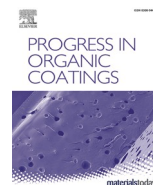




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## Review

# Potential of engineered nanostructured biopolymer based coatings for perishable fruits with Coronavirus safety perspectives

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## ABSTRACT

Fresh fruits are prioritized needs in order to fulfill the required health benefits for human beings. However, some essential fruits are highly perishable with very short shelf-life during storage because of microbial growth and infections. Thus improvement of fruits shelf-life is a serious concern for their proper utilization without generation of huge amount of fruit-waste. Among various methods employed in extension of fruits shelf-life, design and fabrication of edible nanocoatings with antimicrobial activities have attracted considerable interest because of their enormous potential, novel functions, eco-friendly nature and good durability. In recent years, scientific communities have paid increased attention in the development of advanced antimicrobial edible coatings to prolong the postharvest shelf-life of fruits using hydrocolloids. In this review, we attempted to highlight the technical breakthrough and recent advancements in development of edible fruit coating by the application of various types of agro-industrial residues and different active nanomaterials incorporated into the coatings and their effects on shelf-life of perishable fruits. Improvements in highly desired functions such as antioxidant/antimicrobial activities and mechanical properties of edible coating to significantly control the gases ( $O_2/CO_2$ ) permeation by the incorporation of nanoscale natural materials as well as metal nanoparticles are reviewed and discussed. In addition, by compiling recent knowledge, advantages of coatings on fruits for nutritional security during COVID-19 pandemic are also summarized along with the scientific challenges and insights for future developments in fabrication of engineered nanocoatings.

## 1. Introduction

In this 21st century, with the rapid growth of population similar to the medicine and fresh water needs, demand of sufficient and nutritious fresh fruits have also increased as a pivotal component to sustain the human life on the earth [1]. Fruits are not only essential source of dietary fiber and vitamins but also instrumental in cellular detoxification and healing several human diseases [2]. Though the principal source of livelihood in India is agriculture and the country is considered as largest producer of fruits globally [3,4]. Nutritional security has always been a concern due to lack of complete utilization of produced fruits. Fruits are perishable in nature and have very short shelf-life after harvest because of the easy susceptibility to physiochemical disorder (high respiratory rate, fast physiological metabolism, rapid maturation etc.) and microbial contamination [5,6]. It has been reported that >900 million tonnes of food is wasted every year worldwide [7] [<https://www.bbc.com/news/science-environment-56271385>]. Of these, fruits, vegetables and root crops contributed around 40–50% of this total waste generated [1]. It

was also estimated that from the place of harvesting to reaching to the consumer, nearly one third of all fruits produced worldwide are wasted. In this regard, generated fruit wastes have not only social, economical consequences, wastes of water resources for their production, landfills but also act as third-biggest source of global greenhouse gas production (8–10%) and responsible for serious environmental pollution [7–9]. Therefore, the development of environmentally friendly, low-cost and effective technologies that can enhance the shelf-life of fruits to avoid great loss of produced fruits as well environmental pollution concern, are in high demand.

During respiration, consistent utilization of oxygen and carbon dioxide generation are inherent properties of fruits which continue even after harvesting. The metabolism of essential substrates of fruits such as carbohydrates, fats and proteins are takes place, which leads to deterioration of fruit quality in terms of loss of water, nutritional value, colour, weight and flaccidness [6]. Thus, the chemistry and morphology of fruits surfaces have direct influence on the water loss, gas exchange and microbial proliferation behaviour of fresh fruit products. To fulfill the

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consumer demands and extending the fruits shelf-life, researchers have fabricated a number of edible coatings on the surface of fruits by the utilization of materials possessing ability to slow down the respiration rate, moisture transfer, gas exchange and decreasing physiological disorder with antimicrobial activities [6]. For instance, protein based edible coatings derived from plants (e.g., rice, wheat, soy, peanut and corn) and animals (e.g., egg albumin, casein, gelatin and whey protein) have been extensively studied in the recent past [10–12]. Protein based materials adhere well to the hydrophilic food surfaces and act as a suitable barrier for diffusion of oxygen and carbon dioxide [13]. Due to presence of large number of polar groups in their structure, polysaccharides which are naturally occurring polymers (e.g., carboxyl methyl cellulose, chitin, chitosan, alginate and pectin) are widely used to coat selected fruits in the form of sustainable nanomaterials [6,14]. In contrast to the polysaccharides and proteins, use of lipids to fabricate cohesive films or fruit coatings is very challenging. Although, lipids are not biopolymers but their lower polarity, makes them suitable along with biopolymers to form coatings with better water vapor barriers [13]. Thus, those edible materials that show better water-vapor barrier properties, antimicrobial and antioxidant activities to maintain the post-harvest quality of fruits have been most commonly used.

In this article, we have reviewed the recent advances in the development of edible fruit coating technologies with antimicrobial activity to extend the shelf-life of fruits that uses various materials derived from agro-industrial residues and nanoscale materials (organic or inorganic) with specific surface properties. We have provided a comprehensive overview about the concepts, employed nanomaterials (based on plant derived natural organic constituents and their combination with synthetic inorganic nanomaterials) and fabrication methods to increase the fruits shelf-life. Currently ongoing corona virus disease 2019 (COVID-19) have posed a serious threat to the human health, leading to countless morbidities and mortalities. Although few evidence are available to clearly justify the infection of fruits through the COVID-19 virus contamination is likely to happen by the handling of fruits by personnel suffering from COVID-19 from fruit production to storage, packing and distribution. This is specially relevant where harvesting and post harvest operations are mostly manual. Thus, we have also discussed the advantages of nanostructured coatings during the COVID-19 crisis along with the challenges and outlook for this research field.

## 2. Edible coatings and its essential properties for preservation of fruits

Following harvest, the presence of oxygen in fruits is regarded as main enemy to reduce the shelf-life. Oxygen is responsible for several detrimental reactions such as rapid oxidation of vitamins or fats available in the fruit, browning of tissues and also favor the growth of microorganism like molds, yeasts and aerobic bacteria [15,16]. Thus, presence of oxygen eventually leads to decrease of nutritional value and reduce the fruits shelf-life with the growth of microorganisms. However, controlling of minimum and maximum exchange of respiratory gases ( $O_2$  in/ $CO_2$  out) in postharvest fruits has been shown to prolong the shelf-life. It has been reported that  $O_2$  level should never fall below the minimum tolerability of fruits because such conditions favor the accumulation of acetaldehyde, ethanol and carbon dioxide, which lead to the development of off-flavour and undesirable fermentation process, thus, causing deterioration of fruit quality [17]. In addition to the oxygen permeability in postharvest fruits, the water vapor barrier (migration of water from fruit to environment) to prevent moisture loss should be regulated in order to maintain the freshness of fruits.

Keeping in view the issues of short shelf-life of fruits, researchers initiated to develop a thin layer of coating to the outer surface of fruits with the use materials which can be eaten during the fruit consumption [18–21]. This coating was applied as a barrier of gas exchange and moisture loss from the fruit surface without causing anaerobiosis. In addition, coating was also useful in maintaining the soluble solid

content, increasing titratable acidity, colour and firmness of the products. Such developed barrier of thin layer by the use of edible materials on outer surface of fruits was named as edible coating to enhance the fruit shelf-life. The most essential properties of the edible coatings of fruits are based on the physical and chemical modifications in order to extend fruit shelf-life by retard ripening and prevention of physiological disorder (Fig. 1).

In the recent past, edible coating have been developed extensively with the use of a number of agro-industrial residues such as by-products of plants and animal origin like leaves, peels, stems, seeds, husk, skins and shells [22]. These plant and animal originated agro-industrial residues are significantly rich in bioactive compounds such as polysaccharides, lipids and proteins along with excellent antioxidant and antimicrobial properties. In addition to this, these materials have interesting film forming ability and could be used to fabricate eco-friendly, biocompatible edible coatings to extend the shelf-life of fruits. A very well-known example of these agro-industrial residues are hydrocolloids (e.g., alginates, chitosan, pectin, polysaccharides, and proteins), lipids (e.g., waxes, glycerol, fatty acids) and their respective composites [6,13]. Hydrocolloids are partially or fully water soluble in nature due to the presence of several hydroxyl groups in their structure. They have ability to form gel, thickening quality and to increase the viscosity of coating solution with or without use of heat [13,21]. In addition to this, essential oils obtained from various species of herbs and other sources of plants such as clove, garlic, onion, sage and thyme along with the combination of metal alkoxide and organo-modified metal alkoxide precursors are used in specific ratio for the fabrication nanostructured edible coatings to preserve fruit items [15,23].

## 3. Antimicrobial activity

Besides the barrier of gas exchange, loss of nutritional value and moisture from the fruit surface, the prevention of microbial growth is also desirable aspects to prolong the fruits shelf-life. Post-harvest fruit products are highly susceptible to contamination by corrosive or pathogenic microorganism which leads to huge economic loss through spoilage [24,25]. Microbial contamination is possible before or after harvesting of fruits via insects, harvesting equipment, rinse water, processing equipment, transport containers and vehicles [25]. Although fruit peels behave as a barrier to prevent the contact of nutritious inner tissues of fruits with microorganisms, external damage and small cut or bruises during post-harvest operation create the way for penetration and growth of spoilage or disease causing microorganisms [25,26]. In such situations, microorganisms get access not only to nutrients inside but also in acidic environments ( $pH = 1.6$  to  $6.7$ ) which results into the formation of biofilms of the microorganism. Thus, microbial contamination in fruits is also one of the significant reasons for infection in human and the reduction of edible quality of nutritious fruit products with very short shelf-life.

Therefore, in order to overcome the issues of microbial contamination and maintain the quality of post-harvest fruits for longer time, researchers have developed a number of methods including the encapsulation of the natural organic ingredients derived from plants, inorganic nanoparticles, essential oils in a specific ratio of coating solution or nanoemulsions during the development of edible coating for fruits. The addition of antimicrobial components during the formation of edible coatings for fruits shelf-life extension are extensively accepted [6,27–29]. The presence of antimicrobial activity in the fruit coatings imparts more durable protective barrier and extend the shelf-life as compared natural waxy cuticle which are easily denatured during postharvest processes. In this context, many researchers have demonstrated the fabrication of edible coatings with antimicrobial activity on fruit products with use of various types of antimicrobial agents and surface functionalization along with their respective mechanisms. In the next section, we have highlighted the different types of functionalization used in order to addition of better antimicrobial activity along with the

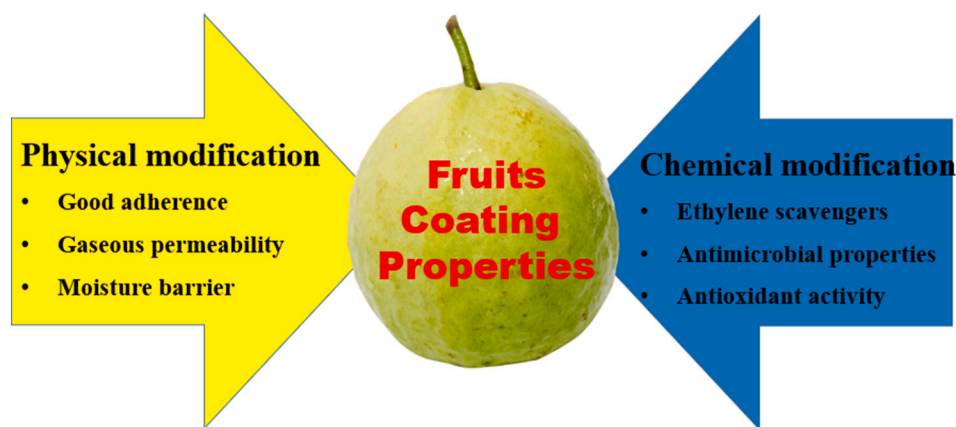


Fig. 1. Essential properties of edible fruit coatings resulting from various modifications.

discussion of their merits and demerits.

#### 4. Agro-industrial residues-based materials in fabrication of edible coatings

A massive quantity of solid waste residues such as pomace, fruits seed fraction and peel are generated during processing of fruits and vegetables in the food industry. These by-products are termed as agro-industrial waste residues and uncontrolled accumulation of such wastes are disadvantageous not only causes economic loss and an alarming bioburden but also responsible for severe environmental complications. Thus, in order to minimize these issues, the valorization of such agro-industrial residues according to their structural components and functional groups into useful products make a good sense in order to benefit environment and mankind. Biomaterials in agro-industrial residues are mostly rich with bioactive compounds such as hydrocolloids and lipids having significant potential as starting materials for the fabrication edible coatings to enhance fruit shelf-life because of their specific chemical properties, biodegradability and biocompatibility. For instance, nanocrystalline and nanofibrillated cellulose can be obtained from lignocellulosic biomass based on agricultural waste such as wheat straw, bagasse, oil palm, cotton and sugar beet [30]. Similar to the nanocellulose, other essential biopolymers (Lignin, chitin/chitosan, pectin, starch, xanthan gum etc.) and their respective derivatives are generally produced from agro-waste industries, which are highly suitable for edible fruit coatings [31]. On other hand, protein-based biopolymers (e.g., gelatin, collagen) can be extracted from protein rich residue sources like skin, cartilage, bones of animals, connective tissue and fish scales [31].

In the recent past, agro-industrial residues (plant and animal by-products) based biopolymers have been used extensively to develop edible fruit coatings to extend their shelf-life. Among the biopolymers, protein-based materials possess amphiphilic character with good mechanical properties and low permeability to oxygen [17]. In the structure of proteins, several amino acids are linked to each other through peptide bonds in the form of long chain and named as either globular proteins (water soluble) or fibrous proteins (water insoluble) [32]. This versatility of protein offers excellent oxygen barrier properties along with good adherence ability to hydrophilic fruit surface as a good coating material. Thus, edible polymers based on protein materials such as gluten, zein, soy, casein, whey protein etc. have been investigated extensively in the fabrication of edible coatings to extend the fruits shelf-life [10,11,32–35].

Similar to the protein and peptide linkage, two or more than two monosaccharides linked with each other via glycosidic linkages and generate a complex carbohydrate molecule which are considered as polysaccharides [17,32]. Polysaccharides are insoluble in nonpolar

solvents, hydrophilic in nature, semipermeable to carbon dioxide and resistant to oxygen (due to the well-ordered hydrogen bonded network [6,17,32,36]). Due to their biocompatibility and versatile functionalities various derivatives of polysaccharides (e.g., chitosan, alginate, cellulose, starch and pectin) are extensively employed in development of edible coatings to prolong the shelf-life of various fruits [19,37–40]. However, due to hydrophilic function of carbohydrates, polysaccharides-based coatings are act as weak water barrier not able to protect the water loss problem of fruit system for long time. Thus, keeping in view of this researchers have incorporated some specific hydrophobic materials (e.g., glycerol, stearic acid, oleic acid, and essential oils) with the use of polysaccharides during the formulation of edible coating solutions in order to extend the fruit shelf-life [17,36,41].

In addition to protein and polysaccharides, due to the hydrophobic and nonpolar structure, coating of lipids plays an important role in prevention of water vapor loss from fruit products. Furthermore, in order to enhance mechanical resistances with the prevention of moisture migration from fruits, researchers have incorporated the use lipids (e.g., carnauba wax, candelilla wax, beeswax, paraffin-wax mineral oil, and fatty acid) with the use of proteins and polysaccharides [17,32,37,42]. Thus, basic materials which are using in the fabrication of edible coatings to prolong the fruits shelf-life are categorized as proteins (animals or plant derived), polysaccharides, lipids and combination of these materials in the form of composites.

On the other hand, innovations such as utilization of nanoparticles based on natural organic ingredients with antimicrobial activities have also been extensively reported that exhibit different physical/chemical properties from those of larger particles of same materials. Nanomaterial are capable to bound with microbial cells and molecules with higher efficiency because of their small dimensions [43]. Initially, nanoparticles interact with microbial cells, penetrating the cell envelope and oxidized the cell components by the production of reactive oxygen species or dissolved ions of heavy metals [43,44]. In order to enhance mechanical, physical and barrier properties of edible coatings, scientist have designed a series of different nanoparticles either derived from plant based natural organic ingredients (e.g., starch nano crystals, nanocelluloses, and chitosan) or inorganic nanoparticles (e.g., silver, zinc oxide, titanium oxide, and silicon dioxide) fabricated through physical/chemical modification methods. Several studies have been reported the antimicrobial efficacy of nanomaterials with the reduction of respiration rate in fruit products. In the next section, we have summarized recent advances around the development of antimicrobial edible coatings with the use of engineered organic and inorganic nanomaterials.

#### 4.1. Engineered organic material-based coatings

This section deals with the recent advances in development of antimicrobial edible coatings using different agro-industrial residues based organic materials (polysaccharides, protein, and lipids). In addition, we principally focused on different techniques and adopted methodologies in developing edible antimicrobial coatings that are effective in preservation of fruits.

##### 4.1.1. Polysaccharides based edible fruit coatings

Dai et al. [45], prepared crosslinked starch nanocrystals (SNCs) coatings with glycerol as plasticizer for the preservation of Huangguan pears by the solution casting method with different concentration (from 0 to 8.0 wt%) of starch. The authors observed that the coating with 6% SNCs on the Huangguan pears with highest elasticity modulus was significantly effective for extending shelf-life for 4 weeks during storage. The authors reported that the shelf-life extending of Huangguan pears occurs due to the good dispersion of SNCs as a reinforcing agent in the eco-friendly coating matrix and effectively inhibition the respiration of pears and preserve titratable acid with excellent water vapor barrier and mechanical properties. In the present study, the presence of eco-friendly SNCs not only maintained the coloration and transparency of coatings during storage period but also responsible for the preservation of soluble solid content of pears. The authors concluded that the greater stiffness and denser structure of SNCs with large number of hydroxyl groups containing nanostructures imparts better mechanical properties.

Shapi et al. [46], reported the fabrication of starch based antimicrobial nanocomposite films for food packaging with the use of different contents (0, 5, 10, 15, 20% w/w) of chitosan nanoparticles (CNPs). In this study, CNPs were synthesized via ionic gelation, reverse gelation, reverse emulsion, precipitation and polyelectrolyte complexation approach and incorporated with gelatinized starch solution by stirring. From the TEM micrographs of the as-prepared starch/CNPs, it was revealed that CNPs were well dispersed without any agglomeration in the matrix of starch. Antimicrobial studies indicated that as-prepared films exhibited inhibitory zones against gram positive bacteria due to the binding ability of CNPs with the cell wall of bacteria. The authors observed that increase of inhibition zone against gram positive bacteria was directly proportional to the increase of CNPs concentration. Moreover, it was also concluded that 15% and 20% w/w concentration of CNPs in the nanocomposite films exhibited sufficient inhibitory zone against bacteria. Therefore, authors decided 15% w/w CNPs as optimum concentration in the fabrication of nanocomposite films. About antimicrobial effects authors explained that cytoplasmic membrane of bacteria was disrupted by the diffusion of CNPs through the cell wall due to the smaller particle size. In addition, authors also investigated the inhibition of microbial growth on tomato and apple slices coated with starch/CNPs films. They reported that the combination of CNPs with starch matrix was the promising approach. In this combination, large surface area of CNPs with tiny particle size have higher efficiency for the interaction with microbial cells which led to microbe's death. Thus, observed results indicating the good efficacy of CNPs for practical application at large scale.

Medina et al. [47] studied the synthesis of chitosan-thymol nanoparticles using ionic gelation and evaluated their antimicrobial activity by disc diffusion method. In addition, chitosan edible film based on this nanoparticle with sunflower oil and tween 80 was prepared by casting method. Thymol is plant derived antimicrobial agent. The basic composition of thymol is based on hydrophobic and phenolic compounds [47]. The fabricated edible film was then characterised and evaluated their effectiveness for the extension of postharvest shelf life of tomato cherries and blueberries. The mechanical properties (using tensile testing machine), water vapor permeability (wet cup method) and weight loss percentage of the fabricated film were evaluated with respect time. From the result obtained, authors observed that the developed chitosan edible films exhibited not only reduced the weight

loss with effective antimicrobial ability but also improved water barrier properties with the incorporation of 1% (mass ratio) of thymol nanoparticles to chitosan films due to the homogeneous distribution of nanoparticles in the matrix of polymer. The authors explained that the negatively charged bacterial residue interact with positively charged molecules of chitosan matrix, leading to inhibition of protein and mRNA via diffused hydrolysis. The authors reported that hygroscopicity was the main reason behind the slow weight loss of coated fruits because water evaporated from fruit is absorbed by chitosan and cause reduction in water transfer externally.

In another work, Ghosh et al. [48] fabricated the chitosan based edible nanocoatings with the dispersion of magnetic cellulose nanofiber (iron loaded) or cellulose nanofiber through the coprecipitation method. In the present study, authors selected cellulose nanofiber as a filler material because of their ability to generate network structure, which led to provide improve mechanical and thermal properties. On other hand, chitosan was chosen because of their antimicrobial activities in order to reduce the microbial effects on coated fruits. The morphological analysis using FESEM photomicrography and XPS analysis images indicated the good dispersion and uniform interaction of iron particles with sphere-shaped structure on cellulose nanofiber surface [Fig. 2]. The authors used cut pineapple fruit in order to evaluate the effectiveness of developed edible coating to enhance the fruit shelf-life by texture analysis and gravimetric analysis. The results of the study indicate that storage quality of coated cut pineapple was improved significantly with higher mechanical properties as compared to the uncoated fruits under ambient conditions. This was due to antimicrobial properties of chitosan and crosslinking network ability of cellulose nanofiber which led to strong interaction between chitosan and cellulose nanofiber under different pH conditions.

On the plant leaf epidermis, the presence of small openings (stomata) are responsible for controlling the leaves gas permeability with desired "switch" function in proper way. Some researchers have introduced the mimicking of this type of smart structure behaviour in the fabricated coatings on fruit surfaces. So, the permeability of storage atmosphere ( $H_2O$ ,  $O_2$ ,  $CO_2$ ) can be regulate with desired physiological metabolism during the storage time of postharvest fruits in order to enhance the fruits shelf-life. For instance, Zhou et al. (2021), reported a biocompatible hybrid material based on biomimetic strategy of leaves stomata for preservation of perishable fruits at room temperature by effectively control the permeability of gases ( $O_2$ ,  $CO_2$ ,  $H_2O$ ) with selectivity [Fig. 3] [49].

In this work, shellac-based hybrid coating solution was developed by the incorporation of poly (L-lactic acid) (PLLA) or chitosan porous microspheres in the bio-based polymer (Shellac) matrix with the deposition of tannic acid as a functional molecule. The washed fruits (oranges and mangoes) were immersed (dip coating approach) in the prepared hybrid coating solution for 20 s and after drying were kept at room temperature as shown in Fig. 2. The resultant coating membrane of hybrid solution was transparent and flexible. The SEM images of surface and cross-section of hybrid coating solution membrane indicated that the chitosan porous microsphere embedded uniformly in the matrix of shellac. The results of the analysis in order to assess the increment in fruits shelf-life indicated the limited weight loss (only 16% after 45 days of storage) in coated fruits as compared to control or uncoated fruits which was due to the slow down respiratory metabolism, higher barrier ability of  $O_2$  and  $CO_2$  as well as reduced dehydration by controlling the storage atmosphere. Authors also observed that the addition of tannic acid in coating solution further improve the fruits shelf-life not only by the antioxidant and antimicrobial properties but also by controlling the gas permeation with selectivity. The presence of tannic acid in the coating successfully inhibit the proliferation of microbes on the coated fruit surfaces. Hence the authors concluded that the prepared hybrid fruits coating demonstrated excellent antimicrobial characteristics with gas permeation-controlled strategy and could be used for scalable application in fruits preservation. In addition to this, other



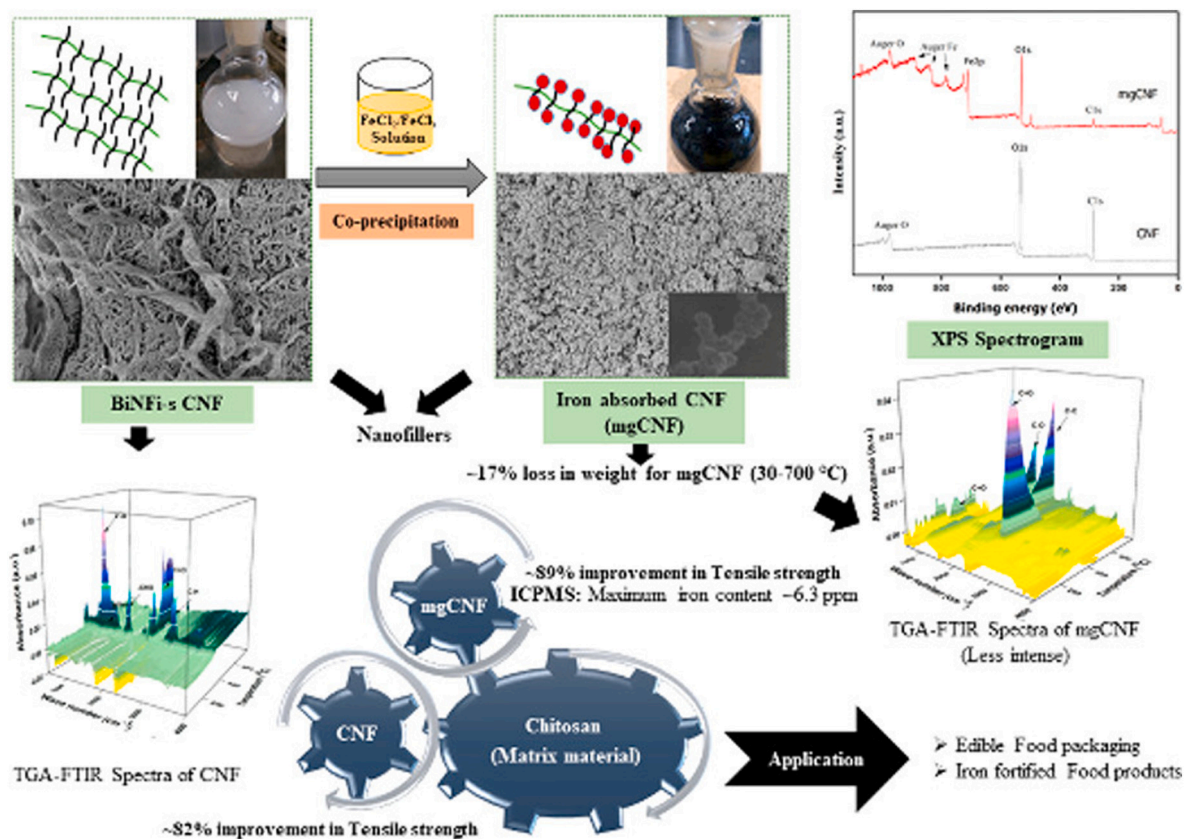


Fig. 2. Synthesis and characterization of Nontoxic Magnetic Cellulose Nanofibers on Chitosan Based Edible Nanocoating. Reproduced with permission from [48]: Copyright 2019, ACS.

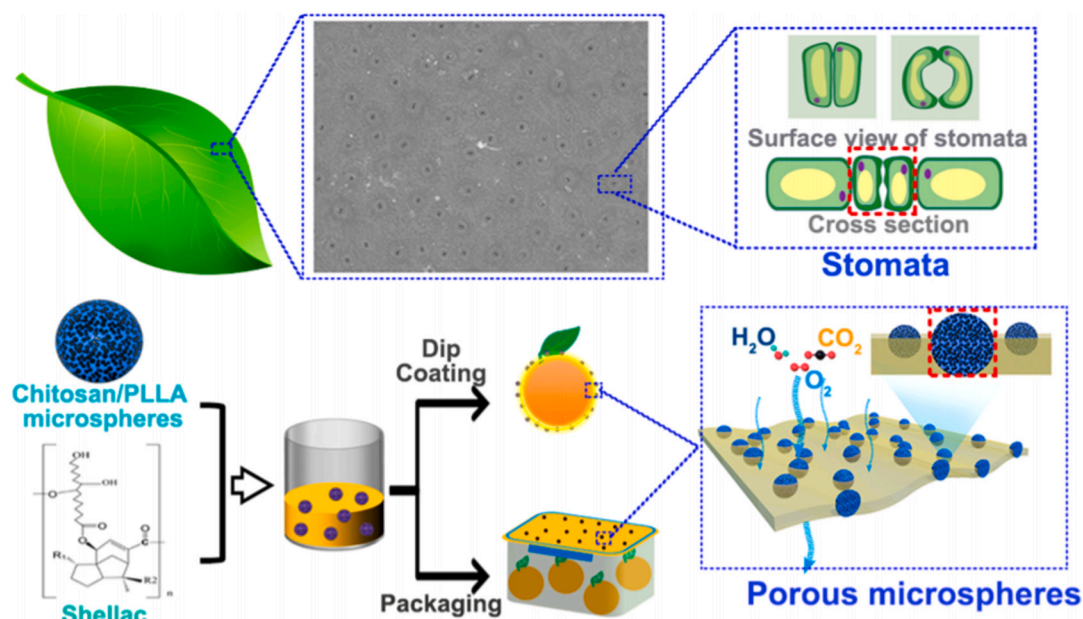


Fig. 3. Schematic illustration of preparation of biomimetic hybrid coating solution and porous microspheres coating on fruits via dip coating approach. Reproduced with permission from [49] ACS.

polysaccharides-based materials (with their properties and composition) that have been tested in many studies for the development of antimicrobial edible fruit coatings in recent years are summarized in Table 1.

#### 4.1.2. Protein-based edible fruit coatings

Proteins are non-toxic, highly biocompatible and amphiphilic biopolymers and derived by combination of similar or diverse amino acids through the peptide linkages [60]. Due to the presence of specific functional groups (such as (a) carboxyl, (b) hydrogen, (c) R-group and

**Table 1**

Application of various polysaccharides-based materials in fabrication of edible fruits coatings and beneficial effects in extension of perishable fruits shelf-life.

Types of polysaccharides	Coatings materials	Fruits	Beneficial effects of final coatings	Reference
Carboxymethyl cellulose Chitosan	Chitosan and carboxymethyl cellulose with stearic acid and phenylalanine elicitor.	Avocado	Carboxymethyl cellulose and chitosan coating significantly improved fruit's resistance to chilling and fungal pathogens, enhanced storability and better taste quality.	[50]
Hydroxyethyl cellulose	Composite coating based on hydroxyethyl cellulose and sodium alginate in combination with asparagus waste extract.	Strawberry	Total flavonoid and phenolic contents maintained in the coated fruits along with delayed in colour change with reduced weight loss. Shelf-life of coated fruits extended to 8 days at 25 °C and 80% relative humidity with effective antifungal activity.	[51]
Chitosan	Multilayer coating of chitosan and sodium alginate layer-by-layer assembly	Strawberry	The developed coating on strawberries significantly reduced weight loss, consumption of total soluble solids, titratable acidity and delayed the accumulation of malondialdehyde with the preservation of antioxidant activity. Coatings exhibited self-healing properties with excellent desired water and oxygen transmission rate.	[52]
Chitosan- and κ-carrageenan	Chitosan and κ-carrageenan based combined coating in the presence of gibberellic acid and methyl jasmonate.	Dragon fruit ( <i>Hylocereus undatus</i> )	Fruit firmness, colour, titratable acidity, total soluble solids were maintained in coated fruits with higher delaying effect on chlorophyll degradation.	[53]
Cashew gum	Edible hydrogel-based coating solution was prepared by the use of cashew gum and polyvinyl alcohol with the mannitol as a plasticizer.	Strawberry	Coating was highly efficient to prevent water loss, fungal deterioration and weight loss of strawberries after 5 days of storage at room temperature.	[19]
Pectin	Pectin and maltodextrin in a ratio of 60:40 with 100 ppm sodium chloride was used for coating	Starfruit ( <i>Averrhoa carambola</i> )	Coating delayed in the reduction of fruit firmness with higher values of greenness and yellowness during 14 days of storage at room temperature	[54]
Pullulan	Pullulan and chitosan in a ratio of 50:50 with pomegranate peel extract was used for coating	Green bell pepper	Degradation of firmness, physiological loss in weight and sensorial characteristics were significantly delayed in coated green bell pepper during storage period of 18 days at both the room (23 ± 3 °C, RH- 40–45%) and cold (4 ± 3 °C, RH-90–95%) storage conditions as compared to uncoated samples.	[55]
Pullulan	Pullulan and chitosan with pomegranate peel extract	Tomatoes	Developed coating improved significant postharvest quality by 9 days as compared to uncoated samples during storage storage at 23 °C and 4 °C.	[56]
Carboxymethylated cellulose nanofiber	Edible coating based on carboxymethylated cellulose nanofiber with 2% (w/w) of multi-valent cations (CaCl <sub>2</sub> )	Strawberry	Respiration and CO <sub>2</sub> released reduced significantly. Delayed in ripening process and maintained firmness during storage period due to the restricted respiration along with the prevention of microbial contamination.	[57]
Alginate	Sodium alginate in hot water with thyme and oregano essential oils and 1% (v/v) Tween 80 as a surfactant	Papaya	Delay in consumption of organic acids, reduced weight loss and respiration rate and improved microbiological safety for 12 days of storage period.	[58]
Starch	Chayotextle starch mixed with microcapsules of resistant starch in presence of ascorbic acid	Guavas	Respiration rate decrease significantly, which led to decrease fruit ripening and reduced the change in of coated fruit surface colour as compared uncoated samples.	[59]

(D) amino group) and unique structure, the mechanical properties of developed protein-based coatings/films are better as compared to the polysaccharides [61]. The role of animal and plant derived protein-based materials in the development of antimicrobial edible coatings have been studied extensively via nanotechnology approaches. For instance, Lemes et al. (2017), developed edible coating based upon enzymatically crosslinked gelatin with curcumin-loaded zein nanoparticles or calcium propionate [62]. In this work, nanoparticles were synthesized by nanoprecipitation approach in the hydroalcoholic solution of zein and curcumin with aqueous solution of sodium caseinate. In the suspension of synthesized nanoparticles, the hydrated gelatin of specific concentration was added under magnetic stirring in order to develop filmogenic solution for coating application. Authors evaluated the antimicrobial and fruit shelf-life enhancing ability of coating solution by the dipping of Benitaka grapes into coating solution. Benitaka grape images clearly indicated the effect of developed edible coating at 25 °C temperature from 0 to 7 days during storage of fruits (Fig. 4). The coated grapes were presented with a shiny surface, whereas control grapes appeared with an opaque surface characteristic. In addition, it was also observed that titratable acidity, weight loss, total soluble solids of gelatin coated grape samples was not affected significantly even after 7 days of storage. The observed result indicates the reduction in respiration metabolism after the utilization of this developed edible fruit coating. On the other hand, no microbial growth was observed on coated grape samples, demonstrating the effectivity of crosslinked gelatin coating with excellent antimicrobial activity.

In another work, Ruggeri et al. (2020) developed bilayered edible

coating by the coupling of poly (vinyl alcohol) with silk fibroin in weight ratio of 1:1 in order to extend shelf-life of fresh-cut apple fruit products during storage. In this work, ascorbic acid was also added to increase the oxygen scavenging properties of the developed coatings [Fig. 5] [63]. The images of SEM and fluorescence microscopy indicated successful formation of binary structure with separate layers of two polymers. The formation of binary layers was due to the different density of these two selected polymers. In addition, the developed film with this coating solution exhibited ductile behaviour which is highly essential property for an edible coating material.

Authors conducted preservation studies for fresh-cut apple coated by dip coating of bilayered of silk fibroin with poly (vinyl alcohol) during storage of 14 days [Fig. 5b]. It was observed that bilayer coating exhibited highest barrier properties to reduce weight, colour change and water vapor permeation from the coated fresh-cut apples as compared to uncoated. This can be attributed to the deep infiltration of silk fibroin into the fresh-cut apple flesh and just underneath the homogeneous and protective outer layer of poly (vinyl alcohol).

#### 4.1.3. Lipid based edible fruit coatings

From the prospective of development of antimicrobial edible coatings, colloidal lipid -based system (e.g., lipid nanoparticles, oils, waxes and triglycerides) has been widely employed to prolong the shelf-life of postharvest fruits during storage. Generally, hot homogenization of lipid and an aqueous surfactant solution is employed to prepared solid lipid nanoparticles. For instance, Zambrano-Zaragoza et al., 2013 prepared solid lipid nanoparticles using the hot high shear stirring method with

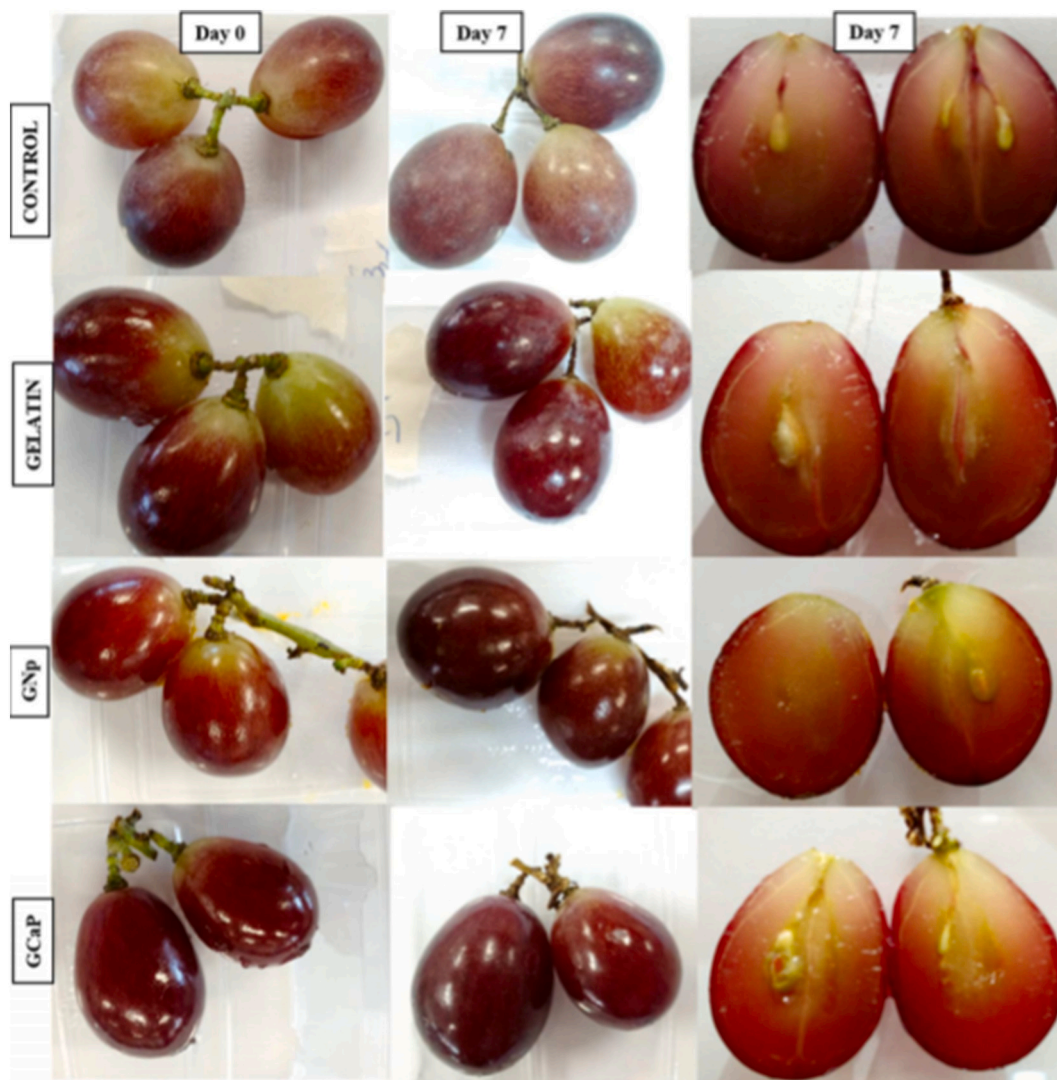


Fig. 4. Images of grapes during storage at 25 °C and 50% relative humidity after the coating process (day 0) and after 7 days. Reproduced with permission from ref. [62]. Copyright 2017 Elsevier.

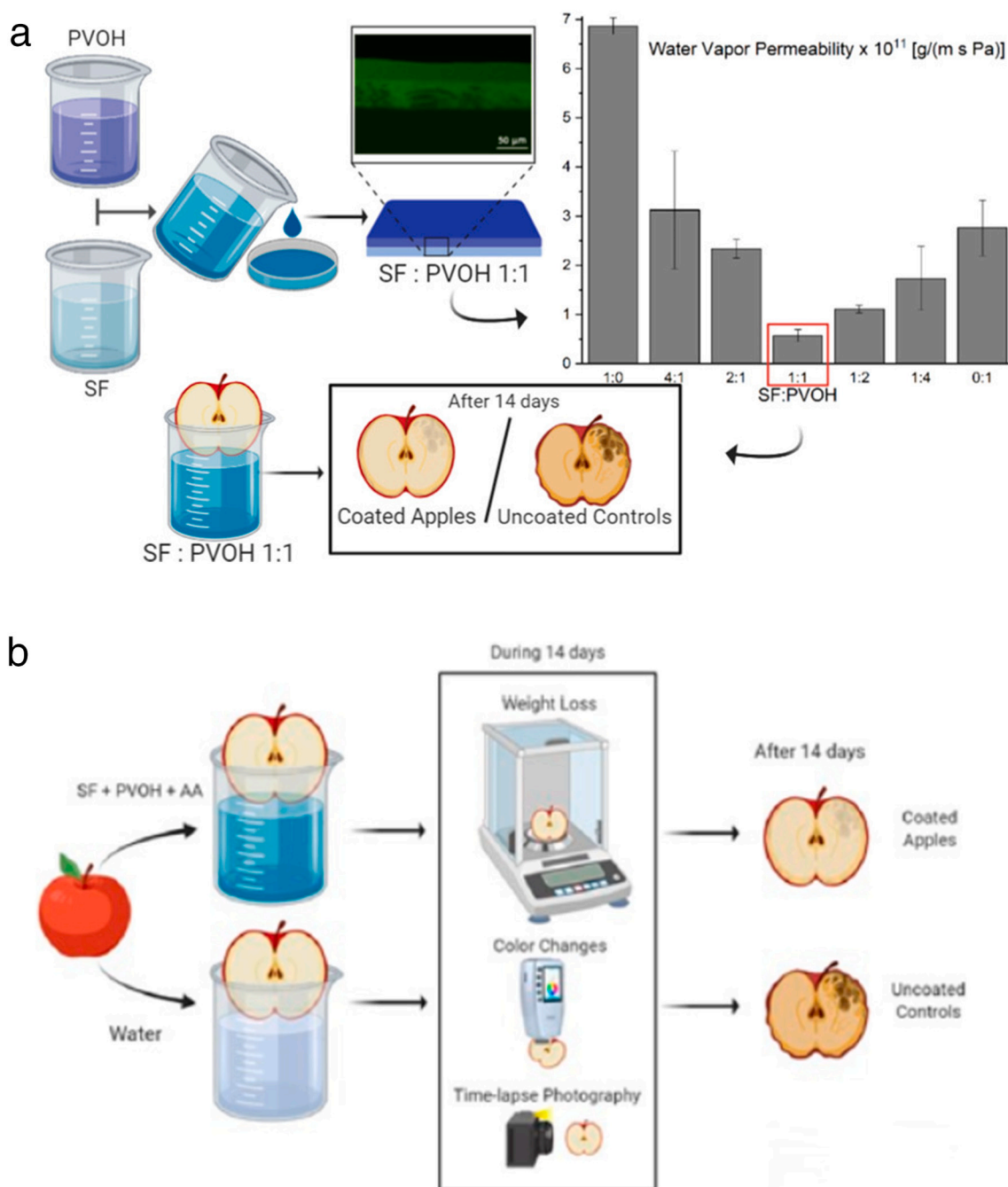
Candeuba® wax [64]. In the present study, coating forming dispersion was prepared by the addition of xanthan gum and polyethylene glycol in a specific ratio with respect to solid lipid nanoparticles concentration. The efficacy of the developed coating was investigated on the guava shelf-life. It was observed that the solid lipid nanoparticles were dispersed properly in the coating and quality postharvest fruits was maintained during storage under refrigeration upto 19 days. The significant reason behind the increase of fruits shelf-life is the lipophilic environment created by the lipid nanoparticles (barrier against water transport) and gas exchange barrier ability of xanthan gum.

Ma et al. 2021 prepared edible coating by the use of shellac and tannic acid and evaluated its efficacy in extension of postharvest mango shelf-life during storage at room temperature [65]. Shellac is a natural biodegradable lipid polymer and has many advantages as excellent coating material owing to its prominent moisture resistance and fast drying ability. However, the major drawback of shellac is its less antimicrobial activity. In view of this tannic acid (TA) was chosen to be mixed with shellac during development of edible coating because of its excellent antimicrobial and antiviral activities. Physical (weight loss, firmness, colour, respiration rate, ethylene production) and chemical (total solid content, titratable acidity, antimicrobial activities) properties of the coated mango fruits was evaluated as compared to uncoated. Authors observed that TA-shellac coated mango fruits exhibited

significantly slow down respiration rate, ethylene production, weight loss and changing in colour from green to yellow upto the 17th day of storage. In addition, it was also observed that addition of TA with shellac significantly enhance the antimicrobial activities of coating along with the protection of total soluble solid content and titratable acidity of coated fruit. The above observations were found to be good to prolong the fruits shelf-life. The major reason behind the obtained observations is the combination of TA-shellac coatings which is protected the destruction of ascorbic acids. The authors postulated that permeability of oxygen was restricted by the shellac and diffusion of oxygen as well as effect of postharvest pathogen were reduced by the presence of TA in coating. Thus, from the above observations, the authors concluded that TA-shellac coating used in the work was versatile and can be used to prolonging the postharvest shelf-life of mangoes in commercial applications.

Natural waxes (e.g., beeswax, candelilla wax) is another type of lipid based lipophilic substances with high content of hydrocarbon (basically alkanes). The presence of long chain alkanes imparts the hydrophobic behaviour to the waxes. This facilitates its utility to fabricate the fruit coating as a protective barrier against humidity and moisture loss during the transpiration process of fruits [66]. In the recent past, many micro-/nano-scale particles derived from natural waxes have been reported in fabrication of nanocoating to extend the shelf-life of fruits. For Instance,





**Fig. 5.** (a) Schematic representation of reaction between silk fibroin (SF) with poly (vinyl alcohol) (PVOH) for the formation of multi-layered membranes and assembling of membrane on fresh-cut fruit upon dip coating. Reproduced with permission from Ref. [63]; Copyright 2020, ACS.

(b). Schematic representation of fresh-cut apple coating with bilayer of silk fibroin (SF) and poly (vinyl alcohol) (PVOH) for the evaluation of preservation studies. Reproduced with permission from Ref. [63]; Copyright 2020, ACS.

León-Zapata et al. 2018 evaluated the efficacy of fruit nanocoating derived from candelilla wax in order to enhance the shelf life of apples. In this present work, nanocoating was prepared from candelilla wax, phytomolecules of tarbush jojoba oil, glycerol and tween 80 by the hot high shear stirring method [67]. Phytomolecules of tarbush have antioxidant activity as well as also useful prevent the agglomeration of nanoparticles with homogenous size. Authors observed that candelilla wax-based nanocoating with phytomolecules of tarbush on apple fruits successfully prevent the weight loss, improve the firmness and enhance the shelf-life until the 8th week during storage under refrigeration and until the 4th week under marketing conditions.

In another study, Formiga et al. 2019 utilized beeswax at different

concentrations of 10%, 20% and 40% (dry basis) with the combination of hydroxypropyl methylcellulose for the preparation of edible coating solution via emulsification process [5]. The characteristics of beeswax is reported as a good moisture barrier and hydroxypropyl methylcellulose as barrier of  $O_2$  and  $CO_2$  gases. Further, they investigated the effect of developed coating solution to extend the shelf-life of red guavas 'Pedro Sato' via dip coating approach. They observed that the developed coating on fruit based on combination of hydroxypropyl methylcellulose + beeswax (20%) produced a modified atmosphere around the fruit and significantly useful in extension of fruit-shelf life. The coating increased fruit firmness, reduced the loss of mass, delaying in ripening process with the proper maintenance of green colour. These improvement in

fruit shelf life is due to the behave of coating as a semipermeable barrier to the gas exchanges ( $O_2$  and  $CO_2$ ) by the entirely or partially covering of micropores, lenticels and stomata. It was also observed that fabricated fruit coating reduced the respiration, starch degradation, ethylene production and inhibiting the action of phosphofruktokinase enzyme in the glycolytic phase during the eight days of storage and led to delay in guavas ripening. In addition to this, other lipid-based materials (with their properties and composition) that have been tested in many studies for the development of antimicrobial edible fruit coatings in recent years are summarized in Table 2.

#### 4.2. Engineered metal nanoparticles based edible fruit coatings

Similar to the other technological and industrial fields such as self-cleaning, hydrophobic and superhydrophobic surfaces fabrication [78–81], inorganic nanomaterials are significantly considered for innovation and improvement in order to hold-up ripening, protect the postharvest fruits and extend their shelf life. In the recent past, there has been increased interest in development of edible nanocoatings with antimicrobial activities by the use of metal nanoparticles with or without use of various natural edible organic ingredients. It has been well established that the use of metal nanoparticles such as silver (Ag), copper oxide (CuO), zinc oxide (ZnO), titanium dioxide  $TiO_2$  and silica dioxide ( $SiO_2$ ) can fabricate highly efficient nanocoatings with antimicrobial activity to prolong the shelf-life postharvest fruits during their storage. The incorporation of metallic nanoparticles with the natural and edible organic materials (derivatives of polysaccharides, proteins, lipids) have emerged to be important techniques in generating antimicrobial edible coating with remarkable changes in surface properties which are highly essential to extend the fruit shelf-life. The storage

stability and shelf-life of a number of fruits have improved successfully after coated with metal nanoparticle-based coatings. For instance, Joshy et al. (2020) reported about the fabrication of biocompatible zinc oxide (ZnO) incorporated xanthan-based antimicrobial edible fruit coatings by double emulsion-solvent evaporation method (Fig. 6) [82].

In this present study, zinc acetate hydrate was used as precursor for the preparation of zinc oxide nanoparticle by the sol-gel method. After the synthesis of ZnO nanoparticle, two emulsion were prepared. Initially, first one emulsion was prepared between poly (ethylene glycols) (PEG, 0.4%) with sesame oil (0.05%), after proper dispersion these components in each other ZnO (0.005%) with xanthan gum (0.5%) added in order to prepare second emulsion. Then stearic acid (SA) was added with stirring to form hybrid suspension for coating application. The authors employed dip coating method to coated selected fruits (apples) and investigated the efficacy of the coating in terms of antimicrobial activity and extension of fruits self-life.

After 13 days of storage at room temperature, the total weight loss was  $17.9 \pm 2.04\%$  on 5th day in case of uncoated samples, whereas it was only  $5.2 \pm 0.66\%$  after day 10 for coated apples, thereby indicating the excellent preservation efficacy of edible coated layer after more than a week. It was expected that metal-based system may be create toxicity, specially erythrocytes. Therefore, authors also evaluated the toxicity of blood compatibility of the hybrid system by incubating the particles along with RBCs and analyzing the percent haemolysis the results of both studies indicated the synthesized nanoparticle-based hybrid coating system was biocompatible and suitable for the fabrication edible coatings. In addition, the author also found that the zinc oxide (ZnO) incorporated xanthan-based coating exhibited significant antibacterial potential which was evaluated by the disc diffusion method with gram positive bacteria (*S. aureus*). Because of the flower like morphology of

**Table 2**

Application of various lipids-based materials in fabrication of edible fruits coatings and beneficial effects in extension of perishable fruits shelf-life.

Types of lipids	Coatings materials	Fruits	Beneficial effects of final coatings	References
Soy-wax	hydroborated-oxidized high-oleic soybean oil and carnauba wax	Citrus fruit	Coating provided better moisture-retaning properties and firmness with efficient antifungal properties.	[68]
Beeswax	Beeswax and hydroxypropyl methylcellulose-based coating with glycerine as a plasticizer	Mangoes	Titratable acidity, soluble solids, pulp and peel colour maintained. Significantly reduces weight loss along with the avoiding activity of fruit fermentation and alcohol dehydrogenase.	[69]
Carnauba wax	Carnauba wax (2.5%) containing orange oil at a concentration of 0.08%	Salacca	Coating enhanced six-days shelf-life as compared to the uncoated fruits. Desired food qualities maintained even after 8 days of storage.	[70]
Beeswax	Beeswax with carboxy methylcellulose and chitosan	Kinnow mandarin	Orange oil enhance the fruit flavour. Beeswax coating minimize the rate of respiration by the blockage of stomata.	[37]
Carnauba wax	Carnauba wax with glycerol monolaurate and oleic acid.	Indian jujube	Reduced firmness and weight loss. Coatings extended fruit shelf-life upto 60 days during cold storage	[71]
Essential oil (Thyme, clove and cinnamon)	Fruits packed in modified atmospheric packaging with essential oil	Mango	Significantly reduced ethylene production, respiration rate and weight loss of postharvest fruits.	[72]
<i>Eryngium campestre</i> essential oil (ECEO)	ECEO and chitosan with pentasodium tripolyphosphate and tween 80	Cherries	Jujube shelf-life and food quality improved for 12 days at 20 °C sale and transportation. Significantly reduces the incidence of postharvest diseases. Effectively delayed in the postharvest decay and extended shelf-life upto 26 days.	[73]
Cinnamon essential oil	Cinnamon essential oil with pullulan	Strawberries	Effective controlling in microbial growth in cherries. Exhibited good physicochemical characteristics (weight loss, pH, titratable acidity, respiration rate, firmness, antioxidant activity, and total phenolic contents) for 21 days as compared to uncoated fruits.	[74]
Cinnamon essential oil	Cinnamon essential oil with gum Arabic and oleic acid	Guava	Excellent antimicrobial activity against bacteria and molds. Extended fruit shelf-life even after 6 days of storage.	[75]
Clove essential oil	Clove essential oil loaded chitosan	Pomegranate arils	Reduces browning index as a chilling marker. Restricted weight loss with high degree fruit firmness.	[76]
Essential oil (ginger, plai and fingerroot)	Essential oil (ginger, plai and fingerroot) incorporated into hydroxypropyl methylcellulose	Mango	After 21 days of storage, maintained the high content of ascorbic acid phenolics, flavonoids and antioxidant activity. Physiochemical characteristics (weight, microbial quality, total soluble solid, total anthocyanin content, pH, total phenol and titratable acidity) maintained significantly.	[77]
			Extended arils shelf-life from 18 days to 54 days. Coating based on ginger oil/hydroxypropyl methylcellulose Exhibited extension of mango fruit shelf-life >18 days at 13 °C. Significant reduction in weight loss, firmness loss, and higher soluble solid content during storage time.	

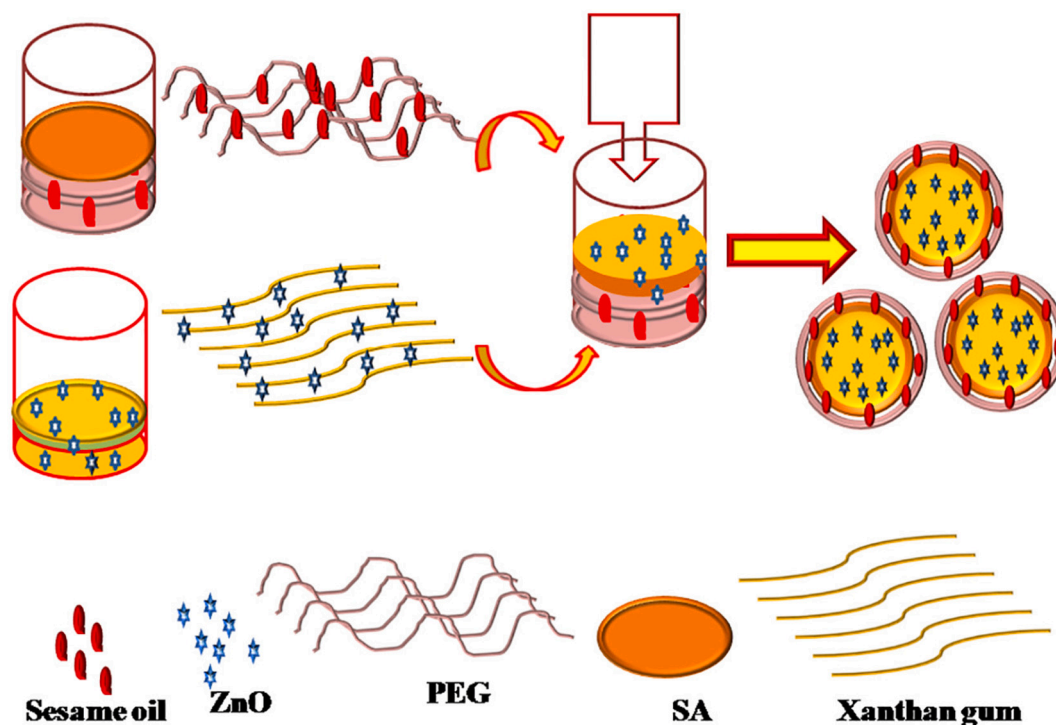


Fig. 6. Schematic representation of preparation of ZnO incorporated xanthan-based hybrid suspension for antimicrobial edible coating on fruits. Reproduced with permission from Ref. [82]; Copyright 2020, Elsevier.

ZnO nanoparticles, there is greater antibacterial activity for coated surface which can display a longer shelf-life of fruits. The authors also concluded that zinc oxide (ZnO) incorporated xanthan-based coating with excellent antibacterial activity indicating a better solution to avoid the utilization of fruit packaging materials based on plastic.

The involvement of metal nanoparticle in the preparation of fruit edible coatings not only add the antibacterial activity but also improve the structural and mechanical properties of the coatings/films along with the antifungal activity. For instance, Guo et al. (2020) developed carboxymethyl cellulose based coating with the addition of cinnamaldehyde and zinc oxide nanoparticle to prolong the postharvest quality of cherry tomatoes [83]. Carboxymethyl cellulose as a matrix is a novel material for fabricating fruit coating owing to its excellent film forming property and biodegradable nature. On other hand, plant-sourced cinnamaldehyde possess antifungal activity and hydrophobicity (not conductive to water attractive), which render them promising components for creating edible fruit coating with good water vapor barrier and antimicrobial properties. The antimicrobial behaviour can be further improved through the incorporation of ZnO nanoparticles with flower like morphology. Keeping in view these facts, authors evaluated the effectiveness of the developed coatings on the postharvest quality of cherry tomatoes during their storage at room temperature with 45% relative humidity. Transpiration and respiration are crucial process during storage to influence the postharvest quality of fruits. Therefore, analysis of weight loss, firmness, soluble solids, acidity and antifungal activity was taken in consideration to evaluate the coating efficacy. It was observed that coated cherry tomatoes showed lowest weight loss and greater firmness as compared to non-coated or only carboxymethyl cellulose treated tomatoes after 10 days of postharvest storage process. In addition, decrease in total acidity values and increase in total soluble were observed. This can be attributed to the suppressing of respiration rate and water evaporation physiological activity of postharvest fruits by the presence of cinnamaldehyde and ZnO nanoparticle in the coated film. Moreover, authors also observed synergistic antifungal effect of cinnamaldehyde and ZnO nanoparticle in coated tomatoes during the postharvest storage by the metabolism of reactive

oxygen species. Hence authors concluded that the ZnO/cinnamaldehyde incorporated coatings demonstrated excellent postharvest protection performance due to their ability to generate reactive oxygen species and water vapor barrier properties.

Madhusa et al. (2020) synthesized bionanohybrid edible fruit preservation coating based upon alginate/ascorbic acid-intercalated layered double hydroxides (Mg and Al) (LDHs) [84]. In this work, initially ascorbic acid-intercalated layered double hydroxides (LDHs) was prepared by the use of green water-assisted mechanochemical grinding technique. After that ascorbic acid-intercalated layered double hydroxides (LDHs) was incorporated with glycerol-based suspension of alginate (polysaccharide) with continuous stirring at 45 °C for 30 min until a homogenous clear suspension. Authors selected washed and dried freshly plucked strawberries and coated by dipping in the homogenous suspension of alginate/ascorbic acid-intercalated layered double hydroxides (LDHs) for 1 min. The coated fruits were allowed to dry at room temperature an evaluated the effect of coatings shelf-life of strawberries as shown in Fig. 7.

The shelf-life studies of coated strawberries indicated that developed coating was effectively maintained the physicochemical parameters such as preserving the titratable acidity and phenolic content, fruit firmness, reduced weight loss, of coated fruits by reducing the permeability of oxygen. In addition, the presence of alginate/Mg-Al layered double hydroxide in the coating material significantly inhibited the microbial growth and extended the shelf-life up to 15 days as compared to control samples. In addition to this, other metallic nanoparticles with the combination organic materials (with their properties and composition) that have been tested in many studies for the development of antimicrobial edible fruit coatings in recent years are summarized in Table 3.

## 5. Advantages of nanostructured coatings on fruits during COVID-19 crisis

The current ongoing corona virus disease (COVID-19) is a contagious diseases and caused by the severe acute respiratory syndrome

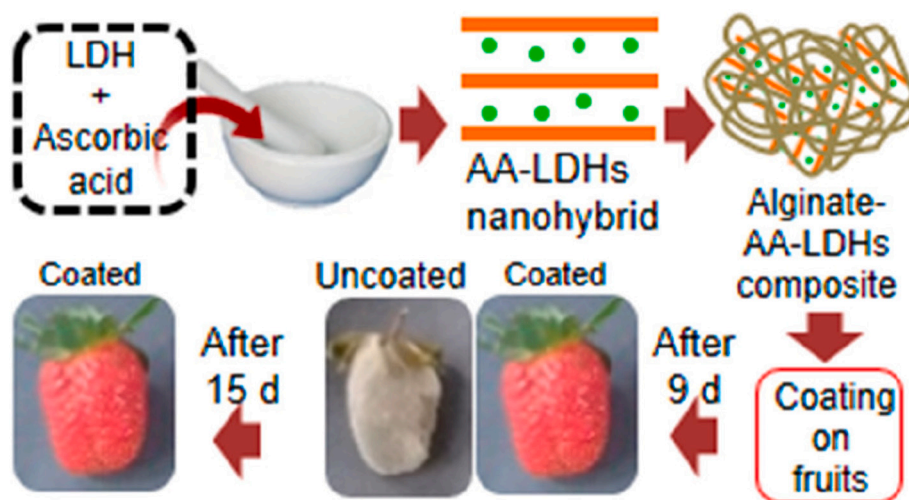


Fig. 7. Schematic representation of fabrication of alginate/ascorbic acid-intercalated layered double hydroxides (LDHs) suspension and coating of strawberries fruits by dip coating. Reproduced with permission from Ref. [84]; Copyright 2020, ACS.

coronavirus 2, Within a short period of time (on 11th March 2020), COVID-19 was declared as pandemic by the World Health Organization [101]. Because of its rapid spreadability, COVID-19 cases led to millions of infections and deaths throughout the globe. During the COVID-19 crisis, similar to the medications, safe fruits with high nutritional value have been emphasized. However, during the pandemic, economic shutdowns for long term significantly affected the nutritious supply chain in the form of fruits from harvesting to the consumption because of the labour shortage, transport restriction and limitation of outdoor activities. These were important reasons for spoilage of fruits in the farms/agricultural fields and generation of huge wastes because of short shelf-life. Thus development of non-toxic, ecofriendly, durable, edible nanostructured coatings with antimicrobial activity on perishable fruits surface is highly advantageous in order to prolong the fruits shelf-life and nutritional security.

In addition to the issues in delay and restriction in fruit supply chain, the detection and long survival ability of virus of current ongoing COVID-19 pandemic on the various surfaces (interior wall of the container, packages etc.) even in cold conditions is a serious concern for fruit nutritional security. The virus-laden droplets of sneeze, cough or exhaled from infected person (would fall quickly on surfaces) are the main mode of COVID-19 transmission and can persist from hours to days. The persistence is varied with type of material characteristics, as shown in Fig. 8 for some common materials [102,103].

The virus present on these surfaces including skin might be able to infect other person through the respiratory system (by touching the nose, mouth or eyes) after contact with contaminated surfaces [103,104]. Still, more than lakhs of infected people as a new cases arising everyday worldwide because of the lack of specific antiviral treatments with respect to this COVID-19. Therefore, each country is facing adverse impacts not only in the economic sectors and activities but also in the global tragedy for human death including food insecurity from a large part of the population [105,106].

Although, there has been no confirmation to justify the transmission of COVID through the utilization of food (vegetables and fruits) it can be contaminated during the handling for processing and buying by the unsanitized hands of person without symptoms. People pick up a product and touch it in order to check the undamaged vegetables, ripe fruits and return it to the shelf or shopping cart. Keeping into account the long time stability of coronavirus on various surfaces, the handling of these food items from production to consumption by the infected hands of either seller or buyer could be a potential source for the indirect transmission of serious coronavirus or similar to this other pathogens [102,105]. A recent investigation has shown that few people become

infected during a conference in Singapore in January 2020 by the shared food and physical contact. Authors postulated that food can be a potential medium for the infection of coronavirus [107]. A Yekta et al. [108] suggested that coronavirus must have been stable in all food products because of its stability in environmental conditions including wide range of pH from acidic (3.0) to basic (10). Authors have also suggested that fruits and vegetables could be contaminated by irrigation of plants and trees with sewage constituting coronavirus and handling by the infected persons. The occurrence of coronavirus in sewage has been reported by the excretion of viral particles from the COVID-19 infected patients [109]. Ultraviolet spectrum with the wavelength of 320–400 nm is the main component of sunlight and almost negligible impact against coronavirus. Authors also suggested that as there is no confirmed treatment available against coronavirus, preventive actions such as antiviral or antimicrobial coatings on foods (fruits and vegetables) and washing hands should be considered to avoid the transmission or direct contact from contaminated surfaces.

Therefore, washing of hands and product surfaces with soap or use of hand sanitizer are highly recommended during worktime to inactivate or remove possibility of virus infections. However, washing of some of the specific fruits surface such as strawberries, raspberries and crinkly lettuce is very difficult [102]. Regarding human safety, there is increasing awareness of the significance of anti-viral edible films and coatings in order to provide protection from infection as well as to prolong the shelf-life of fruits. For instance, Falcó et al. (2019) reported the preparation of antiviral edible coatings by the use of alginate/oleic and containing green tea extract to control the viral infection and improve the safety of berries [110]. They found that strong antiviral efficacy against murine norovirus and human norovirus which are foodborne pathogens. The authors conclude that the development of antiviral edible coatings could be as important vehicles to inactivate the virus infection and rapid transmission in raw and minimally processed fruits.

In addition to this prevention ability of virus transmission, the edible coating on fruits are also useful to prolong the shelf-life of fruits which are highly essential in recovery of COVID-19 patients. Several fruits, such as apples, kiwi, grapes, strawberries, cranberries, blueberries and citrus fruits are richest sources of polyphenols, which are a group of phytochemicals with antioxidants, anti-proliferative, antimicrobial activity and hormonal control ability [111,112]. Polyphenols are highly useful because of their several health benefits in extensive range. Some studies demonstrated that polyphenols such as herbacetin, rhoifolin, pectolarin, sinigrin, hesperetin, quercetin, epigallocatechin-gallate, and gallic acid have potential efficiency in boosting immune and antiviral efficacy against coronavirus without causing major



**Table 3**

Application of metal nanoparticles combine with organic materials in fabrication of antimicrobial edible fruits coatings and beneficial effects in extension of fruits shelf-life.

Nanoparticles	Size (nm)	Coatings materials	Fruits	Beneficial effects of final coatings	References
Zinc oxide (ZnO) nanoparticles	35.17	ZnO nanoparticle with chitosan/gum arabic	Banana	Freshness of postharvest fruit was maintained and prolonged shelf-life for >17 days as compared to control (only 12 days) at 35 °C and 54% RH. Exhibited excellent antibacterial activity against various bacteria.	[85]
Zinc oxide (ZnO) nanoparticles	10–40	ZnO/chitosan/gum arabic	Avocado	Coating with ZnO nanoparticles (0.3 w/w %) significantly improve fruit shelf-life for >7 days as compared to uncoated (Only 4 days). Antimicrobial activity of ZnO preserve the fruit weight, reduces the respiration process and loss of carbon atom in fruits.	[86]
Zinc oxide (ZnO) nanoparticles	–	ZnO nanoparticle with xanthan gum matrix, Poly (ethylene glycols) and sesame oil	Apples and tomatoes	Reduced weight loss and high antibacterial activities due to the protective layer of ZnO reinforced xanthan hybrid system. Enhanced fruits shelf-life >13 days of storage at room temperature.	[82]
Zinc oxide (ZnO) nanoparticles	30–50	ZnO nanoparticle with alginate	Strawberries	Essential physiochemical characteristics of fruits are maintained during 20 days of storage time. Extended shelf-life with microbial safety.	[87]
Zinc oxide (ZnO) nanoparticles	–	ZnO nanoparticle with alginate and chitosan	Guava	Water vapor barrier, mechanical properties and antibacterial properties enhance with the addition of ZnO nanoparticles. Postharvest fruit shelf-life increase up to 21 days as compared to uncoated (only 7 days).	[88]
Zinc oxide (ZnO) nanoparticles	–	ZnO nanoparticle with Soybean protein isolate and cinnamaldehyde	Banana	Delayed in ripening and extended shelf-life >7 days with freshness. Incorporation of nanoparticles enhances antifungal properties 1.25-fold stronger. Significantly inhibited fruit fungus spoilage.	[89]
Silver (Ag) nanoparticles	100–500 nm	Ag nanoparticles with hydroxypropyl Methylcellulose and glycerol	Papaya	Ag nanoparticles (0.25%) exhibited good antifungal activity against Colletotrichum gloeosporioides for >14 days during storage of papaya fruits. Papaya fruit shelf-life increased as compared to uncoated by controlling of water vapor permeability, firmness and weight loss.	[90]
Silver (Ag) nanoparticles	37.01	Silver nanoparticles-polyvinylpyrrolidone (G/CPVP-AgNPs) based glycosomes	Fresh-cut bell pepper	Coating increases shelf-life for 12 days and did not affect the fruit nature with excellent inhibition of microbial contamination.	[91]
Silver (Ag)-Chitosan nanocomposite	20–40	Ag-chitosan nanocomposites into chitosan coatings at a ratio of 1:40 (w: v)	Fresh-cut melon	Significantly prolong shelf-life by reduced respiration rate. Reduced ethylene concentrations within packages were <0.6 µg L <sup>-1</sup> during storage. Maintained fruit firmness, vitamin C concentration even after 13 days of storage.	[92]
Calcium oxide (CaO) nanoparticles	~240 nm	Latex coating with the combination of CaO nanoparticles and poly(vinyl acetate-co-vinyl alcohol	Cucumber	Postharvest shelf-life extended up to 24 days at 10 °C. Superoxide radicals from CaO nanoparticles causes bacteria killing and high antimicrobial activity. Latex coating reduces the respiration rate and delaying the degradation effect.	[93]
Montmorillonite		Chitosan films incorporated with <i>Akebia trifoliata</i> Koidz. peel extracts and montmorillonite	<i>Akebia trifoliata</i>	Prolonged shelf-life by the delaying crack and mature of the postharvest fruits during storage time (35 days) at 5 °C. Significantly controlled gas (O <sub>2</sub> /CO <sub>2</sub> ) by the addition of montmorillonite (0.15%) nanocomposite.	[94]
Nano-SiO <sub>2</sub>	40–60	Nano-SiO <sub>2</sub> based nano film bags (25 × 25 cm <sup>2</sup> )	Loquat	Extended shelf-life of loquat >12 days. Significantly maintain higher levels of extractable juice and ascorbic acid content with better quality as compared to control fruits.	[95]
Titanium oxide (TiO <sub>2</sub> ) nanoparticles	25.78	TiO <sub>2</sub> nanoparticles with chitosan and Carboxymethyl cellulose	Bell pepper	Tensile strength and water barrier properties improved with the incorporation of TiO <sub>2</sub> nanoparticles. Significantly inhibited growth of microorganism. Prolonged shelf-life >15 days.	[96]
Titanium oxide (TiO <sub>2</sub> ) nanoparticles	20.38–28.21	TiO <sub>2</sub> nanoparticle incorporated into alginate and <i>Aloe vera</i> gel	Tomato	Mechanical and antimicrobial properties improved by the incorporation of TiO <sub>2</sub> nanoparticles. Improved shelf-life by significantly reduction in mass loss up to 16th days during storage.	[97]
Titanium oxide (TiO <sub>2</sub> ) nanoparticles	30	Chitosan/titanium dioxide nanocomposite	Mango	Significantly improved moisture retention, maintain firmness, reduced respiration and delayed in fruit ripening during storage up to 20 days.	[98]
Titanium oxide (TiO <sub>2</sub> ) and silver (Ag) nanoparticles	TiO <sub>2</sub> < 100 and Ag < 150	Nanocomposite films based on Poly(lactic acid incorporated with TiO <sub>2</sub> and Ag nanoparticle	Mango	Nanocomposite film extended fruit shelf-life to 15 days with good anti-microbial activities. Exhibited significant reduction in weight loss, firmness, vitamin C and total soluble solid content in coated during storage time as compared to uncoated.	[99]

(continued on next page)

Table 3 (continued)

Nanoparticles	Size (nm)	Coatings materials	Fruits	Beneficial effects of final coatings	References
Selenium (Se) and Silver (Ag) nanoparticles	Se ( $50 \pm 15$ ) and Ag ( $20 \pm 15$ )	Furcellaran and gelatin with the incorporation of Se and Ag nanoparticles	Kiwi ( <i>Actinidia arguta</i> )	The addition of Se and Ag nanoparticles in nanocomposite film exhibited strong antibacterial activity. Prolonged the shelf-life as compared to fruit in LDPE films	[100]



Fig. 8. Illustration of coronavirus persistence on different types of surfaces. Reproduced with permission from [103] Elsevier.

side effects [112,113]. For coronavirus induces severe lung issues in infected patients which is referred as cytokine storm. The cytokine storm causes to increased production of inflammatory cytokines and leading responsible to death of infected patients. The beneficial effects of some naturally fruit polyphenols such as curcumin, apigenin, resveratrol, kaempferol, emodin and epigallocatechin gallate are well documented against cytokine storm induced by coronavirus [113]. Thus, it can be concluded that edible coatings with antimicrobial activity on fruits are significantly advantageous not only with respect to the prevention of virus transmission before infection but also fruitful to extend the post-harvest shelf-life of polyphenolic fruits which is highly essential as immune boosting during the recovery of COVID-19 patients.

## 6. Concluding remarks and recommendations for future studies

After harvesting, high respiration rate, presence of oxygen inside fruits, sugar content variation, rapid metabolism of nutritional ingredients (organic acids, proteins, fats, vitamins and carbohydrates-based components) and microbial growth, are the major causes for shorten the shelf-life of perishable fruits. Shortening of fruits shelf-life aggravates the loss of nutritional security (quality of fruits), economic losses and increases the scale environmental pollution. Therefore, the best possible approach and/or effective materials in order to prolong the fruits shelf-life are highly desirable. Results of this review study

demonstrated that edible fruit coatings, i.e., pristine edible coatings produced from agro-industrial residues (hydrocolloids and lipids) under different chemical and physical modifications, and coating composites (by combination hydrocolloids/lipids with metallic nanoparticles) can be effective and promising to significantly enhance the fruits shelf-life. Ethylene scavenging, controlling of minimum and maximum exchange of respiratory gases ( $O_2$  in/ $CO_2$  out), prevention of moisture loss and possibility of microbial infections are the significant mode of action of edible coatings to extend the postharvest fruits shelf-life. The manner in which exchange of respiratory gases becomes controlled through the coated fruit surfaces depends on the functional groups and cross-linking structures in the utilized coating materials based on selected agro-industrial residues (economical coatings). Additionally, the incorporation of metallic nanoparticles in the fabrication of fruit coatings provides mechanical strength, durability of coatings, significant enhancement in microbiological safety along with the antioxidant activities. It has been shown that edible coatings with antimicrobial activity based on agro-industrial residue are significantly useful in reducing environmental pollution as well as in maintain the nutritional security by enhancing shelf-life of various types of fruits including polyphenolics rich fruits. The utilization of polyphenolic fruits is highly needful as a natural immune boosting source during the recovery of COVID-19 patients because of its beneficial effects against cytokine storm.

Besides having a number of advantages by the incorporation of

metallic nanoparticles in fabrication of edible fruit coatings in lab scale, considering the nanomaterial application in real world (agricultural/industrial) at large scale application, toxicity of nanomaterials is a serious concern. Therefore, it is highly essential to perform further research about evaluation of short and long-term toxicity of nanomaterials at large scale consumption with edible coating in real world application to ensure the safety of environment and human health. The knowledge from this study will be useful to optimize the quantitative concentration of coating matrix and nanomaterials to create highly effective coating for prolonged fruit shelf-life. Furthermore, most of the fruit coating studies were limited against bacterial infection. A limited number of studies are available which are devoted in fabrication fruit coatings with anti-viral activity. Contamination of virus in fruits and vegetables is possible during handling from the production/agricultural fields to the marketing by consumers. Thus, studies based on fabrication of antimicrobial fruit coatings along with anti-viral efficacy are also recommended against prevention of viral transmission and infection. Available results indicate that coronavirus can potentially stay on the surfaces of fruits and vegetables if handled by a person suffering from COVID-19. Therefore, further research needs to be focused in the development of multifunctional antimicrobial engineered coatings with anti-viral efficacy to explore its utilities against coronavirus or similar pathogens of concern.

#### Declaration of competing interest

The corresponding author and co author declare that they have no conflicts of interest with any parties, groups, institutions for publishing the article.

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