Biopolymer-based nanocomposite films and coatings: recent advances in shelf-life improvement of fruits and vegetables

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REVIEW

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Biopolymer-based nanocomposite films and coatings: recent advances in shelf-life improvement of fruits and vegetables

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ABSTRACT

Consumers increasingly prefer healthy and nutritious diet worldwide, and demands for fresh fruits and vegetables are rapidly growing. Fresh produce are perishable commodities, and physical damage, moisture loss, biochemical changes, and postharvest microbial decay are primary causes of quality loss and reduced shelf-life. Packaging, including plastic films and coatings is an effective strategy to improve postharvest-life of whole and cut fruits and vegetables. However, plastic packaging is a significant environmental concern globally. Biopolymer based films and/or coatings are environment-friendly alternative packaging for food. But, these biopolymers, derived from plant, animal and microbial sources, lack some of the primary physico-chemical and mechanical properties compared to conventional plastic packaging. Reinforcement of biopolymer with nanomaterials addresses these shortcomings, and adds functional properties such as antimicrobial and/or antioxidant activities to the nanocomposites. Organic (e.g. nanocellulose fibrils), and inorganic (e.g. montmorillonite, zinc oxide, silver) nanomaterials are effective in achieving these improvements in biopolymer based nanocomposite. Plant-extracts and compounds derived from plant (e.g. essential oil) are also effective in imparting antimicrobial and antioxidant properties to biopolymer based nanocomposites. This is an extensive review of research works on effectiveness of biopolymer based nanocomposite films and coatings used for packaging of whole and cut fruits and vegetables to extend their shelf-life. Numerous reports have demonstrated effectiveness of biopolymer based nanocomposites in improvement in shelf-life of packaged and/or coated whole and cut fruits and vegetables by at least 4–5 days to as much as a few months.

HIGHLIGHTS

- Fresh produce are perishable commodities requiring package or coating.
- Conventional plastics and waxes are major environmental and health concerns.
- Biopolymer based nanocomposites are environment-friendly alternatives.
- These nanocomposite films and coatings are effective in enhancing shelf-life.

KEYWORDS
Bio-based polymer; bionanocomposite; cut-fruits and vegetables; postharvest-life; natural antimicrobials; food packaging and preservation

Introduction

Postharvest loss of fruits and vegetables are due to physical injury caused during harvesting, natural shrinkage due to moisture loss, adverse climatic condition, invasion by pests, molds and other microorganisms. Microbial growth and oxidative deterioration are two primary causes of loss of freshness, quality and shelf-life in fresh produce (Kumar, Mukherjee, et al. 2020). Fruits are living parts of a plant that experience a series of ongoing changes in physical, chemical, biochemical, and sensorial attributes, as they grow, develop, and ripen. Fruits and vegetables continue to respire even after harvesting, and the shelf-life decreases with increased rate of respiration (Fonseca, Oliveira, and Brecht 2002). These effects are more severe in climacteric fruits such as banana, apple and tomato due to abrupt increase in the respiration rate during ripening associated with ethylene production. The increased ethylene production stimulates color development due to synthesis of anthocyanin and carotenoids, and simultaneous chlorophyll degradation. Accelerated respiration rate induces senescence, excessive softening and reduced storage-life. Peel and skin of fruits and vegetables act as protective barrier, damage to which during harvesting and postharvest handling alter natural gas exchange, water and flavor losses, and increases risk of microbial spoilage (Antunes and Cavaco 2010; Szakiel et al. 2012).

In the context of increasing concern of the environmental damage due to synthetic plastic packaging and consumers' awareness on harmful effects of synthetic inputs in our food, biopolymer based nanocomposites offer attractive alternatives. Biopolymers are well-known alternatives of traditional non-biodegradable petroleum-based polymers such as polyethylene terephthalate (PET), polyvinylchloride

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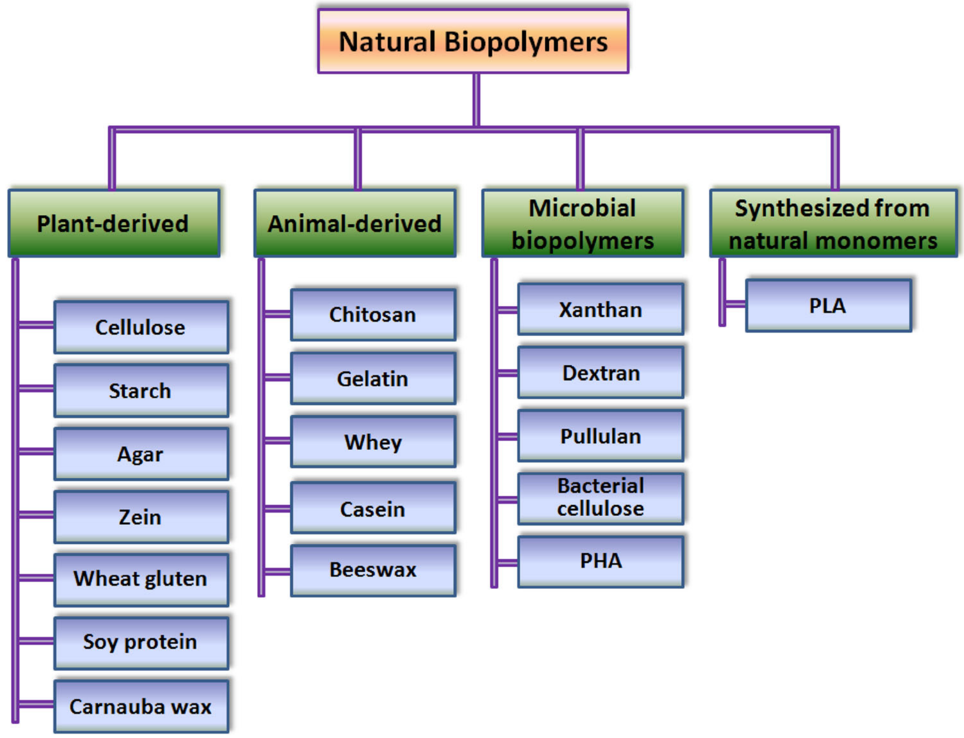

Figure 1. Classification of natural biopolymers.

(PVC), polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyamide (PA) (Song et al. 2009). Biopolymers are obtained from renewable resources such as plant materials (starch, cellulose, other polysaccharides, proteins), animal products (proteins, polysaccharides, lipids), microbial products (xanthan, dextran, pullulan) and polymers synthesized chemically from naturally derived monomers (polylactic acid) (Sharma, Malik, and Jain 2018), as classified in Figure 1. Reinforcement of nanomaterials in biopolymers is made to improve their barrier properties, mechanical strength, thermal properties and functional properties (Sharma, Malik, and Jain 2018; Xiong et al. 2018). Biopoymer-based films and coatings have been extensively studied for their application in enhancing shelf-life of whole and cut-fruits and vegetables. Biopolymer-based nanocomposite materials are combination of biopolymers with nano-fillers such as inorganic and organic nanomaterials (Sharma, Malik, and Jain 2018). Biopolymer matrices can be effective carriers of active ingredients such as anti-browning and antioxidants agents, colorants, nutrients, flavoring and antimicrobial agents (Yildirim et al. 2018). These active agents enhanced the functionalities of the bionanocomposite materials rendering them applicable as active food packaging. The biopolymer-based nanocomposite materials can be designed as oxygen scavengers, carbon dioxide emitters/absorbers, moisture absorbers, ethylene absorbers, ethanol emitters, and flavor releasing/absorbing systems.

Biopolymer based nanocomposite films are mainly fabricated by solution-casting, layer-by-layer, and extrusion techniques. Solution casting methods is a simple technique for preparation of blended nanocomposite films. Coatings on fruits and vegetables surfaces are applied by spreading, spraying, dipping, or immersing of food materials into nanocomposite solutions. Coating process involve many steps; formulation of raw materials using suitable proportion of biopolymers and active agents or nanomaterials, preparation of coating solution by mixing, heating, irradiating, and/or steam flash pasteurizing, food samples disinfection usually by dipping in sodium hypochlorite solution, spreading composite solutions onto food to form uniform coating, followed by drying, and finally packaging and storing in appropriate conditions. In this review, we have summarized recent progress in the development, design, and application of naturally derived biopolymer based nanocomposite films and coatings for shelf-life extension of whole and cut-fruits and vegetables.

Biopolymer nanocomposite for films and coatings

Plant derived biopolymer

Cellulose nanocomposites

Cellulose is the most abundant natural polymer, and it is a linear homopolysaccharide of repeating units of β-1,4 linked D-glucose (Pandey, Nakagaito, and Takagi 2013). There are strong intramolecular or intermolecular hydrogen bondings between adjacent glucose units within the same chain or between different chains. Cellulose can be extracted from its natural precursor sources in two stages. The preliminary step involves pretreatment of raw material to remove hemicelluloses and lignin, mainly by two approaches; alkali treatment and acid-chlorite treatment. In the second step, extraction of cellulose can be achieved by three different methods such as acid hydrolysis, enzymatic hydrolysis and mechanical treatment (eg. high pressure homogenization, grinding, cryo-crushing) (Phanthong et al. 2018). Cellulose is biodegradable, renewable, and has high specific strength, stiffness and high reinforcing potential (Lemos Machado Abreu et al. 2017; Pandey, Nakagaito, and Takagi 2013). Cellulose derived bioplastics such as cellulose acetate (CA), cellulose acetate propionate (CAP), and celluose acetate butyrate (CAB) are thermoplastic materials obtained by esterification of cellulose. CA is of special interest since it has excellent optical clarity and greater toughness (Gemili, Yemenicioğlu, and Altınkaya 2009; Pandey et al. 2010). A number of researchers have explored the suitability of the cellulose and cellulose derivatives-based nanocomposites for food packaging applications (Ghaderi et al. 2014; Quintero et al. 2013; Rodríguez et al. 2014). Ghaderi et al. (2014), developed a high performance cellulose nanocomposite film having tensile strength (140 MPa) from a low value agricultural residue, sugarcane bagasse, and reported that the developed film was suitable for food packaging application (Ghaderi et al. 2014).

Recently, cellulose nanostructures i.e. cellulose nanofiber (CNF) has attracted increasing attention as an organic nano-reinforcement or nano-fillers due to its high crystallinity and aspect ratio, large specific surface area, abundance of surface hydroxyl groups to form hydrogen bonds, and eco-friendly nature. Recently, many studies have reported on biopolymer-based nanocomposite films reinforced with CNF, and they showed that the addition of CNF improved mechanical, barrier and thermal properties (Pelissari et al. 2017; Tibolla et al. 2019). Xiao et al. (2020) developed a soy protein isolate-based nanocomposite film containing CNF, and showed improvement in tensile strength, oxygen and water vapor barrier properties, water resistance ability, and thermal stability in the developed films (Xiao et al. 2020). Similarly, a whey protein isolate and polydextrose based nanocomposite film containing CNF was also reported improved mechanical and barrier properties (Karimi et al. 2020).

Starch nanocomposites

Starch is a polysaccharide composed of amylose, a linear polymer, and amylopectin, a highly branched polymer having the same linear backbone as amylose. Starch is a semi-crystalline polymer abundantly available in cereal grains such as wheat, rice and corn, as well as tubers like potato, cassava and tapioca. Starch has been extensively investigated as a choice material for food packaging applications due to its environmental compatibility, extensive availability, and low-cost (Khan et al. 2017). Starch-based films and coatings vary widely in their characteristics depending upon their botanical origin and fabrication conditions (López-Córdoba et al. 2017). Starch is usually modified to add versatility and enhance functionality for fabrication of films meant for food packaging and coating applications. Out of several processes, crosslinking or reinforcement is one of the suitable methods to improve their physico-chemical and functional properties (Dufresne and Castaño 2017; Gunaratne and Corke 2007). CNFs also have great potential as reinforcing material for starch-based nanocomposite (Kargarzadeh et al. 2018). A new nanocomposites was prepared from banana starch and CNF (isolated from banana peels) using solution casting method (Pelissari et al. 2017). They reported that compared to the pristine starch film, the nanocomposites reinforced with CNF showed higher tensile strength, increased Young's modulus, enhanced water-resistance, and higher thermal stability. The CNF reinforced nanocomposite films exhibit a complex network structure due to strong interactions between CNFs and starch matrix that led to remarkable improvement on mechanical, water barrier and UV light barrier properties (Tibolla et al. 2019).

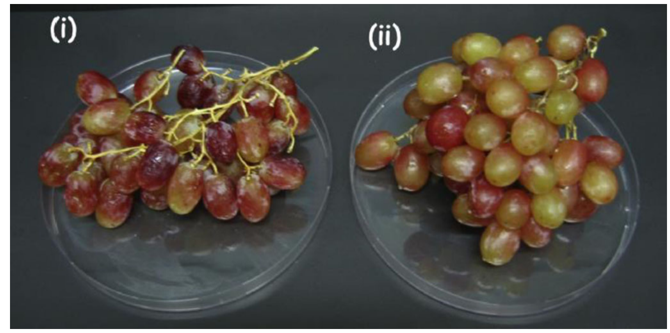

Figure 2. Red Crimson grapes after 21 days storage under refrigerated conditions; (i) control sample and (ii) grapes covered with blend film of modified waxy corn starch and gelatin (1:1), reproduced with permission from (Fakhouri et al. 2015) Copyright 2015 Elsevier.

In a recent study, a bionanocomposite film was fabricated using starch as a biopolymer matrix, pre-oxidised sucrose as a cross-linker, and CNF as reinforcement filler (Balakrishnan et al. 2019). The crosslinking resulted in improvement of barrier properties (reduction in water vapor transmission and oxygen permeability), mechanical performance (increased tensile strength and elongation), and functionality (a decrease in water uptake, diffusion, permeability and swelling) of the film (Balakrishnan et al. 2019). Starch is also modified chemically by esterification or etherification, in which the hydroxyl groups of starch are substituted by other chemical groups resulting in decreased affinity of water molecules (Saliu et al. 2019, Tian, Chen, et al. 2018). Blending of starch with other biopolymers is an approach that has shown significantly enhances moisture resistance and lower brittleness (Noorbakhsh-Soltani, Zerafat, and Sabbaghi 2018). Starch and gelatin blend has been proven to significantly improve mechanical strength of the composite films (Noorbakhsh-Soltani, Zerafat, and Sabbaghi 2018). Fakhouri et al. 2015, developed a hybrid edible film and coating from modified corn starch and gelatin, and used it in refrigerated storage of Red Crimson grapes. The coated grapes showed improved appearance during 21-days storage compared to the uncoated control (Figure 2) (Fakhouri et al. 2015).

Significant improvements in water resistance, mechanical and barrier properties were reported upon addition of inorganic nanomaterials into starch (Ortega, García, and Arce 2019). Starch and natural clay such as Montmorillonite (MMT) based nanocomposites are extensively studied for various food packaging application, due to increased tensile strength and Young's modulus upon addition of MMT (Avella et al. 2005; Li, Zhou, et al. 2019, Wang et al. 2018). Cyras et al. (2008) reported that addition of MMT into starch reduced water uptake due to the tortuous structure formed by the exfoliated clay (Cyras et al. 2008). In another study, starch, ZnO and carboxymethylcellulose based hybrid nanocomposite was formulated, and reported that tensile strength increased from 3.9 to 9.8 MPa, and water vapor permeability significantly decreased by varying the ZnO–CMC content from 0 to 5% (by wt.) (Yu et al. 2009).

Agar nanocomposites

Agar is a fibrous carbohydrate composed of agarose and agaropectin, and extracted from marine algae, Rhodophyceae, and a few seaweeds. Agarose is a neutral, linear molecule of β-1,3-linked-D-galactose and α-1,4-linked 3,6-anhydro-Lgalactose units, while agaropectin is a charged, branched, sulfated, and non-gelling unit (Mabeau and Fleurence 1993). Agar is one of the promising polysaccharides that can be used for fabrication of films and coatings due to their transparency, low hydrophilicity, good film-forming properties, abundant availability and low cost (Mabeau and Fleurence 1993). However, the poor mechanical properties, thermal stability, and poor antibacterial activities of agar films limited their application in food packaging. Recent researches have been focused on the improvement of these properties by reinforcing agar films with nano-fillers such as nanoclay (Lee, Rukmanikrishnan, and Lee 2019), nanocellulose (Reddy and Rhim 2014), metallic (Basumatary et al. 2018), and bimetallic nanoparticles (Arfat, Ahmed, and Jacob 2017; Naskar et al. 2018).

Till date, numerous agar-based nanocomposite packaging films have been developed with improved mechanical and gas barrier properties (Sousa and Gonçalves 2015). Rhim (2011) studied the effect of amount of MMT clay on mechanical and water vapor barrier properties of the agar nanocomposite, and reported that addition of lower concentration of clay (less than 5 wt%) showed higher degree of intercalation and dispersion of the clay, resulting in increased mechanical strength (TS), and decreased water vapor permeability (WVP), and water solubility (Rhim 2011). Zn and Cu minerals incorporated in agar nanocomposite film showed improved mechanical, optical and thermal properties. Addition of Zn and Cu minerals into agar also influenced film morphology, physico-chemical properties and its functionality (Malagurski et al. 2017; Radovanović et al. 2019). A new ternary blend approach, blending of agar with two other biopolymers was also studied to improve flexibility, thermal stability, and UV screening effect of agar (Kavoosi et al. 2018). Agar blend with alginate, and collagen or carrageenan containing silver nanoparticles and grapefruit seed extract (GSE) was developed for food packaging application. They reported that the developed ternary nanocomposite film can be used as antifogging and active antimicrobial packaging for highly respiring fresh produce (Wang and Rhim 2015).

Zein nanocomposites

Zein is a natural protein commercially obtained from kernel of corn, and it is soluble in alcohol (Parris and Dickey 2001). Zein is classified into four classes (α, β, γ and δ) based on their solubilities. Among these, α-zein is the most abundant comprising of 70–85% of the whole zein. Zein has a high content of hydrophobic amino acid residues like leucine, proline, alanine, and phenylalanine (Parris and Dickey 2001). It is abundantly available, biodegradable, biocompatible, hydrophobic, and has film-forming properties. These properties make it a desirable candidate for development of biopolymer-based nanocomposite films and coatings (Arora and Padua 2010). However, zein-based films have limitations, such as brittleness, poor process-ability, low elongation, and poor thermal properties (Arora and Padua 2010). Therefore, plasticizers such as ethers (Naushad Emmambux and Stading 2007), aldehydes (Barber et al. 2019), long chain fatty acids (Scramin et al. 2011; Turasan et al. 2018), and glycerol (Huo et al. 2018) are most commonly used in zein. Physical, chemical or enzymatic methods are also used to enhance functionalities like water solubility, foaming and emulsifying properties of zein (Wang et al. 2019).

Zein can be fabricated into greasy, oil resistant and glossy films and coatings for food packaging applications. It has an inherent antioxidant activity, and can maintain food quality by acting as an oxygen barrier, preventing oxidative damages (Vimala Bharathi et al. 2020; Yıldırım and Barutçu Mazı 2017). Positively charged zein can strongly bind with negatively charged nano-fillers (Lemos Machado Abreu et al. 2017). Recently many authors have reported development and applications of zein-based nanocomposites containing different nano-fillers and plant based active agents for antimicrobial food packaging (Kasaai 2018). Kashiri et al. 2017, prepared zein-based nanocomposite films and coatings containing 5 and 10% of *Zataria multiflora* essential oil for antimicrobial food packaging systems (Kashiri et al. 2017). They have applied nanocomposite coating on the inner wall of polypropylene (PP) bags, and studied the effects on the preservation of pasteurized coẃs milk stored at $4 \pm 1\,^{\circ}C$ for 6 days. The results showed a significant reduction in *E. coli* count compared to control bags during the storage period, achieving reductions of 0.51, 0.92 and 0.99 log CFU/ml on days 1, 3 and 6, respectively (Kashiri et al. 2017). The clay nanomaterials have also been investigated for improvement in thermal stability and hydrophilicity of zein-based nanocomposites films (Kuorwel et al. 2015). Lignin and zein based bionanocomposites was developed that allowed a supramolecular control over the zein structure for food packaging applications (Oliviero et al. 2011). Zein-based coatings have been developed and applied on whole apple as an alternative to shellac. The zein-based coatings showed high-gloss, firmness and weight loss values in fruits and vegetables similar to those achieved by commercial shellac and carnauba coating (Jinhe, Elizabeth, and Robert 2002; Scramin et al. 2011).

Wheat gluten (WG) nanocomposites

Wheat gluten (WG) is a complex mixture of two proteins, gliadins and glutenins (Diao et al. 2014). The gliadins are prolamin proteins with molecular weights of 28–55 kDa, while the glutenins are combined proteins linked by disulfide bonds with molecular weights of 500–10,000 kDa. The gluten system is a unique polymer network that is stabilized

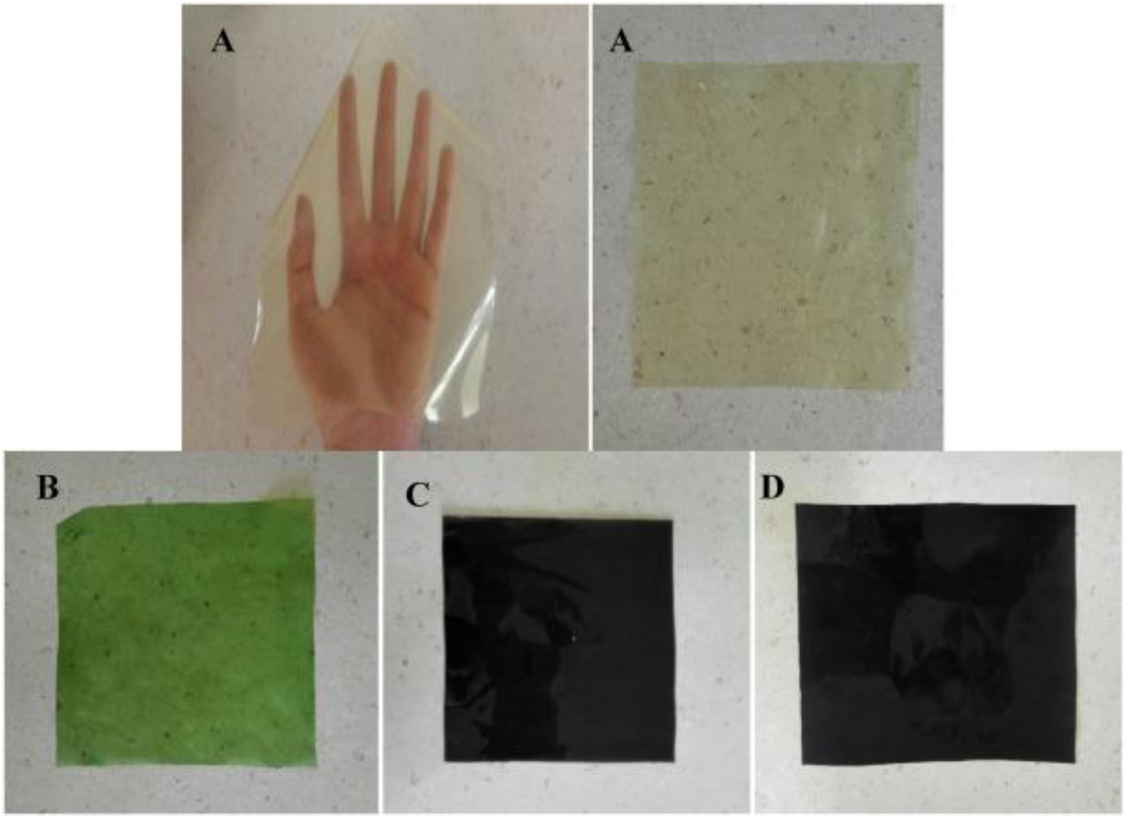

Figure 3. Nanocomposite films of (A) Wheat gluten, (B) Wheat gluten/Chlorophyll, (C) Wheat gluten/Polypyrrole, and (D) Wheat gluten/Chlorophyll/Polypyrrole, reproduced with permission from (Chavoshizadeh, Pirsa, and Mohtarami 2020) Copyright 2020 Elsevier.

by various interactions, such as covalent bonds, non-covalent interactions (hydrogen bonds, hydrophobic or ionic interactions) and entanglements (Lacroix and Vu 2014). Gluten is a heteropolymer that offers various avenues for interactions, cross-linking or chemical grafting. Gliadins are soluble in aqueous alcohol while glutenins are not, but reduction of disulfide bonds in glutenins renders it soluble in aqueous alcohols similar to gliadins (Diao et al. 2014). WG is a by-product of the wheat starch industry, and has been extensively used for both food and non-food applications. The non-food applications of WG are in trends to fabricate biodegradable films and coatings with multi-functional properties for food packaging. Development of edible coatings or films with selective gas permeability is very promising for controlling respiratory exchange and improving the postharvest-life of fresh or minimally processed fruits and vegetables (Kumar, Mukherjee, et al. 2020). Wheat gluten is renewable sources that can form a fibrous network when combined with glycerol (plasticizer) resulting in improved rigidity, flexibility and ductility in film (Langstraat et al. 2018).

Like any other biopolymers, WG exhibits less resistance to water and gas permeation, and also have weak mechanical properties. To enhance barrier and mechanical properties of WG-based films, first approach is to alter the polymer network by formation of intramolecular and intermolecular covalent cross-links, for example by applying thermal treatments or by adding chemical cross-linkers (Langstraat et al. 2018). The second strategy is to blend wheat gluten with hydrophobic biopolymers (Sanchez-Vazquez, Hailes, and Evans 2013). A third approach is reinforcement with nanomaterials, and in this perspective several researchers have reported development of hybrid nanocomposite systems (Chavoshizadeh, Pirsa, and Mohtarami 2020; El-Wakil et al. 2015; Yuan, Lu, and Pan 2010). Tunc et al. (2007), prepared a WG-based nanocomposite films, plasticized with glycerol and reinforced with unmodified MMT, and studied functional properties of the films (Tunc et al. 2007). They reported that MMT nanoparticles significantly decreased water sensitivity and improve barrier properties of the WG hybrid film due to a different structuring of protein network in the presence of layered silicates (MMT), sorption of the permeant molecules, respectively (Tunc et al. 2007). A WG nanocomposite film containing, glycerol, cellulose nanocrystals (CNC) and TiO_2 nanoparticles was developed with improved hydrophobicity, mechanical and antimicrobial properties by casting method (El-Wakil et al. 2015). Recently, Chavoshizadeh et al. (2020) prepared composite conducting films of various color from wheat gluten, chlorophyll (CH) and polypyrrole (PP) nanocomposite (Figure 3). They reported that chlorophyll and polypyrrole can be used to improve the physico-mechanical and antibacterial properties of the WG film suggesting its application as an active/antibacterial packaging system (Chavoshizadeh, Pirsa, and Mohtarami 2020).

Soy protein-based nanocomposites

Soy protein (SP) is extracted from soybean seeds, abundantly available worldwide. Soy proteins are composed of albumin and globulin, and it is commercially available in the forms of soy flour (SF), soy protein concentrate (SPC), and soy protein isolate (SPI) containing 54%, 65–72%, and ≥90% protein, respectively (Rizzo and Baroni 2018). The protein content of SPI is higher than the other SP products offering higher film-forming ability, highly desirable for application as films and coatings. Biodegradability, biocompatibility, and film forming ability of soy-protein have attracted interest of researchers to use it as base material for the production of edible films and coatings (Tian, Guo, et al. 2018).

Researchers have performed blending of soy protein with other natural polymers to enhance its mechanical properties and moisture sensitivity (Koshy et al. 2015). Blending with biopolymers such as starch, cellulose. Gelatin and other protein(s) ensures that the final blended films are also "biodegradable" (Chinma, Ariahu, and Abu 2012; Guerrero et al. 2011; Li, Jin, et al. 2017). Many reports suggested that incorporation of nanocellulose, cellulose nanofibril (CNF) into SP enhance tensile strength, water vapor barrier and light barrier properties of the nanocomposite films (Li, Jin, et al. 2017; Xiao et al. 2020). Recently, Xiao et al. 2020, developed and evaluated SPI-based antibacterial nanocomposite films containing cellulose nanocrystals (CNC) and zinc oxide (ZnO) nanoparticles, and reported that incorporation of CNC (nano-reinforcements) significantly improved tensile strength, oxygen and water vapor barrier properties, water resistance ability, and thermal stability of the composite films (Xiao et al. 2020). Similarly an active nanocomposite film of SP containing MMT, and clove essential oil was prepared to preserve refrigerated bluefin tuna (*Thunnus thynnus*) fillets. The report showed that the prepared composite films increased the shelf-life and the quality of the packaged fillets during chilled storage (Echeverría et al. 2018).

Carnauba wax-based nanocomposites

Wax based coatings are commercially applied on various fruits and vegetables for minimizing dehydration, reducing shriveling and shrinkage. Waxes such as beeswax, carnauba, candelilla, paraffin and rice bran wax have been successfully used in coatings for longtime (Fei and Wang 2017). Various fruits and vegetables such as orange, lemon, grapefruit, apple, tomatoe, rutabaga, cherry, cucumber, apricot, banana, date, grape, guava, mangoe, peache, nectarine, pear have been wax-coated (Galus and Kadzińska 2015). Carnauba is a natural plant based wax extracted from the leaf of the Brazilian palm tree (*Copernica cerifera*), and it is recognized as GRAS (generally recognized as safe) material (de Castro e Silva, de Oliveira, et al., 2020). Carnauba is commonly used since 1930s for fruit and vegetable coating to prevent weight loss and to maintain glossy appearance (Dhall 2013). Carnauba waxes are not effective against postharvest fungal spoilage in fruits and vegetables. In some commercial mitigation strategies, chemical fungicide such as imazalil, thiabendazole, and sodium ortho-phenylphenateare are used in conventional carnauba wax coating (Palou, Valencia-Chamorro, and Pérez-Gago 2015). As an alternative to these chemical fungicides, antimicrobial nanomaterials, and natural antimicrobial agents have been effectively used with carnauba wax coating.

Jo et al. (2014) reported that a combined carnauba-shellac wax (CSW) formulated with nanoemulsion of leomongrass oil reduced weight loss and maintained hardness in postharvest apple during storage (Jo et al. 2014). Effectiveness of carnauba wax in reducing weight loss, respiration rate, ethylene production, and flesh softening in Indian jujube (plum) during postharvest storage at 20 °C was reported (Chen, Sun, et al. 2019). In India, Singh et al. (2016) used the carnauba-based wax for postharvest coating of brinjal, and reported significant improvement in shelf-life and quality retention during storage at 20 °C (Singh et al. 2016). Indian Council of Agricultural Research (ICAR) published a report on effectiveness of 10% carnauba wax coating on quality retention and shelf-life extension of Nagpur mandarin during ambient and refrigerated (6 °C) storage. Carnauba wax-based emulsion coatings containing nanoclay for improvement in postharvest quality of 'Valencia' orange was recently studied (Motamedi et al. 2018). Coating formulations containing different concentrations of nanoclay (i.e., 0.0, 0.5 and 1.0 wt%) were applied on orange, and their performance were evaluated and compared with uncoated fruit and with two different commercially available waxes. They reported that the incorporation of nanoclay (1.0 wt%) in carnauba wax greatly improved sensory, textural and nutritional quality, shelf-life and effectively prevent moisture loss from fruits during storage (Figure 4a,b) (Motamedi et al. 2018).

Animal derived biopolymer

Chitosan nanocomposites

Chitosan (CS) is a polysaccharide of N-acetyl D-glucosamine and D-glucosamine units linked by β - (1 $\rightarrow$ 4), and it is a deacetylated derivative of chitin (Kumar, Mukherjee, et al. 2020). Chitin is mainly obtained from exoskeleton of marine invertebrates and from cell walls of certain fungi. The external shells and other non-edible parts of the marine invertebrates such as crabs, shrimps, lobsters and oysters are usually discarded as waste, which are prominent source of chitin (Kumar, Ye, et al. 2019). Chitosan is a soluble form of chitin, and has been used in various industrial applications including uses in food industries. Chitosan is a hydrocolloid that has inherent antioxidant, antibacterial and antifungal activities (Kumar, Mukherjee, et al. 2020). Although most hydrocolloids are neutral or negatively charged at acidic pH, but chitosan is positively charged due to the presence of highly reactive amino groups. Compared to other biopolymers, chitosan has been widely used in nanocomposite films and coatings due to its distinct advantages, e.g. solubility in weak acids, excellent film-forming abilities, good antimicrobial activity and selective permeability to gases (CO_2 and O_2) (Kumar, Mukherjee, et al. 2020; Sharma, Jafari, and Sharma 2020). However, poor mechanical and water vapor barrier properties limit its application in food packaging (Sharma, Jafari, and Sharma 2020).

Several efforts have been made to overcome these drawbacks including reinforcement of chitosan by nanomaterials such as nano-clays, metal and metal oxides nanoparticles, carbon nanotube, etc (Kumar, Mukherjee, et al. 2020).

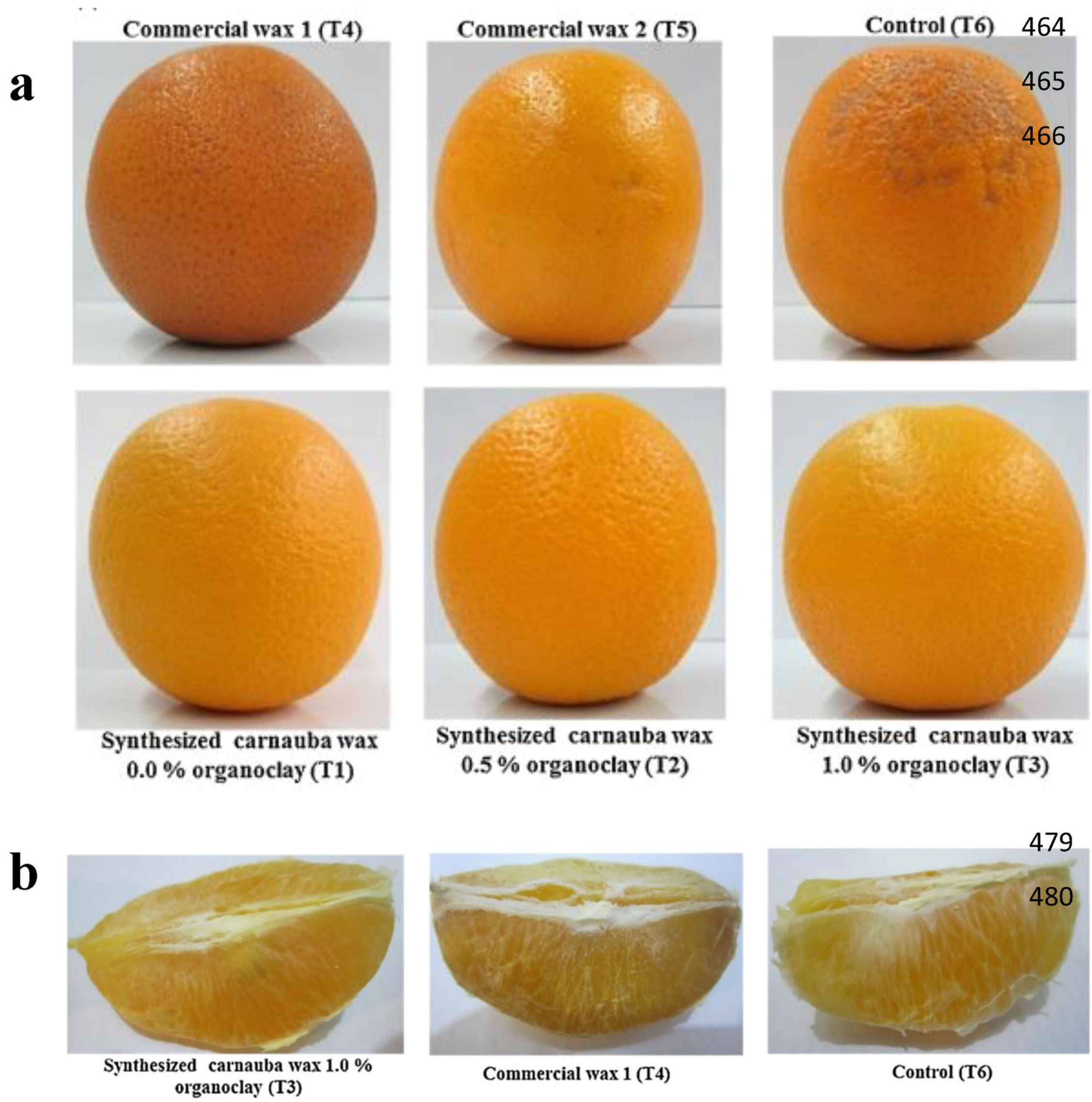

Figure 4. Effects of organoclay-carnauba wax and two commercial waxes coatings on (a) the visual appearance (b) inside texture of 'Valencia' fruit after 8-weeks of cold storage at 4 °C along with additional 1-week storage at 20 °C, reproduced with permission from (Motamedi et al. 2018) Copyright 2018 Elsevier.

MMT is an inorganic natural clay composed of layered silicates, and is well known for its high cation exchange capacity, and good dispersibility in aqueous medium. Incorporation of MMT into chitosan matrix enhances its mechanical and barrier properties because of good dispersion of MMT throughout the biopolymer via intercalation of cationic polymer chains into MMT inter-layers (Sharma, Jafari, and Sharma 2020; Xu, Qin, and Ren 2018). Recently, a nanocomposite coating of chitosan and MMT have been developed, and applied on tangerine fruits. The results showed that the addition of 1% (w/w) MMT reduced the water sensitivity and improved the oxygen barrier properties of chitosan films significantly, and thus provided longer postharvest-life for tangerine fruits (Xu, Qin, and Ren 2018). It has been reported that the incorporation of 3% (w/w) MMT (a natural nano-clay) into chitosan increased tensile strong (TS), and percentage elongation at break (E%) by 58.5% and 52.4%, respectively, while it reduced the water vapor permeability and oxygen permeability by 55% and 32%, respectively (Nouri et al. 2018). Incorporation of MMT in chitosan matrix also increases the tortuosity of the diffusive path for active components (permeates), forcing them to travel a longer path to diffuse through the matrix (Adame and Beall 2009). This leads to slow release of the active components (such as antimicrobials and antioxidants) from the prepared chitosan nanocomposite film(s) and coating(s) ultimately leading to shelf-life extension of coated/wrapped foods.

Chitosan has inherent antimicrobial and antioxidant properties. Several nanomaterials and palnt based active components have been used to further improve its antimicrobial and antioxidant activity. In addition, the nanomaterails also improve physico-chemical properties such as mechanical, barrier and optical properties of the chitosan nanocomposites (Kumar et al. 2018). ZnO nanoparticles are preferred for their strong antimicrobial nature, nutritional importance, and recognition as GRAS (Generally Recognized as safe) material by the US-FDA (Kumar, Boro, et al. 2019). Antioxidants can also play a significant role in shelf-life extension and quality retention by hindering microbial growth, delaying oxidative stress, slowing down respiration rate, and delaying fruit ripening (Kanatt, Chander, and Sharma 2010). *Aloe vera* is known for its antioxidant activities and antimicrobial properties including antifungal activities (Sánchez-Machado et al. 2017). Many natural active antioxidants including *Aloe vera* pulp have been added into chitosan matrix to make the composite films and coatings effective in maintaining fruit quality, and to extend fruit shelf-life (Benítez et al. 2013; Vieira et al. 2016). Khatri et al. 2020, recently studied the efficiency of *Aloe vera* gel and chitosan coatings in prolonging the post-harvest-life of tomatoes (Khatri et al. 2020). Increase in total soluble sugar, phenolic content, lycopene, and activity of pectate lyase during cold storage were observed in coated tomatoes, compared to the uncoated fruits. The composite coating of chitosan and *Aloe vera* gel treatment delayed the ripening process and extended the shelf-life of tomatoes up to 42 days (Khatri et al. 2020). Recently, our group has also extensively reviewed research work on development and applications of chitosan and chitosan based nanocomposites films and coatings for food packaging and preservation (Kumar, Mukherjee, et al. 2020; Kumar, Ye, et al. 2019).

Gelatin nanocomposites

Gelatin is water soluble fibrous protein mainly obtained from skin, bone, connective tissue and tendon of vertebrate and invertebrate animals (Etxabide et al. 2017). Byproducts of fish and meat industries are potential sources of gelatin. Gelatin can be classified into two categories namely, type-A gelatin, obtained from acid treated collagen; and type-B gelatin, obtained from alkali treated collagen. Type-A gelatin shows an isoelectronic point at pH ∼8–9, whereas type-B shows at pH ∼4–5. Gelatin dissolves in aqueous solutions at 40 °C, and they form thermo-reversible gel on cooling, a relevant property for fabrication of films and coatings. Conversely, the highly hygroscopic nature of gelatin, make it easy to swell or dissolve when it comes in contact with high moisture or water (Etxabide et al. 2017).

The functional properties including antimicrobial activity of gelatin can be improved by incorporation of different substances, such as crosslinkers, strengthening agents, plasticizers, nano-fillers, and by blending with other biopolymers such as starch (Loo and Sarbon 2020), chitosan (Kumar et al. 2018), whey (Harper et al. 2013), and others (Oliveira, Furtado, et al. 2018). Among antimicrobial agents, metal oxides nanoparticles such as ZnO NPs are mostly used in food application, as they are GRAS material. Gelatin and silver nano colloids (AgNC) based antimicrobial films and coatings have been developed and showed extended the shelf-life in many fruits and vegetables (Kumar, Mitra, et al. 2017). The antimicrobial mechanisms of ZnO nanoparticles are disruption of cell membrane and oxidative stress due to penetration Zn^{2+} ions through cell wall, reacting to cell components. In addition, ZnO NPs can generate hydrogen peroxide, a well-known oxidizing agent that damages the cell membrane (Kumar, Boro, et al. 2019). Li et al. 2020, prepared a gelatin films incorporated with thymol nanoemulsions, and studied change in their physical and antimicrobial activities. The prepared film containing the natural antimicrobial component were smooth and continuous, showed high hydrophobic nature and increased water contact angle (≥90°). The fabricated film exhibited prolonged effectiveness against both Gram-positive and Gram-negative bacteria (Li et al. 2020). Blending of gelatin with chitosan improves water resistance, mechanical strength and antimicrobial properties of the hybrid film. In this context, a hybrid nanocomposites film of chitosan, gelatin and AgNPs was developed in our research laboratory for active packaging of black grapes (Kumar, Mitra, et al. 2017). The study showed that the grape wrapped in the developed hybrid films had extended shelf-life of up to 14-days during storage at 37 °C (Kumar, Mitra, et al. 2017).

Whey nanocomposites

Whey proteins (WP) are soluble proteins that constitutes 20% of total milk proteins, and it is obtained from whey – one of the most profusely generated food processing byproducts as a result of manufacturing of many dairy products e.g. cheese (Zhao et al. 2008). Whey protein films are formed by heat denaturation in aqueous solutions resulting in breaks in the existing disulfide bonds, and formation of new intermolecular disulfide and hydrophobic bonds. WP-based films have good oxygen barrier properties, but, like many protein-based films, WP films have relatively poor water vapor permeability (Zolfi et al. 2014). Reinforcement of WP-based film with nanoparticles has been evaluated extensively to address these shortcomings of the films. Numerous WP and nanomaterials-based nanocomposites films and coatings with improved physico-chemical and antimicrobial properties have been extensively reported for food packaging applications.

WP-based coatings and films have been evaluated in preservation of fruits and vegetables for the last 20 years. In 2003, Cisneros-Zevallos and Krochta developed a WP based coating and applied it on apple stored at 20 °C, and reported extended shelf-life of coated apple due to reduced ingress of gases from fruit surface (Cisneros-Zevallos and Krochta 2003). WPI-based film blended with flaxseed oil and beeswax showed improved plasticizing and water vapor barrier properties of the film (Reinoso, Mittal, and Lim 2008). The blended film effectively maintained firmness and preserved moisture in plums stored in refrigerated (5 °C) condition for 15 days. WP and antimicrobial components-based packaging films and coatings have been developed as effective antimicrobial packaging for fruits and vegetables (Valencia-Chamorro et al. 2011). Ozer et al. (2016) developed and evaluated a WP-based nanocomposite blended with poly acrylic acid and lysozyme complex. The blended film showed controlled release of lysozyme that lasted for up to 500 h (Ozer et al. 2016). In another study, WP-based coating containing polyvinyl alcohol, pectin and nanoclay showed improvement in its water vapor barrier properties (Weizman et al. 2017). Blending of WP with polylactic acid (PLA) resulted in 27% and 90%, improvement in water vapor barrier and oxygen barrier properties, respectively.

Casein nanocomposites

Casein is the major milk protein that has been utilized in several industrial applications due to its water-resistant nature. Calcium-caseinate based films and coatings have greater mechanical properties than the whey protein-based counterparts (Dangaran, Tomasula, and Qi 2009). Like WP-based films and coatings, casein-based films and coatings are also plasticized with glycerol or sorbitol to improve their mechanical and barrier properties (Chick and Ustunol 2006). Blending with other biopolymers has also been used to improve mechanical and functional properties of casein-based films and coatings, so that they are more applicable as a food packaging alternative (Chevalier et al. 2018; Pellá et al. 2020). Calcium caseinate and WP based composite film was prepared using γ-irradiation to increase cross-linking, and when blended with methylcellulose, the hybrid film had improved puncture strength, whereas addition of peppermint increased antimicrobial activity. The application of developed hybrid film significantly improved shelf-life of strawberry. Recently, Pella et al. (2020) developed biodegradable film by blending polymers such as starch, casein, and gelatin, using sorbitol as the plasticizer, and the results showed incresed moisture vapor barrier properties, and improved shelf life of whole guava packaged and stored in the developed film (Pellá et al. 2020).

Casein-based nanocomposites reinforced with nanomaterials improve mechanical, barrier and antimicrobial properties of the composite films rendering them suitable for food packaging applications. Casein, caprolactum and ZnO NPs based nanocomposite showed significant improvement in mechanical and antimicrobial properties (Wang et al. 2017). More recently, casein and ZnO NPs based nanocomposite film was prepared via double layer polymerization technique, and the developed film with 3 wt. % ZnO showed 50% improvement in moisture vapor barrier properties, and good antibacterial activity against *E. coli*. Casein-based films have been evaluated for coating or packaging fresh or minimally processed fruits and vegetables (Chen, Wang, et al. 2019; Lin and Zhao 2007). Calcium caseinate coating applied on bell pepper was an effective gas barrier, inhibited color change, and reduced decay during storage leading to enhanced postharvest shelf-life (Lin and Zhao 2007). Similarly, casein films were effective in reducing moisture loss from peeled carrots, effective gas barrier on apple, cherry, celery, and potato. Caseinate-WPI-based films showed good antimicrobial properties during storage of strawberry (Lin and Zhao 2007).

Beeswax-based nanocomposites

Beeswax is a natural wax produced by honey bees, and is traditionally used in food packaging film or coatings as a useful moisture vapor barrier, gas barrier, and grease resistant alternative (Fabra, Talens, and Chiralt 2008; Fabra et al. 2012; Zhang, Xiao, and Qian 2014). Beeswax blending with other biopolymers significantly improves barrier and grease resistance properties of the composite film but does not affect mechanical properties (Kristo, Biliaderis, and Zampraka 2007). The blending of beeswax also improves color/appearance of the film that made it appropriate for food packaging applications. In several recent studies, such improvements were reported in case of WP-pullulan (Khanzadi et al. 2015), HPMC (Klangmuang and Sothornvit 2016), carrageenan-ZnO NPs (Oun and Rhim 2017), and guar gum (Saurabh et al. 2016) based composite or nanocomposite films upon incorporation of beeswax.

Applications of nanocomposite films or coatings containing beeswax have been extensively studied for shelf -life improvement in apple slices (Perez-Gago et al. 2003), plums (Navarro-Tarazaga, Massa, and Pérez-Gago 2011), strawberry (Velickova et al. 2013), cherry tomato (Fagundes et al. 2014; Fagundes et al. 2015), guava (Oliveira, Santos, et al. 2018), mandarin (Navarro-Tarazaga et al. 2008), and tangerine (Navarro-Tarazaga et al. 2007). The blend of 2% (w/v) modified tapioca starch with 0.5 or 1.0% (w/v) beeswax microparticles was spray-coated on blackberries, and the treatment resulted in reduced moisture loss, and gas exchange during refrigerated storage of the fruit at 88% RH (Pérez-Gallardo et al. 2015).

Microbial biopolymers

Dextran nanocomposites

Dextran is the generic name for a diverse family of microbial exopolysaccharides (EPS) or glucans. The polymerization of glucose by extracellular enzyme dextran-sucrase is carried out on sucrose as the primary substrate. Dextran was the first microbial EPS that was commercialized, and *Leuconostoc mesenteroides* is the most commonly used bacteria for industrial production of the biopolymer (Lule et al. 2016). Dextrans are widely used as additives in food, pharmaceutical, and cosmetics, and in many clinical applications because of their hydrophilicity, biocompatibility, and low toxicity. Dextrans are used in food applications as stabilizers in confectionery products, texturizing agent in puddings and gluten-free bread, crystallization inhibitors in ice cream, moisture retention agents and viscosifiers in food pastes (Kothari et al. 2015). In recent years, dextran is garnering research attention as an attractive resource for production of prebiotic oligosaccharides (Kothari et al. 2021).

The first few patents for using dextran in preservative coating for perishable foods were filed in the United States in as early as 1950s. Dextran-based nanocomposites have been developed and used in biomedical applications, however, there is very few reports on fabrication of films and coatings for food packaging applications (Maia et al. 2014; Xu et al. 2020). Davidovic et al. (2018) reported that 3.4% (by wt.) dextran and 20% (by wt.) sorbitol as plasticizer resulted in an edible film that had improved water vapor barrier properties, optimum tensile strength and elasticity (Davidović et al. 2018). Azeredo and Waldron (2016) reported that dextran can be useful as a crosslinker in polysaccharide or protein-based films (Azeredo and Waldron 2016).

Xanthan nanocomposites

Xanthan, a microbial exo-polysaccharide (EPS), is produced most commonly by *Xanthomonas campestris*, and it was commercialized primarily as a water-soluble gum. It has been applied as a safe and standardized food additive (gum) in cheese, dressing, syrups and sauces since 1970s. Xanthan alone, or in combination with other biopolymers such as starch and gelatin has been applied in films and coatings. Several researchers have reported that xanthan gum improves water-vapor barrier and mechanical properties in such films or coatings (Melo et al. 2011)

It has been reported that addition of xanthan gum in carnauba wax coating maintained quality of peeled apple during refrigerated storage, and also improved juice quality (Chen and Nussinovitch 2000). Nur Hazirah, Isa, and Sarbon (2016) reported that incorporation of xanthan gum in gelatin-carboxymethyl cellulose edible films improved its barrier properties against UV-light, increased its thermal stability and puncture resistance (Nur Hazirah, Isa, and Sarbon 2016). In 2014, Zambrano-Zaragoza et al. reported on a poly-ε-caprolactone and xanthan gum based coatings incorporated with α-tocopherol nanocapsules, and applied on freshly cut apple slices (Zambrano-Zaragoza et al. 2014). The results showed improved preservation of fruit firmness and decreased browning index in coated slices indicating reduced water loss and enhanced antioxidant activity of the coating, respectively. Recently, a few studies have explored xanthan-based nanocomposites for their physico-chemical, rheological (Rukmanikrishnan et al. 2020), antioxidant (Singh, Kumar, Kaur, et al. 2020), and antimicrobial (Balasubramanian et al. 2019, Rukmanikrishnan et al. 2020) activities, and their potential applications in food packaging.

Pullulan nanocomposites

Pullulan is a glucan that has regularly repeating maltotriose units, and is produced by yeasts like *Aureobasidium pullulans* through aerobic synthesis process (Ponnusami and Gunasekar 2021). Numerous agricultural and agro-based materials such as beet molasses, jaggery, carob cob, potato starch, corn syrup, cornmeal hydrolysate are used as substrate in industrial production of pullulan (Singh, Kaur, and Kennedy 2019). Pullulan and its derivatives are popular choices for numerous foods, pharmaceutical, and other industrial applications (Singh, Saini, and Kennedy 2008). Pullulan is traditionally applied as dietary supplement for fiber, as prebiotic, as filler in beverages and sauces, and as texturizer in food pastes such as mayonnaise. Alternative α-1,4 and α-1,6 linkages in the structure give pullulan its distinctive physical traits such as flexibility, solubility, adhesiveness, moldability, spinnability, and heat-sealability (Hassannia-Kolaee et al. 2016). Besides, pullulan is water soluble, nontoxic, biodegradable, edible, and is capable of forming a film that has good oxygen barrier property. Since 2002, pullulan has been a GRAS substance, and subsequently in 2004, it was approved by the EU as a food additive (Karolina, Katarzyna, and Małgorzata 2019).

Pollulan film is an excellent barrier against oxygen, but it is soluble in water. So, most food packaging applications use pullulan film in combination with other moisture barrier layer(s). These films are very effective in protecting foods rich with unsaturated lipids (e.g. meat, fish, nuts) and vitamins (fruits and vegetables) (Singh, Saini, and Kennedy 2008). Pullulan coating was first applied in food preservation in 1990s, and it became popular as an edible thin-layer of protection (Farris et al. 2014). Several recent studies have evaluated effectiveness of pullulan-based nanocomposite films and coatings with potential food preservation applications (Alizadeh-Sani et al. 2019, Farris et al. 2014, Uysal Unalan et al. 2014, Zhang, Huang, and Zhao 2019). Application of pullulan-based nanocomposite films and coatings to enhance shelf-life of fruits and vegetables is an emerging area of research. Trevino-Garza et al. (2015) used edible coating composed of pullulan, pectin, and chitosan incorporated with sodium benzoate and potassium sorbate, and reported enhanced shelf-life of the coated strawberries from 6 days to 15 days (Treviño-Garza et al. 2015). These results are consistent with another previous study, in which an edible film composed of pullulan-sorbitol-sucrose fatty acid ester was applied on strawberries by dipping, and shelf-life enhancement was reported during storage at 20 °C (Diab et al. 2001).

Bacterial cellulose nanocomposites

Bacterial cellulose is an extracellular polysaccharide synthesized by *Komagataei bacterxylinus* (previously known as *Acetobacter xylinum* or *Gluconaceto bacterxylinus*) (Lin et al. 2013). In contrast to plant-based cellulose, one of the biggest advantages of bacterial cellulose is that it is completely pure i.e. free from other biogenic compounds such as lignin and pectin. This facilitates the process of micro- or nanofibril generation from bacterial cellulose. Excess hydrogen bond formation in bacterial cellulose leads to its crystalline structure, porosity, excellent water-holding capacity, good tensile strength, moldability, and biodegradability. Bacterial cellulose has been primarily used in food applications such as diet foods and food thickeners (Lin et al. 2013).

Bacterial cellulose-based nanocomposite films and coatings have been explored extensively to enhance scope of their applications in food packaging and preservation (Esa, Tasirin, and Rahman 2014). Bacterial cellulose-based nanocomposite with improved antimicrobial properties have been reported due to incorporation of graphene oxide-copper oxide nanohybrids (Xie et al. 2020), carbon quantum dots and titanium dioxide (Malmir et al. 2020), glass nanoparticles (Abdelraof et al. 2019), and bacteriocin like nisin (Esa, Tasirin, and Rahman 2014), ZnO NPs (Shahmohammadi Jebel and Almasi 2016), AgNPs (Sureshkumar, Siswanto, and Lee 2010), and chitosan-AgNPs (Salari et al. 2018) composite have been reported. Tensile strength, thermal stability, and water vapor permeability of bacterial cellulose based films and coatings were improved by addition of nanomaterials (George and Siddaramaiah 2012, Salari et al. 2018, Shabanpour et al. 2018), and these improved bionanocomposites were applicable as edible coatings on fresh fruits.

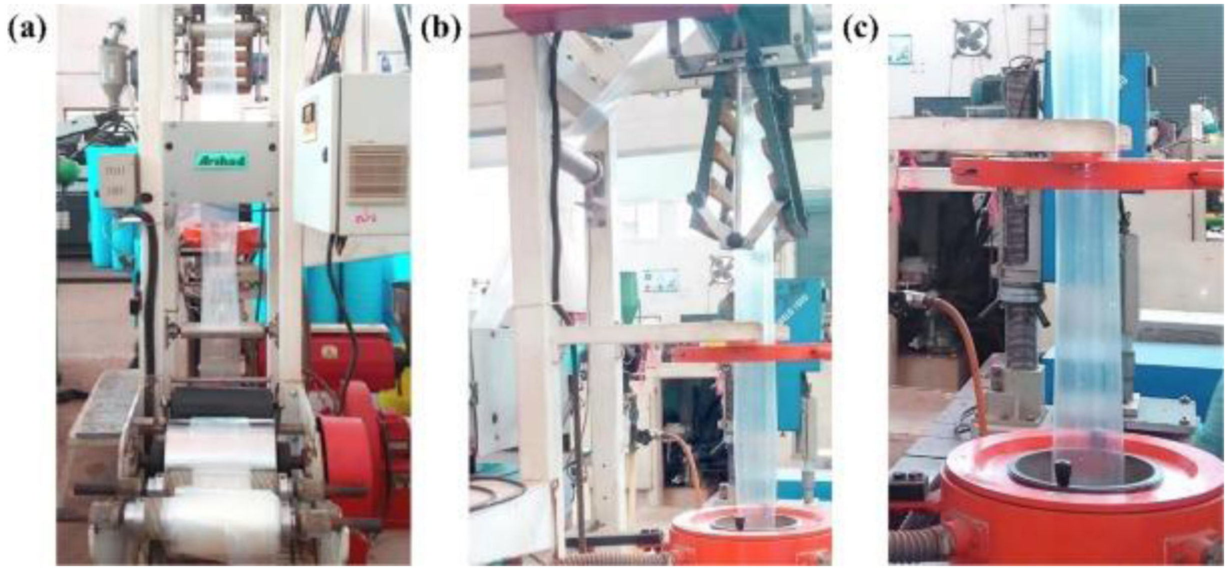

Figure 5. Industrial scale film making process by blowing: (a) neat PLA film, (b and c) PLA/MgO nanocomposite (1%) film, reproduced with permission from (Swaroop and Shukla 2019) Copyright 2019 Elsevier.

Polyhydroxyalkanoates nanocomposites

Polyhydroxyalkanoates (PHAs) are polymers of hydroxyalkanoates (HAs) synthesized by numerous bacteria such as *Alcaligenes*, *Azotobacter*, *Pseudomonas*, recombinant *Escherichia coli*, and methylotrophs (Khanna and Srivastava 2005) using renewable carbon sources such as sugar, starch, alcohol, and industrial byproducts like molasses and fatty acids (Chanprateep 2010). These bacteria accumulate the synthesized PHAs as intracellular carbon and energy storage compounds, which can be isolated as nontoxic, biodegradable thermoplastics (bioplastics), and serve as environment-friendly alternatives to petroleum-based plastics (Verlinden et al. 2007). The best known polyhydroxyalkanoates that have been explored for food packaging applications are poly-hydroxy-butyrates (PHB), and polyhydroxyl-valerate (PHBV). PHA-based films and coatings have attracted interest for food packaging applications due to their renewability, biodegradability, and water vapor barrier properties. However, these films and coatings suffer from shortcomings like high cost of production, brittleness, and low thermal stability.

In order to address some of the primary shortcomings of bacterial PHA-based films and coatings, development of PHA-based nanocomposites with inorganic (Castro-Mayorga et al. 2016) and organic (Fabra, López-Rubio, et al., 2016) nanofillers have been reported. Nanocellulose, nanosilicate layers, nano-MMT, carbon nanotubes and graphene are some of the frequently used nano-fillers in bacterial PHA-based nanocomposites (Sun et al. 2018). Reinforcement with nano-fillers increases the crystallinity, improves thermal stability, Young's modulus, tensile and impact strength of the nanocomposites including barrier properties (Israni and Shivakumar 2019). The PHA-based nanocomposites containing Ag, Au, ZnO, and/or TiO_2 nanoparticles showed good antibacterial activity against foodborne pathogens and spoilage microorganisms. Similar antimicrobial activities were reported when PHA-based nanocomposites were impregnated with essential oils like eugenol, bacteriocins like pediocin, and natural plant-based extracts like vanillin. The PHA-based nanocomposite films and coatings are frequently used as supplementary layer or coating in various multi-layered food packaging system for fruits and vegetables. A nano-hybrid film composed of elctrospun-poly3-hydroxybutyrate reinforced with bacterial cellulose nanowhiskers showed effective barrier properties, and was reoprted to be an alternative to low-density polyethylene (LDPE) for food packaging applications (Fabra, López-Rubio, et al., 2016).

Chemically synthesized polymers from naturally derived monomers

Polylactic acid (PLA) nanocomposites

PLA is a polymer of lactic acid obtained through fermentation of agricultural products such as starch-rich substances like maize, corn, and wheat (Gan and Chow 2018). Compared to biopolymers such as poly(hydroxyalkanoates) (PHAs) and poly(ethylene glycol) (PEG), PLA has good thermal processability that can facilitate various processing such as extrusion, film casting and fiber spinning (Shankar, Wang, and Rhim 2018). Food and Drug Administration (FDA) has approved its applications in food contact, and due to biodegradable and biocompatible nature, it has become a promising candidate for food packaging applications (Ingrao et al. 2015). The high molecular weight PLA is preferred in packaging industry, and it is commercially obtained by ring opening polymerization. PLA is one of the potential biodegradable thermoplastic polyesters that have good mechanical properties. However, the innate brittleness, low thermal stability and impact strength of PLA limit their applications. Considerable efforts such as blending with nanomaterials (like clay, nanocellulose, etc.), elastomers, plasticizers, and with other biopolymers have been carried out to improve its physico-chemical and functional properties.

TABLE 1. Biopolymer nanocomposite films and coatings for shelf-life extension of whole fruits and vegetables.

Biopolymer based nanocomposites	Concentration	Fruits/Vegetables; Storage condition	Effects	Reference
Agar/ZnO NPs films	Agar- 2.5 % (w/v) ZnO – 2–4% (w/w)	Green grapes; Ambient condition, 25 days	Composite film extended shelf-life of Green Grapes up to 21 days	(Kumar, Boro, et al. 2019)
Chitosan coatings	Chitosan – 1%, 2% or 3% (w/v)	Guava $25 \pm 2\,°C$, 85% RH, 4 days	Chitosan coatings maintained the quality in guava fruits and delayed ripening during storage	(Batista Silva et al. 2018)
Chitosan coatings	Chitosan – 2 % (w/v) Tween 80–0.1 % (w/w)	Santa Rosa plum; $1 \pm 1\,°C$, $90 \pm 5\%$ RH, 35 days	Coating effectively maintained the quality and extended the storage life of plum up to 35 days	(Kumar, Sethi, et al. 2017)
Chitosan films	Chitosan – 2 % (w/v) Glycerol –0.5 % (w/w) Citric acid – 2 % w/w	Green chili; 27°C, 7 days	Packaged green chili showed slow coloration and appeared greener till 7 days	(Priyadarshi et al. 2018)
Chitosan/nano-silica coatings	Chitosan – 20 mg solution Hydrolyzed tetraethyl orthosilicate (TEOS) –11.5 mL	Table grapes; $1 \pm 1\,°C$, 90% RH, 30 days, followed by 1 week of shelf-life at $22 \pm 2\,°C$.	Fabricated coating can control gray mold of table grapes and also maintaining shelf life of grape during storage.	(Youssef et al. 2019)
Chitosan/TiO_2 NPs coatings	Chitosan – 1 % (w/v) TiO_2 – 0.01 to 0.03 % (w/w)	Mango fruits; 13 °C, 25 days	Coated mango delayed decay rate, and repining of mango leading to extended shelf-life up to 25 days	(Xing et al. 2020)
Chitosan/Cellulose acetate phthalate/ZnO NPs films	Chitosan:Cellulose acetate phthalate varying ratio ZnO- 2.0–7.5 % (w/w)	Black grape; Ambient condition, 9 days	The film loaded with 5% ZnO extended the shelf-life of black grape fruits up to 9 days	(Indumathi, Saral Sarojini, and Rajarajeswari 2019)
Chitosan/Aloe vera coatings	Chitosan– 0.5 % (w/v) Aloe vera – 0.5 % (w/v) Glycerol – 0.1 % (w/v) Tween 80–0.5 % (v/v)	Blueberry; $5 \pm 0.6\,°C$, $90 \pm 3\%$ RH, 25 days	Coated blueberry fruit showed reduction in postharvest contamination of fungi and extended the shelf life for about 5 days	(Vieira et al. 2016)
Chitosan/Aloe vera coatings	Chitosan – 1 % (w/v) Tween 80–0.1 % (v/v) Aloe vera–1 % (v/v)	Tomatoes; $4 \pm 1\,°C$, 6 weeks	The combined *A. vera* gel and chitosan treatment on tomatoes efficiently delayed ripening process, and extended the shelf-life up to 42 days	(Khatri et al. 2020)
Chitosan/nano- TiO_2 or nano-SiO_2 coatings	Chitosan – 1.00% (w/v) TiO_2 – 0.02% (w/v) or SiO_2 – 0.05% (w/v)	Ginkgo seeds; $0 \pm 1\,°C$, 180 days	Coated seeds delayed decay rate, shrinkage rate and maintained firmness during storage and thus extend shelf-life	(Tian et al. 2019)
Chitosan/Zein/ α-tocopherol films	Chitosan – 2 % (w/v) Zein – 2 % (w/v) α-tocopherol-50 % (w/w) Glycerol – 30% (w/w)	Mushroom (*Agaricus bisporus*); 4 °C, 12 days	Packaged mushroom showed the lower weight loss, leakage rate, browning index, respiration rate, polyphenol oxidase, peroxidase activity and malondialdehyde content compared to control chitosan only and chitosan/ zein film	(Zhang et al. 2020)
Chitosan/ZnO NPs coated Polyethylene films	Chitosan – 2 % (w/v) Zinc Oxide – 0.1 % (w/v)	Okra (*Abelmoschus esculentus*); 25 °C, 12 days	Coated LDPE films retarded microbial and fungal growth and maintained the quality of the packed okra up to 12 days	(Al-Naamani, Dutta, and Dobretsov 2018)
Chitosan/Pullulan coatings	Chitosan — 0.5% (w/v) Pullulan 0.5% (w/v)	Papaya (*Carica papaya*); 25°C, 50% RH, 14 days	Coatings maintained the physiological and nutritional attributes of papaya and extended the fruit shelf life -Multilayer coating better maintained flavor and commercial value of papaya throughout 14 days storage	(Zhang, Huang, and Zhao 2019)
Chitosan/nano-SiOx coatings	Chitosan – 1 % (w/v) Nano-SiOx – 0.05 % (w/v)	Green tomato; 23 ± 1°C, 15 days	Coating delayed weight loss, softness, senescence, and significantly extended shelf-life of green tomatoes	(Zhu et al. 2019)

(*continued*)

TABLE 1. Continued.

Biopolymer based nanocomposites	Concentration	Fruits/Vegetables; Storage condition	Effects	Reference
Chitosan/Organic acids edible coating	Chitosan-0.5 % (w/v) Lactic acid – 0.5 % (v/v) Levulinic acid – 0.5 % (v/v) Acetic acids – 0.5 % (v/v)	Ginseng root; 4 °C, 38 weeks	Coating treatment and modified atmosphere packaging extended the shelf-life of fresh ginseng roots to 38 weeks	(Jin et al. 2016)
Soy protein/Chitosan/Stearic acid films	Acylated soy protein – 5–8% (w/v) Chitosan – 0.29–0.46 % (w/v) Stearic acid – 0.21 to 0.34% (v/v)	Apple; Ambient condition, 6 weeks	Packaged apple showed extended shelf-life up to 6 weeks. Film containing 6% acylated protein, 0.34% chitosan and 0.26% stearic acid showed best sensory quality of apple compared to others	(Wu et al. 2017)
Carboxymethyl chitosan (CMCH)/ Brassinolide (BR) coatings	CMCH – 1% (w/v) Glycerol – 0.5% (w/w) BR – 10 μM	Green asparagus; 4 ± 1°C, 90–95% RH, 24 days	Combined coating maintained the quality of asparagus spears and extended its postharvest-life up to 24 days.	(Wu and Yang 2016)
Chitosan/Olive oil (OLE) coating	Chitosan – 2% (w/v) Glycerol – 1.6% (w/w) Olive oil – 1–2 % (w/v)	Strawberry (*Fragaria ananassa.*); 4 ± 1°C, 16 days	Coating effectively inhibited the fruit decay, fungal count and malondialdehyde development during entire storage period	(Khalifa et al. 2016)
Clove essential oil (CEO)/ Chitosan nanoparticle coatings	Chitosan – 0.3% (w/v) Tween 80 – 1% (w/v) CEO – 0.3% (w/w)	Pomegranate arils; 5 ± 0.5 °C, 90 ± 5% RH, 60 days	Coatings extended aril shelf-life up to 54 days while uncoated arils became unusable after 18 days	(Hasheminejad and Khodaiyan 2020)
Chitosan/Salicylic acid (SA) coatings	Chitosan– 2% (w/v) SA – 2 mmol L^{-1}	Fresh Pistachio; 4 °C, 28 days	Treatment reduced weight loss, total phenolics, enzymatic activities, color, oxidation of lipids, sensory quality, and microbial growth during storage	(Molamohammadi et al. 2020)
Carrageenan/ZnO NPs coating	Carrageenan – 0.8% (w/w) ZnO NPs – 0.5–1.0 (w/w)	Mango (*Mangifera indica*); 20 °C, 61% RH, 33 days	Nanocomposite coating 1% ZnO NPs maintained the shelf-life of mango up to 19 days	(Meindrawan et al. 2018)
Starch/ α-Carrageenan/Sucrose ester of Glycerol coating	Starch – 3 % (w/v) α-carrageenan – 2% (w/v) Sucrose ester – 2 (w/v) Glycerol – 1.5% (w/w)	Cripps pink apple; 20 °C 55 ± 2 RH 5 weeks or 5 °C 90 ± 2 RH 10 weeks	Coated apple fruit showed reduced weight loss, respiration, firmness, color change and greasiness.	(Thakur et al. 2019)
Alginate coating	Alginate – 1–3% (w/v)	Mango fruit; 15 ± 1 °C 85 ± 1% RH, 30 days	3% alginate showed significant reduced in weight loss and maintained higher firmness and flavonoids content.	(Rastegar, Hassanzadeh Khankahdani, and Rahimzadeh 2019)
Sodium alginate (SA)/Gum acacia/AgNPs films	SA – 2% (w/v) Gum acacia- 2% (w/v) $AgNO_3$ – 2% (w/v) Basil leave extract- 1 % (w/v)	Black grapes; Ambient condition, 18 days	Developed film greatly reduced the weight loss and also retaining shape and freshness of the grapes during storage for 18 days	(Kanikireddy et al. 2019)
Carnauba wax (CW)/ Polyethylene glycol (PEG)/ Sodium alginate (SA) coatings	CW emulsion – 1: 4 ml PEG-2.5% (w/v) SA – 0.5% (w/v)	Eggplant; 20 ± 2°C, 52–54% RH 7 days	Coating significantly extended the postharvest-life of white eggplant genotypes by 7 days as compared to 3–4 days in control	(Singh et al. 2016)
Soybean protein Isolate (SPI)/ Cinnamaldehyde/ZnO NPs coatings	SPI – 6% (w/v), Cinnamaldehyde- 0.1% (v/v); ZnO NPs – 1 (w/w)	Banana; 25 °C, 40% RH, 7 days	Prepared composite maintained nutrient content, and delayed water loss, carbohydrate hydrolysis, pectin conversion and fruit respiration, and effectively inhibited fruit fungus spoilage during storage	(Li, Sun, et al. 2019)
Soy protein isolate (SPI)/ Hydroxypropyl methylcellulose (HPMC)/ Olive oil coatings	SPI – 5.0% (w/v) HPMC – 0.40% (w/v) Olive oil – 1% (w/v)	Pear fruit; 28 ± 5°C, 60 ± 10% RH, 15 days	Coating extended postharvest-life of pears up to 15 days, in contrast to 8 days for untreated pear	(Dave, Ramana Rao, and Nandane 2017)

(*continued*)

TABLE 1. Continued.

Biopolymer based nanocomposites	Concentration	Fruits/Vegetables; Storage condition	Effects	Reference
Pectin/Mg NPs films	Pectin – 1% (w/v) Glycerol – 2.5% (v/v) Magnesium hydroxide $Mg(OH)_2$ – 1% (w/w)	Cherry tomato; $0 \pm 2\,^{\circ}C$, 61.2 % RH or $10 \pm 0.5\,^{\circ}C$, 90% RH	The developed composite coating extended the shelf-life of cherry tomatoes upto 24 days during storage at 10°C	(Kumar, Kaur, et al. 2020)
Bacterial cellulose/ Pomegranate peel extract (PPE)/ Green tea extract (GTE)/ Rosemary extract (RE) films	BC pellicle – $10 \times 10\,cm^2$ PPE – 25 to 50% (wt.) GTE –25 to 50% (wt.) RE – 25 to 50% (wt.)	Button mushrooms; $4 \pm 1^{o}C$, 15 days	Mushrooms packaged in the developed film remained good and acceptable within limit of marketability after 15 days of storage	(Moradian, Almasi, and Moini 2018)
Methyl cellulose/Oleic acid coatings	MC – 1 % (w/v) Oleic acid- 0.6% (w/v) Glycerol – 0.5% (w/w) (MC) Soya lecithin- 0.06 % (w/v)	Indian pepper; $24 \pm 1^{o}C$, $70 \pm 5\%$ RH, 8 days	Coating extended the shelf-life of green chilies up to 8 days, and delayed senescence, fruit ripening	(Chaple, Vishwasrao, and Ananthanarayan 2017)
Pullulan coatings	Pullulan – 5%, 10%, or 15% (w/v) $CaCl_2$ – 1% (w/v) Lemon juice-2% (v/v)	Bananas (Rastali and Chakkarakeli); $25 \pm 1\,^{\circ}C$, 70% RH, 20 days	Coating with 10 % pullulan reduced weight loss, color saturation, browning index, and extended shelf-life of fruit up to 20 days	(Ganduri 2020)
Carnauba wax/ Glycerol monolaurate (GML) coatings	Carnauba wax – 50.0 g, Oleic acid- 8.0 g, Myristic acid – 2.0 g, Glycerol monolaurate – 1.5 g	Indian jujube (*Zizyphus mauritiana*); 20°C, 60–70% RH, 12 days	The coated jujube inhibited retained sensory quality, delayed flesh softening and color change, weight loss, respiration rate and ethylene production	(Chen, Sun, et al. 2019)
Coconut oil/Beeswax coatings	Beeswax —10 or 20 g in Coconut oil-80 or 90 mL	Lemon; $21 \pm 2\,^{\circ}C$, $50 \pm 5\%$ RH, 18 days	Coconut oil-beeswax (both formulations, 90:10 and 80:20) coated lemon was acceptable up to 15 days	(Nasrin et al. 2020)
Zein/Poly(ethylene oxide) PEO/Hexanal coatings	Zein – 10% (w/w) PEO – 20% (w/v)	Peach; Ambient condition, 0 % RH, 20 days	The coated peach showed improvement in shelf-life of fruits up to 4 days	(Ranjan et al. 2020)

Swaroop and Shukla (2018) developed a PLA and MgO nanoparticles based composite films using solution casting methods for food packaging applications (Swaroop and Shukla 2018). In this study, MgO nanoparticles (up to 4 wt%) were reinforced with PLA, and they reported that 2 wt% reinforced PLA film had maximum improvement in tensile strength and oxygen barrier properties by 29% and 25%, respectively. The produced films were transparent, exhibit antibacterial properties, and had ability to protect food from UV radiations. In continuation to their previous work, recently the authors (2019) have developed blown PLA-MgO nanocomposite film by extrusion method employing an industrial scale melt-processing setup (Figure 5) (Swaroop and Shukla 2019). The extruded film with 2 wt% MgO reinforcement showed improved tensile strength and plasticity by nearly 22% and 146%, respectively. The oxygen and water vapor barrier properties were improved by nearly 65% and 57%, respectively, for 1 wt% formulation. Moreover, they suggested that the blowing process can be used for large scale production of PLA/MgO nanocomposite with improved physico-chemical and antimicrobial properties for food packaging applications (Swaroop and Shukla 2019). Accordingly, ZnO nanoparticles have been incorporated into PLA matrix to improve mechanical, water vapor barrier, UV-light barrier, and antibacterial properties of the nanocomposites (Shankar, Wang, and Rhim 2018). In addition to that, cellulose nanofibrils were also considered as an ideal reinforcing material for PLA nanocomposites because of its high aspect ratio, large specific surface area and high mechanical strength/weight performance. Blending PLA with another biopolymer such as poly-hydroxybutyrate (PHB) is mostly investigated for food packaging applications. Arrieta and colleagues developed ternary blends of PLA, PHB and limonene and reported that the blending PLA with PHB (3:1) improved oxygen barrier properties, surface water resistances and mechanical properties (Arrieta et al. 2014).

Applications of bio-nanocomposite for food packaging and preservation

Films and coatings for whole fruits and vegetables

Deteriorations in postharvest fruits and vegetables are due to several pre-harvest, harvest-related and postharvest causes (Maringgal et al. 2020). Enzymes inherently present in fruits and vegetables e.g. oxidases, amylases, pectinases, cellulases, and ethylene causes oxidative damage to nutritive quality and appearance, and dissolution of plant tissues causing softening of fruits and vegetables, and excessive maturation. Oxidation of chlorophyll, anthocyanin and other pigments, non-enzymatic browning, oxidation of vitamins (e.g. ascorbic acid), and conversion of starch to sugar are some of the primary chemical/biochemical changes that accelerate postharvest quality deteriorations such as loss of color, flavor, texture, firmness and nutrition in fresh produce. Microbial spoilage occurs due to bacteria, fungi, and foodborne pathogens rendering fresh produce unacceptable and potentially hazardous for consumers. Loss of moisture is the primary physical cause of postharvest deterioration of fruits and

TABLE 2. Biopolymer-based edible coatings for shelf-life extension of fresh-cut fruits and vegetables.

Biopolymer-nanocomposites	Coating method	Cut-fruits/ vegetables; Storage condition	Effects on quality of F & V	Reference
Chitosan coating	Dip-coating	Fresh-cut cucumber; 5 °C, 12 days	Coating alone did not affect significantly but in combination with modified atmosphere packaging maintained the quality and prolonged the shelf-life of slices cucumber up to12 days	(Olawuyi et al. 2019)
Sodium alginate/Thyme oil coating	Dip-coating	Fresh cut apple; 4 °C, 16 days	Edible coating containing 0.05% thyme oil preserved the sensory characteristics of fresh-cut apples during storage	(Sarengaowa et al. 2018)
Chitosan/Organic acids (acetic, lactic, and levulinic acids)/L-cysteine edible coating	Dip-coating	Fresh cut apple; 4 °C, 35 days	Coating inhibited spoilages microbes on apple slices (<1 log CFU) during storage up to 35 days	(Jin et al. 2020)
Denature protein/Guar gum/ Calcium chloride/Mango puree bilayer coating	Dip-coating	Fresh cut mango; 5°C, 65% RH, 15 days	Bilayer coated mango slices maintained firmness, color changes, sensory and microbial quality of fresh-cut mangoes	(Sharma et al. 2019)
Chitosan/Carbon dots	Dip-coating	Fresh cut cucumber; 4°C, 15 days	Coating inhibited the growth of mold and yeast, effectively reduced weight loss, firmness, and total soluble solids in fresh-cut cucumber	(Fan et al. 2019)
Alginate/Glycerol/ Sunflower oil coating	Dip-coating	Fresh cut cantaloupe; 4 ± 1 °C, 40 days	Coating prolonged shelf-life of fresh-cut cantaloupe up to 24 days	(Koh et al. 2018)
Pectin coating	Dip-coating	Fresh cut carrot; 8 °C, 12 days	Shelf-life of fresh-cut carrots extended up to 12 days by pectin based coating	(Ranjitha et al. 2017)
Alginate/Thyme oil/Oregano oil	Dip-coating	Fresh cut papaya; 4 °C, 12 days	Coating significantly reduced weight loss, respiration rate, and enhanced antimicrobial activity.	(Tabassum and Khan 2020)
Soy protein isolate/Lemon extract	Dip-coating	Fresh cut melon; 4 °C, 12 days	Coating retained quality of fresh-cut melon and extended the shelf-life	(Yousuf, Srivastava, and Ahmad 2020)
Gellan gum/*Aloe vera* Gel/α-carrageenan or Sodium alginate coating	Spray-coating	Fresh cut papaya; 5 °C, 12 days	Coating improved oxygen barrier and reduced respiratory rate, maintained firmness	(Farina, Passafiume, Tinebra, Palazzolo, et al. 2020)
Aloe vera/Lemon essential oil/ HPMC coating	Spray-coating	Fresh cut 'Fuji' Apple; 4 ± 1°C, 9 days	Coating delayed weight loss, browning processes, and maintained excellent color during cold storage	(Farina, Passafiume, Tinebra, Palazzolo, et al. 2020)
Chitosan/AgNPs composite coating	Dip-coating	Fresh cut melon; 5 °C, 13 days	Coatings reduced respiration rate, ethylene production, and microbial growth	(Ortiz-Duarte et al. 2019)
Gellan/Geraniol/ Pomegranate extract	Dip-coating	Fresh cut strawberry; 5 °C, 7 days	Coating significantly reduced microbial count and did not change sensory quality throughout the storage period	(Tomadoni et al. 2018)
Sodium alginate/Pectin/Eugenol/ Citral coating	Dip-coating	Fresh cut apple; 4°C, 8 days	Coatings enhanced shelf-life of fresh-cut apple by preventing microbial growth, without affecting sensory and nutritional qualities	(Guerreiro et al. 2016)
Bacterial cellulose nanofiber coating	Dip-coating	Fresh cut apple; 4°C, 7 days	Coated apple slices showed reduced weight loss, browning index, improved firmness and titratable acidity compared to control and bacterial cellulose coating	(Zhai et al. 2020)
Pectin/Honey coating	Dip-coating	Fresh cut apple, Cantaloupe melon, Mango and Pineapple; 4 °C, 15 days	The coated fruit maintain moisture content, polyphenol and vitamin C contents, and thus improved antioxidant properties	(Santagata et al. 2018)
Soy protein isolate/Ferulic acid edible coatings	Dip-coating	Fresh cut apple; 10 °C, 7 days	Coated fruit showed extended shelf-life by controlling weight loss, firmness and oxidative degradation	(Alves, Gonçalves, and Rocha 2017)
Sodium alginate/Pectin/ Carboxymethyl-cellulose/ Chitosan coating	Dip-coating	Fresh-cut mango; 4 ± 1°C, 14 days	Coated mango slices showed lowest microbial count during 14 days storage.	(Salinas-Roca et al. 2018)
Chitosan/ Transcinnamaldehyde coating	Dip-coating	Fresh-cut melon; 4°C, 20 days	Coating retained firmness, improved total soluble solid, total vitamin and carotenoid content, and reduced respiration rate, and activity of browning-associated enzymes, G-POD and PPO	(Carvalho et al. 2016)

(*continued*)

TABLE 2. Continued.

Biopolymer-nanocomposites	Coating method	Cut-fruits/ vegetables; Storage condition	Effects on quality of F & V	Reference
Alginate/poly-ε-lysine (PL) coating	Dip-coating	Fresh cut kiwifruit, 4 ± 0.5°C, 14 days	Coated fresh-cut kiwifruit had minimal electrolyte leakage and retained color, chlorophylls and ascorbic acid content, and improved antioxidant properties	(Li, Zhang, et al. 2017)
Soy protein isolate/Honey edible coating	Dip-coating	Fresh cut pineapple; 4°C, 16 days	Coating retarded microbial growth, ripening, and extended the shelf-life of fresh-cut pineapple up to 14 days during storage at 4 °C.	(Yousuf and Srivastava 2019)

vegetables. This leads to weight loss, poor appearance and loss of turgor/firmness in produce. Mechanical damage to skin or peel or surface tissues may occur during harvesting and/or postharvest handling of fruits and vegetables resulting in accelerated deteriorations (Kumar, Mukherjee, et al. 2020).

Globalization of produce (fruits and vegetables) marketing, formation of alliances among producers and marketers, consolidation of retail organizations, and increased demand for year round supply of many fresh fruits and vegetables are current trends, and are expected to continue in foreseeable future. Other trends mainly include use of processing and packaging technologies that are least invasive to the natural freshness, flavor and nutritional quality of produce. Minimal processing technologies, such as high pressure processing, UV radiation, mild heat and use of nanotechnology based active packaging are areas of contemporary research and development. Films and coatings are applied to inhibit or retard these deteriorations in fresh produce by controlling or minimizing or eliminating the postharvest causes such as enzymatic, chemical/biochemical, physical, and/or microbiological changes, as listed in Table 1. Solution casting, layer-by-layer assembly and extrusion are the most frequently used techniques of film fabrication, whereas, spreading, spraying, dipping, or immersing are few coating techniques used to coat fruit and vegetable surfaces by nanocomposite solutions.

Films and coatings for cut-fruits and vegetables

Fresh-cut fruits and vegetables are obtained by cleaning, peeling, and cutting/slicing/cubing of freshly harvested produce for convenience of ready-to-eat consumption. Today's consumers demand good quality, healthy foods in ready-to-eat form so that they are convenient for on-the-go consumption. Cut-fruits and vegetables are healthy foods, whose demands are rapidly growing worldwide. In general, cut-fruits and vegetables have significantly shorter shelf-life than whole fruits and vegetables. Use of edible coatings is one of the very few effective strategies to enhance shelf-life, and keep them fresh for on-the-go consumption for longer period. The use of nanotechnology based innovative strategies to enhance the functionality of edible films and coatings are gaining much attention for preservation of cuts-fruits and vegetables. Reinforcement of edible biopolymers with nanomaterials of active compounds from animal and plant sources improves their functionalities such as antimicrobial and antioxidant properties, which are essential for enhancing shelf-life of cut fruits and vegetables (Galus and Kadzińska 2015).

The application of edible coating has been extensively investigated in the past, however researchers interest has intensified with the increased demand for of fresh-cut fruits and vegetables. Biopolymer based edible coatings have become emerging packaging strategy for improvement of shelf-life of fresh-cut fruits and vegetables (Maringgal et al. 2020). Edible coatings can reduce moisture loss, solute migration, gas exchange, respiration and oxidative reaction rates leading to suppressed physiological disorders. In addition, edible coatings are also good carriers for active ingredients such as antimicrobials, antioxidants, flavors, colors, etc (Ma et al. 2017). Phytochemicals including essential oils (EO's) and EO-derived components are rich in biologically active antimicrobials and antioxidants. Many studies have shown that essential oils are effective antibacterial agents against a wide spectrum of foodborne pathogenic bacteria including *L. monocytogenes*, *L. innocua*, *E. coli* O157:H7, *Shigella dysenteria*, *Bacillus cereus*, *Staphylococcus aureus* and *Salmonella typhimurium*. Incorporation of essential oils (EOs) in biopolymer based edible coatings has been described as a good alternative to preserve fresh-cut fruits (Ju et al. 2019). Many essential oils such as thyme, lemongrass, cinnamon, and castor oil have been used against postharvest losses due to microbial spoilage in fruits and vegetables. However, essential oils have some limitations such as low water solubility and bioavailability, highly volatile nature, and their ability to alter the sensory properties of the fresh/fresh-cut produce. Nanotechnology based approaches have been used to mitigate these limitations by encapsulations (micro and nano) of active compounds. Fernandez, Picouet, and Lloret (2010) developed a cellulose-AgNPs based composite material along with MAP for preservation of fresh-cut melon (Fernández, Picouet, and Lloret 2010). The results indicated delayed senescence in coated melon slices, and extension of postharvest-life by 5 days in 4 °C storage. Today, a variety of fresh-cut fruits and vegetables have been coated for improvement in their shelf-life with appropriate edible coating, as summarized in Table 2.

Conclusions

Biopolymers derived from plants such as starch, cellulose, agar, carnauba; those derived from animals such as gelatin, casein, whey protein, beeswax; and those derived from microorganisms such as dextrans, xanthan, pullulan, bacterial cellulose and polylactic acids have been extensively studied and applied as biodegradable alternatives to synthetic plastic packaging. Solution casting method is most commonly used to develop these films including their blends or hybrids. Numerous studies have reported that reinforcement of these biopolymers with nanomaterials such as CNF, nano-MMT, ZnONPs, AgNPs not only effectively improved physico-chemcal, mechanical, barrier properties, but also enriched them with functionalities such as antimicrobial and antioxidant activities. The biopolymer based nanocomposites have been applied to package fresh produce, and studies have shown postharvest-life ranging from 4 days to 2 months depending on types of whole fruits and vegetables and storage conditions. Applications of the nanocomposite coatings on cut fruits reported shelf-life of 14 to 40 days depending on type of fruits. Further research are needed on scale-up and commercialization of the biopolymer based nanocomposite films and coatings, so that they are affordable and easily applicable to produce growers or handlers.

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