additionally, titanium dioxide is effective against allergens and foodborne microorganisms. On the other hand, the polycationic nature of chitosan and nanochitosan has an ability to make a conjugate with other components, which helps in improving the antimicrobial property of chitosan. However, the antimicrobial activity of nanochitosan is better than chitosan. Additionally, the antimicrobial activity of chitosan nanoparticle is found to be increased when metals are loaded such as silver nanoparticles. Additionally, the small-sized silver nanoparticles provide better antimicrobial property than large-sized silver nanoparticle; thus, silver nanoparticles are widely utilized to develop biopolymer composites to be used as edible films and coatings. Besides, the active components used for developing edible films and coatings are N-acetylcysteine, glutathione, cinnamon oil, rosemary oil, lemongrass essential oils, palmarosa essential oils, ascorbic acid, silver–montmorillonite nanoparticles, citric acid, sodium benzoate, α-tocopherol, potassium sorbate, sodium benzoate, nisin, trans-cinnamaldehyde, etc. The incorporation of antimicrobial agents in biopolymer nanocomposites makes it a remarkable candidate against microbial spoilage to improve the shelf life of food products.

9.4.5 Surface Properties

The application of nanocomposite-based edible coating helps to reduce the oil uptake, reduce water loss, improve sensory property, reduce fat contents, and better nutritive contents in fried food products. The bionanocomposite-based edible coatings are considered as a potential candidate to deliver functional compounds, which reduce the oil uptake ratio [16]. The various coating materials used for reduced oil uptake ratio include egg white, gelatins, sodium caseinate, soy protein isolate, wheat gluten, whey protein isolate, whey protein concentrate, etc.

9.5 Recent Advances of Biopolymer Nanocomposites in Edible Food Packaging

The unique properties of nanostructured materials in terms of mechanical, optical, surface property, nutritional attributes, and others make them a potential candidate in developing bionanocomposite-based edible food packaging with tailor-made properties for highly perishable food products (Table 9.1). The development of edible coatings on acerola fruit and edible films using acerola puree, alginate, cellulose whisker (CW), or montmorillonite (MMT) as a nanofiller provides reduced water vapor permeability of films and coatings on fruit and helps to reduce the weight loss of fruit and ripening rate [17]. The edible nanocoatings based on the nanocomposites of xanthan gum, zinc oxide, and stearic acid have superior antibacterial property and have non-toxic nature [18]. Additionally, the application of this kind of edible nanocoating on apples and tomatoes has negligible weight loss at ambient conditions. The nanocomposite-based edible biodegradable films developed using carboxymethyl CNC and cassava starch have improved mechanical, physicochemical property and provide a cohesive structure to the developed films, where the use of carboxymethyl CNC (0.4 g/100 mL) and cassava starch improves the mechanical property in terms of tensile strength by 554% and water solubility by 123% [19]. The nanocomposite edible films based on HPMC, beeswax, clay, thai essential oils (ginger, finger roots, plai) have a good antimicrobial property and can be used as an active coating for agricultural produces [20]. The HPMC and chitosan/tripolyphosphate (TPP)-based edible films are also preferable due to offering enhanced mechanical, barrier, and thermal stability in comparison with the neat HPMC films [21].

Moreover, the use of fish protein and organo-clay (montmorillonite)-based nanocomposite as an edible coating material on fresh-cut papaya (minimally processed) improves the quality in terms of weight loss, color, microbial count, firmness, lightness during storage (12 days and 5 °C) [22]. Additionally, the edible films based on nanocomposites of *Salvia macrosiphon* and nanoclay are a kind of antimicrobial films and provide improved physical, thermal, and mechanical property [23]. Further, the addition of nanoclay increased the hydrophobicity of *Salvia macrosiphon* seed mucilage films, which can act as a replacement for food packaging materials. The development of edible coating using silver–chitosan-based nanocomposite on fresh-cut melon provides better keeping quality (storage condition: 13 days and 5 °C) such as reduced respiration rate, better sensory property, and reduced mesophilic count, and also enhances the shelf life of fresh-cut melon [2]. The application of coating on cashew nut kernels using starch, cashew tree gum, and nanoclay helps to reduce the moisture loss, from cashew nut and also a good coating material in extending the stability of cashew nut kernel [24]. On the other hand, the pullulan and lysozyme nanofibers-based nanocomposite films have good mechanical attributes of films (Young's modulus of 1.91–2.50 GPa), good thermal stability till 225 °C, antioxidant activity in terms of 2,2-diphenyl-1-picrylhydrazyl (DPPH) scavenging activity of 77%, antibacterial activity against *Staphylococcus aureus*, and others [25]. Further, the nanocomposite edible films based on whey protein isolate and titanium dioxide have water vapor permeability of $\sim 3.19 \times 10^{-10}$ g s^{-1} m^{-1} Pa^{-1}, 2.89×10^{-10} g s^{-1} m^{-1} Pa^{-1}, and 2.92×10^{-10} g s^{-1} m^{-1} Pa^{-1}, respectively, for 0, 1, and 2 w/w % of titanium dioxide [27]. Similarly, the nanocomposite edible films based on whey protein isolate and titanium dioxide have solubility of $\sim$17% and 15%, respectively, for 0, and 1 w/w % of titanium dioxide [27].

Table 9.1 Biopolymer nanocomposite-based materials for edible food packaging as edible films and coatings

Sl. no	Components	Type of packaging	Property	References
1.	Fish protein	Edible coating on minimally processed cut papaya	Low cost	[22]
	Nanoclay		High shelf life	
			Maintained quality of minimally processed cut papaya	
			Improved appearances	
2.	Silver–chitosan nanocomposite	Edible coating on fresh-cut melon	Reduced shelf life	[2]
			Better sensory quality	
			Reduced mesophilic count	
			A potential coating for fresh-cut fruit products	
3.	Acerola puree	Edible coatings on acerola fruit and edible films	Provide reduced water vapor permeability of films	[17]
	Alginate		Coatings help to reduce the weight loss of fruit	
	CW		Coating helps to reduce ripening rate	
	MMT		Coating also significant in retaining ascorbic acids	
4.	Gelatin	Edible films	Improves mechanical property	[15]
	BCNC		Improve thermal property	
			Reduce moisture affinity of gelatin	
5.	Starch	Edible coating for cashew nut	Use of MMT improves the moisture barrier attributes	[24]
	Cashew tree gum		Improved oxidative stability of kernels	
	MMT		Improve mechanical property	
			Provide reduced moisture content of coated cashew nut (120 days storage)	
			Decrease textural changes of coated cashew nuts	
6.	Whey protein isolate	Edible films	More than 70% visible light can be blocked	[26]
	Titanium oxide		More than 90% UV light can be blocked	
			Tailored tensile properties of the nanocomposite films	
7.	HPMC	Edible films	The nanocomposite films with plai and finger root-based	[20]
	Thai essential oils (ginger,			

(continued)

Table 9.1 (continued)

Sl. no	Components	Type of packaging	Property	References
	finger root, plai)		essential oils increase the oxygen permeability	
	Organically modified clay		A kind of active packaging	
	Beeswax			
8.	Pullulan	Active edible food packaging	High mechanical performance	[25]
	Lysozyme nanofibers		Thermal stability	
			Antimicrobial property	
			Antioxidant property	
9.	Cassava starch	Biodegradable edible films	Improved physicochemical property	[19]
	Modified CNC		Improved barrier property	
			The bionanocomposite film has cohesive structure	
			Can be a potential candidate in developing water-soluble films	
10.	Salvia *macrosiphon*	Edible nanocomposite films	Increased hydrophobicity	[23]
	Nanoclay		Improved mechanical and thermal property	
	Glycerol		Antimicrobial films	
11.	Xanthan gum	Edible nanocoatings	Superior antibacterial property	[18]
	Zinc oxide			
12.	Chitosan/TPP nanoparticles	Edible films	Improved barrier property	[21]
	HPMC		Improved mechanical property	
			Improved thermal property	

CWCW Cellulose whisker; *MMT* montmorillonite; *BCNC* bacterial cellulose nanocrystal; *CNC* cellulose nanocrystal; *TPP* tripolyphosphate; *HPMC* hydroxypropyl methylcellulose

9.6 Application of Nanotechnology in Edible Food Packaging

Considering the environmental concerns associated with the consumption of conventional plastics, biobased polymers have found application in the food packaging industry because of their inherited sustainability and biodegradability [27, 28]. Recent exploration of nanotechnology in edible packaging promises fascinating improvement in the safety and quality of food by improving its mechanical strength, barrier properties, and shelf-life. However, food packaging derived from natural polymers has limitations in terms of barrier properties and mechanical strength; thus, the preparation of a protective edible coating involves blending of the edible polymers with other components, basically bioactive agents and plasticizers and

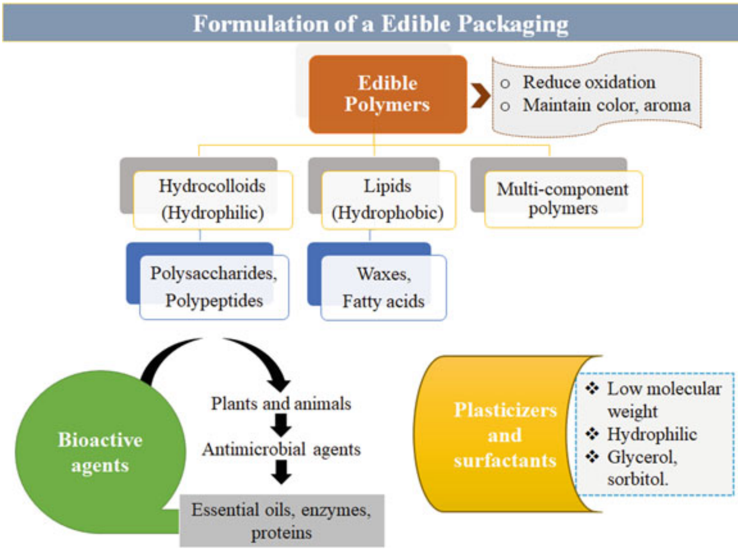

Fig. 9.3 Formulation of a protective edible packaging

surfactants, as shown in Fig. 9.3 [29]. Edible coatings are thin layers applied on the food surface, either by spraying, solvent evaporation, immersing the food into a coating solution or by rubbing the food with the coating material to maintain the features and properties of the food, thereby increasing their shelf life. These edible coatings should be compatible with the food on which they are applied, in an organoleptic manner, and do not always require to be removed from the food surface before consumption [30].

Nanotechnology involving the use and incorporation of the nanomaterials in the preparation of edible coating helps to enhance the barrier properties, antioxidant activity, and mechanical stability which thereby eliminates packaging waste and improves the shelf life [31]. Figure 9.4 discusses the various attributes which are expected to improve with the introduction of nanotechnology in the food packaging industry. With the intention to improve the quality of edible food packaging, nanomaterials play an important role in the preparation of the packaging material. The nanomaterials, often considered as functional materials, possess one of their dimensions in nanometer scale (nm) and are basically categorized as nanoparticles (NPs), nanocrystals (NCs), nanofibers (NFs), nanocolloids, micro- and nanoemulsions [32]. Based on their preparative techniques, distinct physical properties of nanoparticles could be achieved and accordingly they are used in the food industry.

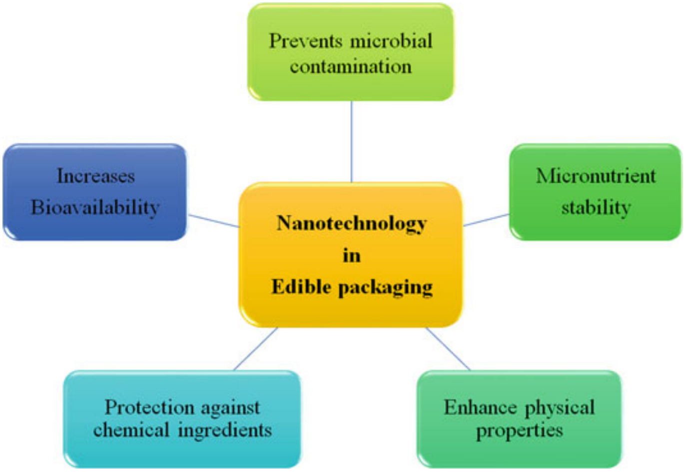

Fig. 9.4 Functionality of nanotechnology in edible packaging

9.6.1 Nanosystems in Edible Packaging

Nanotechnology opens new doors of possibilities in food industry basically in edible packaging by promoting the transport of essential oils and fat-soluble vitamins, incorporated with antimicrobial properties, thus improving the mechanical stability and transparency of edible coatings with the easy transport of gas molecules. The nanometer ranges of materials used in nanosystems make them more stable and do not alter the organoleptic property of the food; also, their higher aspect ratio enables the bioavailability or mobility of the encapsulated nutrients as compared to microsized particles [33].

The nanosystems used in edible packaging basically involve polymer nanoparticles, solid–lipid nanoparticles, nanofibers, nanotubes, nanocrystals, and their nanoemulsions; these nanosystems when embedded into the polymer matrix are commonly termed as polymer nanocomposites and act as a barrier in the controlled release of components to the environment. Polymeric nanosystems with different properties are formulated with the help of nanotechnology/edible coating technique, which encapsulates bioactive molecules and when incorporated in edible packaging acts as preservatives, food enhancers, and nutrient supplements. In this regard, some of the nanostructured materials such as nanocapsules, nanosphere, nanoemulsions, nanofibers, nanoparticles, and organic/inorganic nanofiller have been represented in Fig. 9.5.

Polymeric Nanoparticles. Depending on their structure and morphology, polymeric nanoparticles are categorized as nanospheres and nanocapsules. In nanospheres, bioactive molecules are trapped and dispersed into the polymer matrix, whereas in nanoencapsulation oil core in which the bioactive molecules are retained is surrounded by a polymer membrane. The selection of polymer plays a

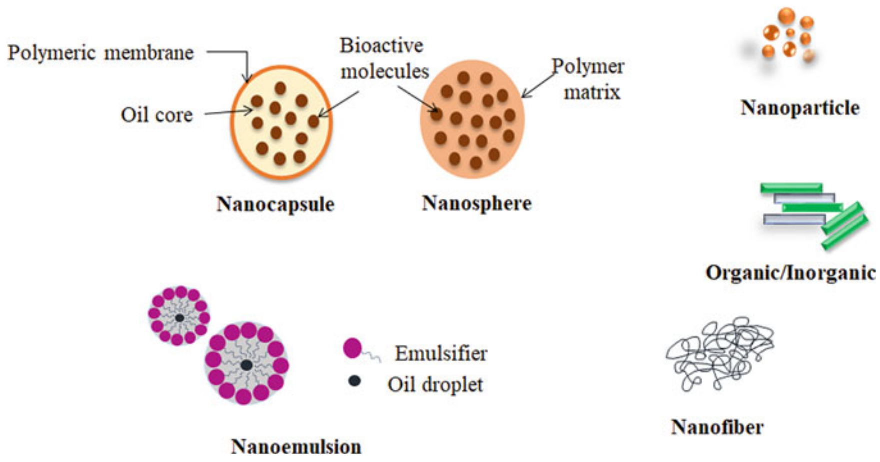

Fig. 9.5 Nanostructured materials for biopolymeric composite-based edible food packaging

critical role in both nanosphere and nanocapsule systems, such as encapsulation efficiency, release of the bioactive component, protection ability, and degradation process. Polymers commonly used in the food industry for the preparation of polymeric nanoparticles are polylactic acid, poly(ε-caprolactone), chitosan, and alginate [30]. Synthesis of chitosan nanoparticles and their application in edible packaging has been widely practiced recently due to the biodegradable, biocompatible, non-toxicity, and natural abundance of chitosan [28]. Because of its solubility in water at lower pH, film-forming ability, and antimicrobial, chitosan is the most widely practiced polymer in edible packaging industry. The edible coating of chitosan can be prepared by dip coating or simply by spraying the chitosan nanoparticle into freshly cut fruit. Curcumin, a common type of polyphenol with its inherent antioxidant and antimicrobial characteristic, acts as an active molecule which can be easily incorporated into nanocapsules in edible packaging. Essential oils are largely used in the preparation of edible coatings because of their antimicrobial activity, and some of the common examples are lemongrass oil, turmeric oil, peppermint oil, etc [30]. The utilization of nanotechnology in the food packaging industry has an exceptionally advantageous impact on the society in terms of reduction of environmental impact, cost-effectiveness, and lower energy consumption. However, depending on the ethical responsibility of using these nanomaterials in edible packaging, a better knowledge of the effects of these materials on the health and environment has to be considered [31].

9.7 Synthesis Strategy for Modification of Polymer Composite

The interest in the utilization of polymer nanocomposite in edible food packaging is tremendously increasing. The demand of supplementing natural and acceptable food packaging, built on economically feasible, effortlessly processed, accessible, and ready-made fresh foodstuffs, has given rise to an increase in customer needs for healthy and high-grade quality food product [32]. To meet up with these consumer requirements and improvements of the quality of edible food packaging, certain strategic modifications are shown in Fig. 9.6. These trends lead to the variations in the normal procedures of food processing. The growing interest to get food products with an extended storage life, with improved properties related to the packaging materials, leads to the preparation of polymer composites blended with active agents, functional additives, plasticizers, cross-linkers, and compatibilizers among other things [1]. This will result in better edible packaging products.

9.7.1 Binding Agents

A binder or a binding agent is a kind of material that tends to hold components of the polymer composites together to improve its mechanical and chemical properties. Commonly, the interfacial linkages in nanocomposites are a critical concern; thus, the interface of the polymer matrix with the filler (nanoparticles) needs to be interacted strongly, which can alter the polymer flexibility and mobility. This indicates that to improve the interaction and reduce the chain, use of a food-grade binder can be effective in edible food packaging. Especially, to maintain the mechanical and barrier properties, the use of binders and compatibilizers serves as a good candidate for edible packaging [33]. In this regard, the surface-active substance provides a route toward linking the chains within the polymer composite; this results in stronger mechanical behavior, increased texture, glossiness, and surface smoothness [34]. These can be obtained by using different types of binding agents such as gluten, gums, agar, gelatin, and starch jellies. Additionally, the

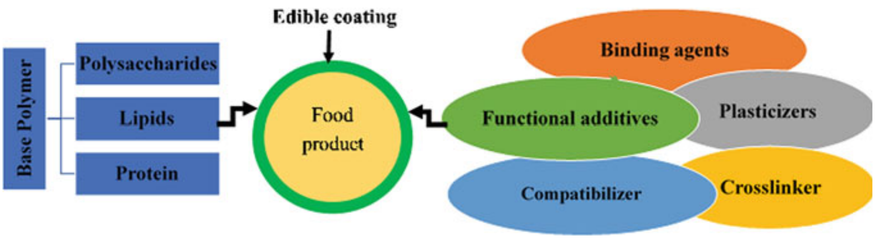

Fig. 9.6 Edible polymer composite constituents

binding agent is essential for the stabilization, thickening, and networking of the polymer composite chains [33]. Thereby, a binding agent serves as an important agent in the modification of edible food packaging to boost the physical, mechanical, chemical, and handling characteristics to deliver desired functionalities of the films and the products.

9.7.2 Plasticizers

Plasticizers are additives used for modification and improvement of the edible food packaging. Many polymeric materials used for packaging and film coating are stiff in nature. To resolve this challenge, plasticizers are blended to tailor the plasticity and pliability of the film [35]. This is achieved basically by reducing the intermolecular forces and intensifying the motion of polymer chains, which in turn tends to enhance the mechanical characteristics of the edible polymer composite. The use of plasticizers in the fabrication of biopolymer nanocomposite also provides tunable properties in developing edible food packaging [1]. Common plasticizers for improving the polymer composites for edible food packaging and layers are comprised of polyols, oligosaccharides, monosaccharides, lipids, and derivatives. Although plasticizers improve the plasticity, mechanical properties and reduce the friction during handling, and it also increases film permeability which affects the barrier properties. Therefore, a suitable selection of plasticizers for a specific material would enhance the performance of the films and also help to achieve the desired effect with the least permeability. Hence, the choice of plasticizers is governed by many factors such as plasticizer's compatibility, effectiveness, stability, and cost, while the performance of the plasticizer depends on the type, concentrations, interactions between the plasticizers and the polymer matrix, etc [36]. Based on these, the suitable selection of plasticizers can deliver effective film properties for targeted application.

9.7.3 Cross-linkers

The chemical networking agent is known as cross-linkers and is beneficial in modifying polymer composites. The reduced polymer movement and effective attributes of polymers can be obtained by the application of cross-linkers via chemical, physical, or biological treatment [35]. The properties of polymer composite film are determined by the chemical and physical nature of the constituent polymers. Most individual polymers have distinct characteristics. To achieve a desired edible food packaging, film, and coating, a blend of polymer composite with different desired properties is required to attain, where the improved functionality is an essential factor and cross-linkers have a remarkable role in this regard. The improved synergetic interaction can be obtained between the different components of the polymer composites using cross-linkers. Thus, cross-linkers are introduced to generate firm networking assembly of the polymer chains for enhancing perpetual characteristics within the polymer composite [37]. The chemical bonding generated by covalently bonded polymer chains generally forms firm network together. Hence, they normally do not split or soften in aqueous solutions. The characteristics of the subsequent polymer composite after the introduction of cross-linkers depend on the degree of the cross-linking pattern. Various networking agents have been utilized as cross-linkers in the processing of edible polymer composite for packaging and coatings such as formaldehyde, glutaraldehyde, carbodiimides, genipin, glyoxal, and transglutaminase. Among all, formaldehyde, the common networking agents, has the widest chain linking specificity. Though formaldehyde encompasses a single functional group, it can link in more than single reaction and consequently cross-link the targeted compound [38].

9.7.4 Functional Additives

Functional additives are groups of organic or inorganic substances incorporated into polymer biocomposite to enhance the functional attributes of edible films and coatings. This can be attained by the application of metal and metal oxide-based nanofillers. The metal oxides are commonly used to provide antimicrobial, antibacterial, antiradiation, and other properties. The polymer matrix and filler interaction can be tuned through different interactions, like hydrogen bonding, and others to achieve the desired outcome. Biopolymer nanocomposite and nanoparticles have advantageous applications in the food and other related manufacturing companies. This is because they have the tendencies to be used as a health-benefitting delivery system, encapsulating candidates, texture agents, and lightening modifiers [39]. The functional additives are also applied to serve as bioactive ingredients. In some instances, specific reactive agents or catalytic agents are imbedded as modifiers. Furthermore, some class of polysaccharides (dietary fibers) has been revealed to possess health-benefitting attributes, like reduction in cholesterol, prevention of cancer, or general improvement in human well-being [40]. Therefore, ingesting of biopolymer nanoparticles loaded with the polysaccharides may benefit human well-being. However, the bioactivity of some polysaccharide films can be improved using several functional agents. Additionally, various proteins such as gelatin, lysozyme, casein, and soy proteins are used as a blend of nanocomposite to provide functional packaging. The various biological activities of edible films and coatings such as antioxidant, antimicrobial, antibacterial, anti-inflammatory, antihydrolytic activity, antiviral, antitumor, and other benefits can be obtained [41]. Consequently, increased attention is generated toward the advancement of numerous types of functional biopolymer additives for viable applications.

9.7.5 Compatibilizers

The edible compatibilizer helps to generate and improve the plasticization of the edible polymer composite film. The incompatibility between the polymer matrix and its disperse phase can lead to poor dispersion or agglomeration of the nanocomposite within the polymer matrix [42], thereby resulting in low moisture resistance, poor performance, and limited polymer composite interactive properties. Therefore, to enhance the interaction between the polymer matrix and its disperse composite interface, suitable compatibilizers can be introduced in the polymer matrix. The several appropriate compatibilizers are comprised of, but not restricted to the following: lactic acid (LA), adipic acid, high molecular weight polyethylene glycol (PEG), and polysorbate [42]. In recent times, due to environmental consciousness researchers are exploring the application of ecologically friendly fillers as compatibilizers in polymer composites. Additionally, an economically viable means to depend on the utilization of natural compatibilizers as a substitute for typical conventional compatibilizers. In this respect, vegetable oils are a fascinating group of modifiers that can deliver a dual benefit of plasticizing and a compatibilizing outcome.

9.8 Effective Properties of Nanoparticles in Edible Packaging

The growing demand for increased fresh food shelf life as well as the need for protection against foodborne diseases urged the development of antimicrobial food packaging. Among the most efficient methods, the combination of organic–inorganic and packaging, i.e., polymer embedded metal nanoparticles, proved to be highly effective. This is normally done by incorporating the active inorganic nanoparticles within the polymer matrix to be used in the proposed application.

9.8.1 Metal Ion Release Property

The importance of inhibiting foodborne diseases and various food-grade agents is applied on food products. Among available, the need of synthesizing the antimicrobial edible polymer film for food packaging is of great interest. The point of concern is the modification of packaging materials with unique nanoparticles that would deliver active biocide constituents to its surrounding [1]. In order to enhance the life span of the food and its packaging, and delaying the decomposition process, the application of either inorganic and/or organic substances is remarkable [43]. The inorganic nanoparticles are primarily silver, iron, or other metals and their oxides, and the organic nanoparticles are mainly carbon-based acid, polymers, and enzymes. The carbon-based antimicrobial substances are unstable at elevated temperatures in comparison with the inorganic counterparts because the nanoparticles of metal and their oxides withstand higher thermal processing situations and handling. This indicates that metal-related nanoparticles are more preferred for the controlled release of the nanoparticles in the polymer composite for the antimicrobial process. Especially, silver nanoparticles have antifungal, antiviral, antimicrobial, and antiyeast activities [43]. Hence, it can be blended with edible polymer composite for beneficial antimicrobial edible food packaging. Additionally, the metal ion release property is also required in an edible food package. The effectiveness of delivering silver, iron, and other metal ions using polymer biocomposites is very crucial. The ability of polymer nanocomposite to release metals is dominant to restrict microbial activities.

9.8.2 Defensive Mechanism

The defensive mechanism of polymer composites in edible packaging is a required attribute. The various food supplements can be delivered with other requirements via including edible food packaging and can further provide improved characteristics. The active additives utilized in polymer composite are edible packaging and coatings, which consist of antiviral, antimicrobials, antioxidants, and biological agents that regulate microbial development, prevent oxidative degradation, and prefer a targeted biocide that preserves food. The nanocomposite and other additives used in edible packaging encompass phenolic and aromatic moieties that are capable of antibacterial activities and antioxidant properties. These compounds react with their surroundings and affect their antimicrobial activities. Chitosan has been established for its antimicrobial activities, and it hinders the development and growth of fungi by triggering a defensive mechanism in fruits against contaminations initiated by some pathogens [44, 45]. The various mechanisms were proposed for the antimicrobial properties of nanoparticles. The interactions and interruption of the microbial cells with the biocides and the transmembranes can have different effects such as destructing the cell cover and oxidizing membrane cell, and produce responsive oxygen species. For instance, the antimicrobial properties of silver nanoparticles in protein-rich products can bind with the cysteine, lysine, arginine, and methionine components [41]. Silver nanoparticles are elucidated by adhesion to the surface of the cell, damaging lipopolysaccharides and degrading the cell, basically increasing absorptivity by penetrating membrane cell, discharging antimicrobial molecules, and destroying the DNA.

9.8.3 Health Benefits

One of the fundamental issues in food processing and packaging is the protection against foodborne diseases which still represent a worldwide issue of general well-being. This is carried out by the delivery of bioactive compounds using biopolymer composite. Polymer nanoparticles and colloids are accumulated from single or multiple biopolymer compounds, which have some possibilities for applications in the food manufacturing process. The composite could be utilized to encapsulate bioactive constituents for the controlled release of health-benefitting ingredients like macro- and micronutrients to the human system [39]. The delivery principle is governed by the concentration of the active constituents encapsulated within the polymer composite. The loading effectiveness depends on the binding sites accessible for phenolic compounds. Further, antidiabetic, antimicrobial, anti-inflammatory, antihydrolytic activity, antiviral, hypolipidemic, antitumor, and antioxidant properties can be linked to polyphenols when consumed at the appropriate level [46]. Biopolymer nanocomposites play a vital role as a delivery system for delivering encapsulated nutritional and nutraceutical health-benefitting compounds manufactured from edible food packaging. The strategic alteration of polymer composite may lead to the advancement of edible polysaccharides and protein-based food packaging with novel bioactive materials that can enhance human well-being and global health.

9.9 Recyclability of the Edible Food Packaging Material

The global yearly consumption of plastic has greatly increased, among which about 40% of the products are used in packaging. This draws attention from environmentalists and policymakers. In this regard, the continuous research and developments are going on to reform the ways of handling waste plastic to create economic and environmental sustainability [47]. The increasing recycling capacity of waste plastic is presently a primary point on the world agenda of global sustainability. Food packaging has a substantial portion, reducing or recycling would yield a significant decrease in solid waste generation, and it may also reduce cost. The present trend in edible food packaging manufacturing is continuously putting efforts that the packaging materials should be natural, edible, functional, economical, and ecologically friendly. Therefore, the mentioned properties when achieved provide biodegradable and eatable film or coatings. This results in substantial interest in edible packaging due to their sustainability and possibilities in reducing conventional non-degradable plastic food packaging. Hence, the food-grade edible biopolymer composite is not only recyclable but also edible, stable, safe, with enhanced storage life. Consequently, this can reduce the nominal values of waste plastic generated via food packaging and will supplement or substitute the conventional plastic with the biodegradable polymer nanocomposite. Biopolymer nanocomposite can be reused and/or valorized in combination with other biological waste in composting amenities, which will generate manure as valuable conditioners and fertilizers for soil amendments [48].

9.10 Application of Biopolymeric Nanocomposite in Edible Food Packaging

The application of edible packaging is gaining momentum in recent times because of its numerous advantages. The issues related to environment, waste generations, food quality, ethics, and product cost are becoming more important to global sustainability and present-day consumers. This leads to the synthesis and strategic modification of polymer composite for edible food packaging to meet the global challenges while satisfying consumers' needs. The use and availability of polymeric composites have increased in several fields including both edible and non-edible food packaging. Researchers and scientists have recognized polymer nanocomposite in preparation of edible film for food packaging in addition to the conventional means of packaging to improve beneficial characteristics, reduce risk and waste, and enhance safety and storage life. This is normally done by incorporating modifiers with targeted applications into the polymer matrix to tune the properties of the polymer composites for the desired application. The fruits, vegetables, meat and meat products, fish and fish products, and dairy products are attracting more attention in edible packaging due to their susceptible nature to microbial attacks. Therefore, one of the foremost applications of edible packaging apart from its environmental benefit is its antimicrobial effect. This is mainly achieved through the leading techniques in the preparation of edible food packaging such as spraying, dipping, and spreading [41]. Among them, spraying is the one with high demand in industrial packaging in comparison with spreading or dipping because of some main issues like the economy and quality of the finished product. The possibility of reducing cost by the application of the spraying method and the superiority of the finished packaging are major factors. Nevertheless, coatings still have challenges in food packaging applications owing to their inadequate barrier to water vapor and poor mechanical characteristics. Hence, the application of polymer composites for edible food packaging via blending with various biopolymers, nanoparticles, incorporation of hydrophobic constituents like oils or other chemical amendments of the polymer composite through structural adjustment has been projected to take care of the challenges in the application of edible food packaging.

9.11 Future Trends and Conclusion

The fabrication of various kinds of edible packaging using biopolymeric composites has been done by several researchers. Its efficacy and usefulness have been identified by the pharmaceutical and food manufacturers as a substitute or supplement to conventional packaging. However, the manufacturing of edible biopolymer films is typically at the research level and the large-scale application of edible biodegradable films at the commercial point is challenging in recent times, due to cost implications, water barrier properties, and other constraints. Thus, studies on large-scale economic feasibility are essential to encourage the full participation and commercialization of edible food packaging. Furthermore, food industries required a long storage life for foodstuffs and the commercial handling, and safety issues are also challenging that need to be studied further. The eatable packaging substances are themselves having bioactive property. Consequently, the defensive mechanism of biopolymer composites is viable for shorter periods than conventional packaging. Hence, the steadiness and handling behavior of edible packaging under specific conditions need to be examined systematically. However, recent advances show that metal and metal oxides are used as an active agent for antimicrobial activities within the edible package. This also draws concern from some quarters, about how much concentration of metal nanoparticles is safe and how best to achieve the controlled release of the nanoparticles for the targeted applications. Another limitation is the lower physical properties compared to the conventional ones. For instance, the sole lipid-based edible coating has better barrier behavior but lacks adequate mechanical properties. On the other hand, protein-based coatings have an organized structural matrix that supports better mechanical strength with low barrier properties. Therefore, there is a need to combine different substances to attain the desired outcome. In order to enhance edible food packaging, various materials and techniques are employed to achieve the desired consumer and manufacturer requirements. Nevertheless, the benefits and potentiality of edible films using eatable biopolymer nanocomposites have been appreciated and have a greater role to play in the future of sustainable packaging.

Bibliography

1. Ghosh T, Teramoto Y, Katiyar V (2019) Influence of nontoxic magnetic cellulose nanofibers on chitosan based edible nanocoating: a candidate for improved mechanical, thermal, optical, and texture properties. J Agric Food Chem 67:4289–4299. https://doi.org/10.1021/acs.jafc.8b05905
2. Ortiz-Duarte G, Pérez-Cabrera LE, Artés-Hernández F, Martínez-Hernández GB (2019) Ag-chitosan nanocomposites in edible coatings affect the quality of fresh-cut melon. Postharvest Biol Tec 147:174–184. https://doi.org/10.1016/j.postharvbio.2018.09.021
3. Perez-Gago MB, Rojas C, DelRio MA (2002) Effect of lipid type and amount of edible hydroxypropyl methylcellulose-lipid composite coatings used to protect postharvest quality of

mandarins cv. fortune. J Food Sci 67:2903–2910. https://doi.org/10.1111/j.1365-2621.2002.tb08836.x

4. Poverenov E, Rutenberg R, Danino S, Horev B, Rodov V (2014) Gelatin-chitosan composite films and edible coatings to enhance the quality of food products: layer-by-layer vs. blended formulations. Food Bioprocess Technol 7:3319–3327. https://doi.org/10.1007/s11947-014-1333-7
5. Pereda M, Amica G, Rácz I, Marcovich NE (2011) Structure and properties of nanocomposite films based on sodium caseinate and nanocellulose fibers. J Food Eng 103:76–83. https://doi.org/10.1016/j.jfoodeng.2010.10.001
6. Dhar P, Kumar A, Katiyar V (2016) Magnetic cellulose nanocrystal based anisotropic polylactic acid nanocomposite films: influence on electrical, magnetic, thermal, and mechanical properties. Appl Mater Interfaces 8:18393–18409. https://doi.org/10.1021/acsami.6b02828
7. Mondal K, Ghosh T, Bhagabati P, Katiyar V (2019) Sustainable nanostructured materials in food packaging. In: Dynamics of advanced sustainable nanomaterials and their related nanocomposites at the bio-nano interface. Elsevier, pp 171–213. https://doi.org/10.1016/B978-0-12-819142-2.00008-2
8. Ghosh T, Bhasney SM, Katiyar V (2020) Blown films fabrication of poly lactic acid based biocomposites: thermomechanical and migration studies. Mater Today Commun 22:100737. https://doi.org/10.1016/j.mtcomm.2019.100737
9. Ghosh T, Borkotoky SS, Katiyar V (2019) Green composites based on aliphatic and aromatic polyester: opportunities and application. In: Katiyar V, Gupta R, Ghosh T (eds) Advances in sustainable polymers. Materials horizons: from nature to nanomaterials. Springer, Singapore, pp 249–275. https://doi.org/10.1007/978-981-32-9804-0_12
10. Dhar P, Tarafder D, Kumar A, Katiyar V (2016) Thermally recyclable polylactic acid/cellulose nanocrystal films through reactive extrusion process. Polymer 87:268–282. https://doi.org/10.1016/j.polymer.2016.02.004
11. Borkotoky SS, Ghosh T, Katiyar V (2020) Biodegradable nanocomposite foams: processing, structure, and properties. In: Advances in Sustainable Polymers. Springer, Singapore, pp 271–288. https://doi.org/10.1007/978-981-15-1251-3_12
12. Borkotoky SS, Ghosh T, Bhagabati P, Katiyar V (2019) Poly (lactic acid)/modified gum arabic (MG) based microcellular composite foam: effect of MG on foam properties, thermal and crystallization behavior. Int J Biol Macromol 125:159–170. https://doi.org/10.1016/j.ijbiomac.2018.11.257
13. Dhar P, Tarafder D, Kumar A, Katiyar V (2015) Effect of cellulose nanocrystal polymorphs on mechanical, barrier and thermal properties of poly (lactic acid) based bionanocomposites. RSC Adv 5:60426–60440. https://doi.org/10.1039/C5RA06840A
14. Zhao R, Torley P, Halley PJ (2008) Emerging biodegradable materials: starch-and protein-based bio-nanocomposites. J Mater Sci 43:3058–3071. https://doi.org/10.1007/s10853-007-2434-8
15. George J (2012) High performance edible nanocomposite films containing bacterial cellulose nanocrystals. Carbohydr Polym 87:2031–2037. https://doi.org/10.1016/j.carbpol.2011.10.019
16. Kurek M, Ščetar M, Galić K (2017) Edible coatings minimize fat uptake in deep fat fried products: a review. Food Hydrocoll 71:225–235. https://doi.org/10.1016/j.foodhyd.2017.05.006
17. Azeredo HM, Miranda KW, Ribeiro HL, Rosa MF, Nascimento DM (2012) Nanoreinforced alginate–acerola puree coatings on acerola fruits. J Food Eng 113:505–510. https://doi.org/10.1016/j.jfoodeng.2012.08.006
18. Joshy KS, Jose J, Li T, Thomas M, Shankregowda AM, Sreekumaran S, Kalarikkal N, Thomas S (2020) Application of novel zinc oxide reinforced xanthan gum hybrid system for edible coatings. Int J Biol Macromol 151:806–813. https://doi.org/10.1016/j.ijbiomac.2020.02.085

19. Ma X, Cheng Y, Qin X, Guo T, Deng J, Liu X (2017) Hydrophilic modification of cellulose nanocrystals improves the physicochemical properties of cassava starch-based nanocomposite films. LWT 86:318–326. https://doi.org/10.1016/j.lwt.2017.08.012
20. Klangmuang P, Sothornvit R (2016) Barrier properties, mechanical properties and antimicrobial activity of hydroxypropyl methylcellulose-based nanocomposite films incorporated with Thai essential oils. Food Hydrocoll 61:609–616. https://doi.org/10.1016/j.foodhyd.2016.06.018
21. de Moura MR, Aouada FA, Avena-Bustillos RJ, McHugh TH, Krochta JM, Mattoso LH (2009) Improved barrier and mechanical properties of novel hydroxypropyl methylcellulose edible films with chitosan/tripolyphosphate nanoparticles. J Food Eng 92:448–453. https://doi.org/10.1016/j.jfoodeng.2008.12.015
22. Cortez-Vega WR, Pizato S, de Souza JTA, Prentice C (2014) Using edible coatings from Whitemouth croaker (Micropogonias furnieri) protein isolate and organo-clay nanocomposite for improve the conservation properties of fresh-cut 'Formosa'papaya. Innov Food Sci Emerg Technol 22:197–202. https://doi.org/10.1016/j.ifset.2013.12.007
23. Davachi SM, Shekarabi AS (2018) Preparation and characterization of antibacterial, eco-friendly edible nanocomposite films containing Salvia macrosiphon and nanoclay. Int J Biol Macromol 113:66–72. https://doi.org/10.1016/j.ijbiomac.2018.02.106
24. Pinto AM, Santos TM, Caceres CA, Lima JR, Ito EN, Azeredo HM (2015) Starch-cashew tree gum nanocomposite films and their application for coating cashew nuts. LWT-Food Sci Technol 62:549–554. https://doi.org/10.1016/j.lwt.2014.07.028
25. Silva NH, Vilela C, Almeida A, Marrucho IM, Freire CS (2018) Pullulan-based nanocomposite films for functional food packaging: exploiting lysozyme nanofibers as antibacterial and antioxidant reinforcing additives. Food Hydrocoll 77:921–930. https://doi.org/10.1016/j.foodhyd.2017.11.039
26. Li Y, Jiang Y, Liu F, Ren F, Zhao G, Leng X (2011) Fabrication and characterization of TiO_2/whey protein isolate nanocomposite film. Food Hydrocoll 25:1098–1104. https://doi.org/10.1016/j.foodhyd.2010.10.006
27. Gutiérrez TJ, Morales NJ, Pérez E, Tapia MS, Famá L (2015) Physico-chemical properties of edible films derived from native and phosphatedcush-cush yam and cassava starches. Food Packag Shelf Life 3:1–8. https://doi.org/10.1016/j.fpsl.2014.09.002
28. Das M, Mandal B, Katiyar V (2020) Environment-friendly synthesis of sustainable chitosan-based nonisocyanate polyurethane: a biobased polymeric film. J Appl Polym Sci 137(36). https://doi.org/10.1002/app.49050
29. De la Fuente-Salcido NM, Favela-González KM, Marszalek JE (2019) Polymers and nanotechnology, the new face of bioactive edible coatings. Polym Res Commun Curr Adv Contrib Appl Educ Asp 27–35
30. Zambrano-Zaragoza ML, González-Reza R, Mendoza-Muñoz N, Miranda-Linares V, Bernal-Couoh TF, Mendoza-Elvira S, Quintanar-Guerrero D (2018) Nanosystems in edible coatings: a novel strategy for food preservation. Int J Mol Sci 19(3):705. https://doi.org/10.3390/ijms19030705
31. Sorrentino A, Gorrasi G, Vittoria V (2007) Potential perspectives of bio-nanocomposites for food packaging applications. Trends Food Sci Tech 18(2):84–95. https://doi.org/10.1016/j.tifs.2006.09.004
32. Treviño-Garza MZ, García S, del Socorro Flores-González M, Arévalo-Niño K (2015) Edible active coatings based on pectin, pullulan, and chitosan increase quality and shelf life of strawberries (Fragaria ananassa). J Food Sci 80:M1823-M1830. https://doi.org/10.1111/1750-3841.12938
33. Janjarasskul T, Krochta JM (2010) Edible packaging materials. Annu Rev Food Sci Technol 1:415–448
34. Navarro-Tarazaga ML, Sothornvit R, Pérez-Gago MB (2008) Effect of plasticizer type and amount on hydroxypropyl methylcellulose—beeswax edible film properties and postharvest quality of coated plums (cv. *Angeleno*). J Agric Food Chem 56:9502–9509. https://doi.org/10.1021/jf801708k

35. Ghasemlou M, Khodaiyan F, Oromiehie A (2011) Rheological and structural characterisation of film-forming solutions and biodegradable edible film made from kefiran as affected by various plasticizer types. Int J Biol Macromol 49:814–821. https://doi.org/10.1016/j.ijbiomac.2011.07.018
36. Zhang P, Zhao Y, Shi Q (2016) Characterization of a novel edible film based on gum ghatti: Effect of plasticizer type and concentration. Carbohydr Polym 153:345–355. https://doi.org/10.1016/j.carbpol.2016.07.082
37. Ma Y, Yang R, Zhao W (2020) Innovative water-insoluble edible film based on biocatalytic crosslink of gelatin rich in glutamine. Foods 9:503
38. Hernández-Muñoz P, Villalobos R, Chiralt A (2004) Effect of cross-linking using aldehydes on properties of glutenin-rich films. Food Hydrocoll 18:403–411. https://doi.org/10.1016/S0268-005X(03)00128-0
39. Arroyo-Maya IJ, McClements DJ (2015) Biopolymer nanoparticles as potential delivery systems for anthocyanins: Fabrication and properties. Food Res Int 69:1–8. https://doi.org/10.1016/j.foodres.2014.12.005
40. Jones OG, McClements DJ (2011) Recent progress in biopolymer nanoparticle and microparticle formation by heat-treating electrostatic protein–polysaccharide complexes. Adv Colloid Interface Sci 167:49–62. https://doi.org/10.1016/j.cis.2010.10.006
41. Vasile C (2018) Polymeric nanocomposites and nanocoatings for food packaging: a review. Materials 11:1834
42. Sarasini F, Luzi F, Dominici F, Maffei G, Iannone A, Zuorro A, Lavecchia R, Torre L, Carbonell-Verdu A, Balart R, Puglia D, Puglia D (2018) Effect of different compatibilizers on sustainable composites based on a PHBV/PBAT matrix filled with coffee silverskin. Polymers 10:1256. https://doi.org/10.3390/polym10111256
43. Carbone M, Donia DT, Sabbatella G, Antiochia R (2016) Silver nanoparticles in polymeric matrices for fresh food packaging. J King Saud Univ Sci 28:273–279. https://doi.org/10.1016/j.jksus.2016.05.004
44. Wang SY, Gao H (2013) Effect of chitosan-based edible coating on antioxidants, antioxidant enzyme system, and postharvest fruit quality of strawberries (Fragaria x aranassa Duch.). LWT-Food Sci Technol 52:71–79. https://doi.org/10.1016/j.lwt.2012.05.003
45. Edirisinghe M, Ali A, Maqbool M, Alderson PG (2014) Chitosan controls postharvest anthracnose in bell pepper by activating defense-related enzymes. J Food Sci Technol 51:4078–4083. https://doi.org/10.1007/s13197-012-0907-5
46. Zhang L, McClements DJ, Wei Z, Wang G, Liu X, Liu F (2020) Delivery of synergistic polyphenol combinations using biopolymer-based systems: advances in physicochemical properties, stability and bioavailability. Crit Rev Food Sci Nutr 60:2083–2097. https://doi.org/10.1080/10408398.2019.1630358
47. Aji MM, Narendren S, Purkait MK, Katiyar V (2020) Utilization of waste polyvinyl chloride (PVC) for ultrafiltration membrane fabrication and its characterization. J Environ Chem Eng 8:103650. https://doi.org/10.1016/j.jece.2019.103650
48. Cruz-Romero M, Kerry JP (2008) Crop-based biodegradable packaging and its environmental implications. CAB Rev Perspect Agric Vet Sci Nutr Nat Resour 3:1–25