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Polymer nano-composite coatings and films: modern insights and emerging strategies to lengthen the lifespan of fruits and vegetables

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Abstract

A definite worldwide shift towards healthier and more nutrient-dense meals has emerged in the past couple of decades. There exists an emerging need for efficient preservation solutions that can effectively mitigate the perishable nature due to the increasing interest in healthy and fresh food products. An efficient method for lengthening the post-harvest lifespan of whole as well as chopped vegetables and fruits is packaging, which includes plastic films and coatings, however plastic packaging has the shortcoming of being a significant environmental threat in nearly every nation. Therefore, sustainable alternatives to traditional food packaging comprise films and/or coatings composed of bio polymers. However, compared to conventional plastic packaging, these biopolymers, which come from nature, have shortcomings such as essential physio-chemical and mechanical qualities. These flaws are fixed by strengthening biopolymers with nanomaterials, which also gives the resulting nanocomposites useful features including antioxidant and/or antibacterial activity. These advances in biopolymer-based nanocomposite can be made with the application of both inorganic (eg., zinc oxide, montmorillonite) and organic (such as nanocellulose fibrils) nanomaterials. This review article discusses the worth of biopolymer coating and films reinforced with nanocomposites to package whole and sliced fruits and vegetables to enhance their lifespan.

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Introduction

A growing middle class, urbanisation, a boost in financial freedom, and changing tastes among consumers are all contributing to an explosive surge in the need for premium fruits and vegetables worldwide. By 2027, it is expected that the international trade for fresh produce could be worth more than 200 billion dollars worldwide[1]. A well-rounded diet must include fruits and vegetables in order to be healthy, being rich in dietary fibre, minerals, vitamins, and antioxidants, all of which are vital for health and can treat a variety of illnesses and deficits[2]. However, fresh produce is extremely fragile and is damaged for a variety of reasons after harvest. Post-harvest losses, also known as food loss and waste, are the largest loss of fresh produce from farm to table that occurs on a global scale (25%–50%). About one-third of the food produced worldwide is lost in this way[3].

Food can be shielded from the outside environment with the help of consumable packaging , which are thin layers of natural polymers with adequate resistive qualities as well as a strong foundations[4,5]. Edible polymeric substances, that are widely distributed naturally, are applied to create eatable coatings and formulations because they are safe, environmentally friendly, biodegradable, and may be taken accompanying food[6,7]. In accordance with the matrix of polymeric substances, they can be divided into four categories: synthesised from polysaccharides (like starches, pectin, gums, alginate and chitosan), made from proteins (such as zein, casein, gluten, whey and gelatin), derived from lipids (such as oils and waxes), and composites made of mixtures of these polymers[8,9].

However, these conventional coatings' rather low antibacterial activity, poor mechanical properties, and weak barrier qualities, require the addition of suitable nano-scale materials in order to create these coatings with higher performance[10]. Biopolymers are reinforced with nanoparticles to increase their functional, physical, thermal and mechanical properties including their resistance capability to moisture and gases[11,12]. Numerous studies have shown how easily conductive, optical, physical, and antibacterial capabilities of these nanocomposites can be tailored by varying their size and dosage[13]. The addition of nanomaterials to an appropriate sustainable polymeric matrix enhanced both the apparent and nurishing qualities of fruits through reducing their weight loss during storage[14], antioxidant capacity[15], antimicrobial properties[16], along with broadened firmness[17], thermal properties[18], and a barrier to gases and moisture[19], hence lengthening the average duration of these products on the shelf[20]. Not only this, other benefits include that these nano-composite films also show oxygen scavenging, carbon dioxide emitting/absorbing, ethylene absorbing, moisture absorbing, and flavour releasing/absorbing properties. Therefore, it is the specialty of these films and a step up from other films that nanocomposites made of polymers combined with nanomaterials demonstrate enhanced characteristics and more substantial adsorption[21].

The basic fabrication methods for these nano-composite coatings include extrusion, layer-by-layer, and casting of solution. A straightforward method for creating blended nanocomposite films is solution casting. Applying films on the surfaces of vegetables and fruits involves smearing, dip coating, spraying or submerging food ingredients with nanocomposite solutions. The technique of coating entails a number of steps, including the synthesis of initial components by using an appropriate ratio of these biopolymers and efficient ingredients including nanoparticles, the formulation of the film solution by stirring, heating, irradiation, and/or pasteurisation, the application of prepared solutions to create uniform and thin coatings on food, followed by drying, and then storage in the proper environment. Figure 1 shows the mechanism through which edible coatings enhances the life-span of fresh produce.

Sources and classification of biopolymers

Figure 2 provides a schematic illustration of various kinds of biopolymers. According to their source and mode of manufacture, biopolymers can be categorised into three main groups: those that are directly taken from biomass; those that are synthesised from bio-derived monomers; and those that are created by microbes[22]. The most intriguing natural polymers used for the development of coating materials are polysaccharides and proteins[23,24]. For a number of reasons, including their propensity for paper-based materials, ability to create a film, suitable barrier to gases and odours, and superior durability, polysaccharides provide excellent replacements for oil-based polymers. Animal proteins and polysaccharides are two biopolymers that are directly derived from biomass and utilised most frequently for the production of food-packaging substances.

Mode of action of nano-composites films and coatings

By distributing a filler ingredient into nanoparticles that form flat platelets, polymer nanocomposites are created. These platelets are subsequently distributed within a framework of polymer, establishing several layers in parallel that force gases to pass through the polymeric material in a 'torturous path', forming intricate barriers to gases and water vapour. Higher barrier qualities come from a polymer structure that is more tortuous. Diffusion and solubility coefficients are used to calculate a polymer film's permeability coefficient: $P = D \times S$.

Effectively, a polymer's permeability is greatly decreased by increased nanoparticle diffusion across it. The United States Army's Natick Soldier Centre claims that the physical strength plus resistive capabilities of the resultant nano-composite thin films have enhancements over the characteristics of pure polymeric films owing to the degree of nanoparticle dispersion inside the polymer. Additionally, due to interactions with nanoparticles, the antimicrobial effect of these nano-composites results in lysis of cells with abnormal organelle function, which disrupts the microbial electron transport mechanism and causes cell death[13].

To achieve optimal performance, nanoparticles require far lower dosage levels than conventional fillers. The weight reduction of nanocomposite films is strongly impacted by the introduction of nanofillers in order that are typically less than 5%. This dispersion approach produces polymers with superior performance than those made with conventional fillers

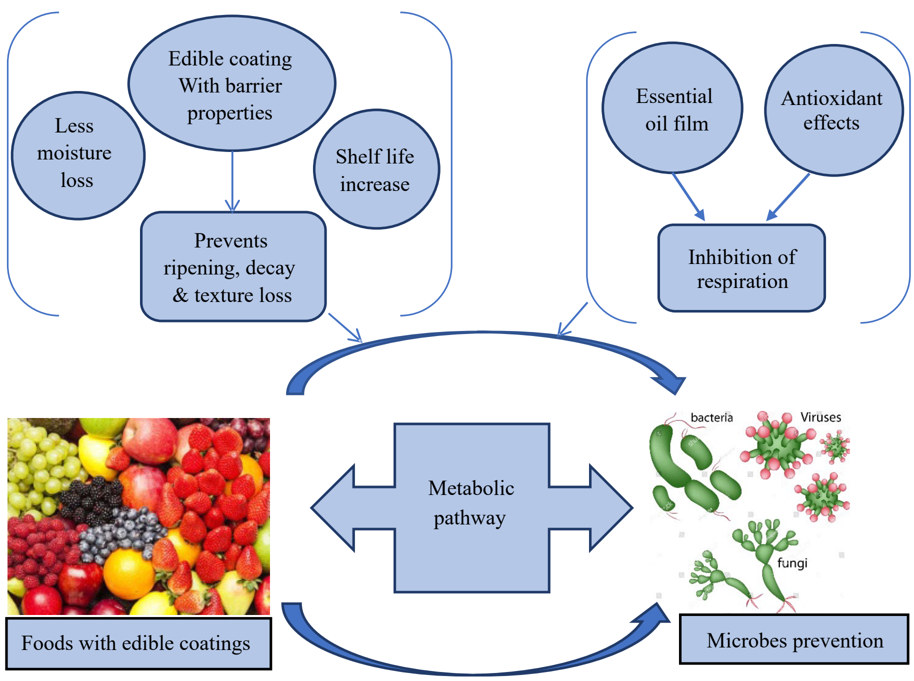

Fig. 1 Edible coating enhances the life-span of fresh produce.

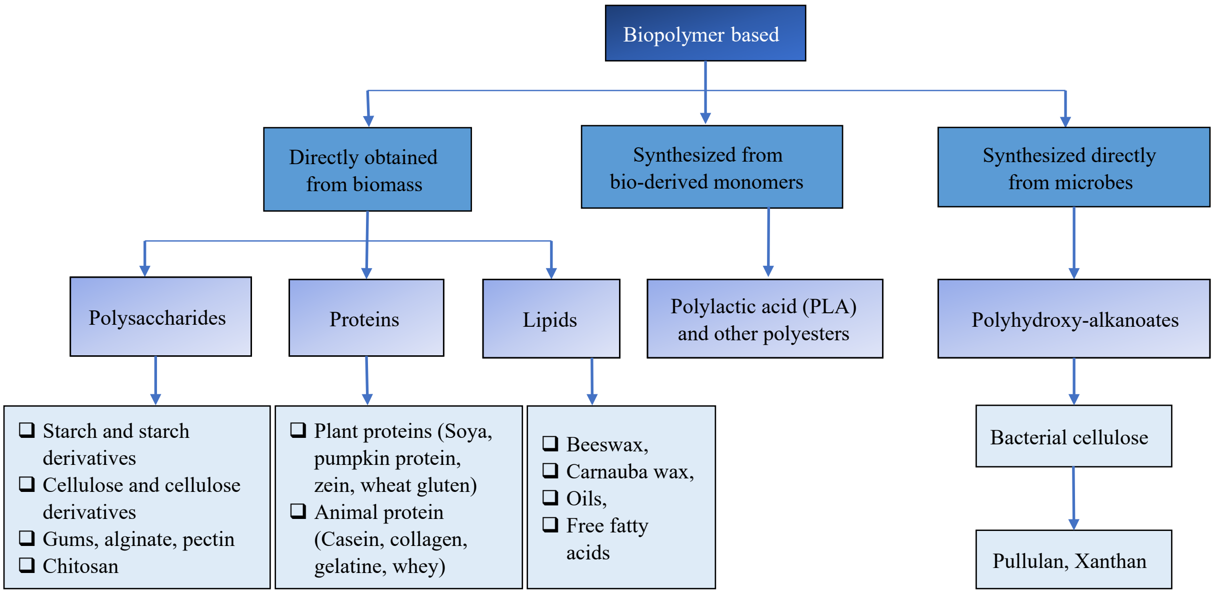

Fig. 2 Illustration of the types and sources of biopolymers.

owning to their greater surface area aspect ratio[25]. The most popular filler is a layered smectite clay known as montmorillonite, which is a form of nanoclay. Clays are hydrophilic in their natural form, whereas polymers are hydrophobic. The polarity of the clay must be changed to be extra 'organic' in order for it to communicate with the polymers satisfactorily[26]. Carbon nanotubes, graphite platelets, carbon nanofibers, and other nanofillers under investigation like synthetic clays, natural fibres (hemp or flax), and POSS (polyhedral oligomeric silsesquioxane) are further nanofillers. Although slightly more costly than some of the more frequently available nanoclay fillers, carbon nanotubes have superior thermal and electrical conductive attributes.

Applications of nano-composite polymeric coatings and films in the food sector

One of the technologies that is most likely to revolutionise current food science and the food industry is nanotechnology. Food systems have demonstrated the effectiveness of processing and packaging helped by nanotechnology[27]. The food business is unquestionably being revolutionised by nanotechnology. The majority of reported uses for nanocomposites in food consist of (i) enhancing the quality of food, (ii) fortifying foods with bioactives, (iii) controlling the discharge of bio-active ingredients by a nano-encapsulation strategy, (iv) improving the asthetic properties of food as well as (v) using intelligent packaging systems to detect and neutralise biochemical, microbiological, and chemical changes[28].

Furthermore, several of the biggest food corporations in the world are constantly investigating the prospective of nano-materials to be applied in food applications[29]. Incorporation of nano-composite biopolymers as food packaging substances are therefore become an emerging topic for researchers as it has become the need of the hour to substitute for plastic packaging[30]. Moreover, the increased application of bio-polymeric materials to package fresh produce can result in less plastic waste, fewer emissions of greenhouse gases and ensures the sustainable use of natural resources[31−34].

Nowadays, fruit and vegetable preservation is receiving a lot of attention thanks to the adoption of novel nanotechnology-based strategies to enhance the functioning of consumable coatings and films. Edible coatings are proven successful in doing so and some examples in this regard are listed ahead. Strawberry was coated with a bio-nanocomposite coating created by Emamifar & Bavaisi[35] using sodium alginate and nano-ZnO. Their findings showed that nano-ZnO considerably improved the moisture barrier of films, reducing strawberry weight loss as a result. At the completion of 20-d storage duration, uncoated fruits had lost more weight than coated fruits. According to Chi et al. silver and titanium nanoparticles enhanced the moisture resistance ability of prepared films[36]. The weight loss of mangoes packed with nano packaging film was also the least of all packages. According to Zhang et al. the PLA sheets loaded with silver nanoparticles had an exceptional barrier to moisture[37]. Furthermore, they claimed that PLA-Ag's mass loss of strawberry fruits was smaller than that of the untreated film (which did not contain NPs).

According to Resende et al. the chitosan and cellulose nanofibril (CNF) film limits the diffusion of oxygen, reduces respiration rate and slowed the oxidation of strawberries by vitamin C response[38]. Since coatings with an increased CNF content demonstrated a greater resistance against oxygen, consumable films with an elevated CNF content were advantageous for the greater retention of the lifespan of strawberry. According to Li et al. the increase in nano-ZnO caused a decrease in the diffusion coefficient for PLA sheets[39]. According to Emamifar & Bavaisi[35], adding nano-ZnO to edible films made of sodium alginate improved its antioxidant properties. Additionally, it resulted in a reduction in the amount of oxygen needed for the enzyme-mediated oxidation of phenolic and anthocyanin chemicals. On the strawberries surface, it served as a protective layer for the exchange of gases. At the conclusion of storage (20 d), they noticed that uncoated strawberries had more phenolic degradation and antioxidant activity decrease than treated strawberries. Several research and investigations of these films and coatings and their effect on the shelf life of fresh produce are summarised in Table 1.

Regulation of nanomaterials in coatings and films

Consideration must be given to both the potential risk of packaging materials harming consumers and their potential to contaminate food. However, only a few studies have looked at the impacts of consuming nano-materials and the interactions that might occur between food contact materials made of nanomaterials and food components[49,50]. The aggregate migration limit for all chemicals that may leak from things near foods is now 10 mg component / dm^2 surface area as per European law (Commission Regulation (EU) No. 10 year 2011) (https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:012:0001:0089:en:PDF). Echegoyen & Nerin explored whether silver moved as ions or particles when it was transferred from nano-composites into food enhancers[51]. Silver and copper mobility from nanocomposites used in packaging for food to investigate their antibacterial capabilities has additionally been examined[52]. The investigation found that, in comparison to the size of the particles, temperature, and contact time, the amount of nanofiller in the nanocomposites was one of the most important factors influencing migration.

Despite the efficient applications of nanotechnology in the field of food packaging, the use of these technological developments brings up a number of potential hazards and ethical issues that should be wisely addressed with additional study and development. As a result, the effective as well as safe implementation of applications based on nanotechnology depends on continual communication between the researchers, enterprises, and users of those applications. The standards that will be utilised in calculating the safety of packaging of food items and the use of nano-materials infused polymeric films with unique characteristics and functionalities ought to have been established by regulatory agencies.

The development of novel methodologies, strategies, and standardised test procedures is required to evaluate the critical risks linked with human exposure to nanoparticles. These procedures will be used to examine the impact of nano-particles during consumption or the possible interaction with food material. However, it is projected that in the next years, consumers will have more opportunities for food packaging made possible by nanomaterials. Compounds that have a physiological effect should be disclosed on the label since edible coatings may contain them[53]. A concern for food safety has been the condition of the food quality , their effect on nature, and the migration of substances into the human body that adhere to general and specific migration limitations. The Food and Drug Administration (FDA) in the US is in charge of ensuring the safety of food contact materials as well as the protection of health of the public. It additionally serves a critical significance in assessing quality of food items including nanoparticels and components created at the nano-scale level[54]. To assist the trade and provide suggestions for science, analysis, and regulating policy, the FDA has issued a number of publications on nanotechnology. According to the FDA Commissioner, dealing with items based on nanotechnology has been approved[55]. Furthermore, nano-sized particles can only be applied in accordance with European Union regulations if authorised and mentioned in rules of Annex I ; furthermore, their transfer to food items below a specific recognition range must be tightly monitored.

Conclusions

This review examined the traits of edible coatings and bionanocomposite films used on fruits and vegetables. The influence of metallic nanoparticles inserted into the framework of

Table 1. Nano composites coatings and their quality parameters for fresh produce.

Sr. No.	Main component	Active component or NP's	Targeted fruit/ vegetable	Effects/significance	References
1	Chitosan/chitin	Silver NPs	Cantaloupes	Enhanced antimicrobial activity and greater antibacterial effects.	[40]
2	Cassava starch	Zinc oxide NPs	Fresh-sliced Okra	Better product quality and improved packaging characteristics.	[41]
3	Carrageenan	Zinc oxide NPs	Mango	Shelf life increased up to 19 d	[42]
4	Sodium alginate	Citral nano-emulsions	Pineapples	(1) Enhanced antimicrobial activity, (2) Improved colour quality, (3) Less respiration ability.	[43]
5	Polyvinyl pyrrolidone/glycerosomes	Silver NPs	Fresh-cut bell pepper	Antibacterial and biocidal effect and shelf life enhancement.	[44]
6	Carboxymethyl cellulose (CMC) and Guar gum	Silver NPs	Strawberry	(1) Antimicrobial activity on gram-positive and gram-negative bacteria including fungi, (2) Strawberries packed in antimicrobial coatings lose less weight overall than non-coated strawberries.	[45]
7	Pectin	Magnesium NPs	Cherry tomato	Enhanced shelf life of cherry tomato	[46]
8	Polyvinyl alcohol (PVA)	Chitosan nanoparticles	Mangoes	(1) Improved antifungal activity, (2) Shelf life enhance upto 20 d.	[47]
9	Cellulose nanofibrils (CNF)	Nano-cellulose	Spinach	(1) Retentions of texture, appearance, chlorophyll and color, (2) Moisture content retention after three days storage at 25 °C	[48]

biopolymeric materials and their effect on overall outcome for decreasing the post-harvest damage of fresh produce was the focus of attention. The findings showed that metal NPs can enhance the qualities of nano-composite polymeric films and coatings. Biocomposites comprising nano-sized are the greatest options for vegetables and packaging applications that can extend their time span on the shelf. Additionally, edible coatings and bio-nanocomposite films help to delay fruit ripening and further reduce weight loss, respiration rate, colour changes, and ethylene. However, very few nations in the world recommend any kind of uniform regulatory framework for the implementation of nanotechnology in food items. This is primarily as a consequence of the lack of awareness regarding the potential health risks of nano-particles in the food packaging sector. The governments and industry appear to face considerable obstacles in achieving the above estimates concerning the efficacies of nanomaterials due to scant or unsuitable scientific debates in this sector.

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Conflict of interest

The authors declare that they have no conflict of interest.

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