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GENERAL AND APPLIED PHYSICS

Recent Advances in the Application of Nanotechnology to Reduce Fruit and Vegetable Losses During Post-Harvest

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Abstract
Fresh fruits and vegetables are essential sources of nutrients and bioactive compounds with a beneficial effect on human health. However, these products are highly perishable and have a short post-harvest life with significant losses worldwide. New advanced technologies, such as nanotechnology, have been used to help reduce post-harvest losses of fruits and vegetables. Nanotechnology can be applied on (i) designing edible coating materials with improved properties extending produce shelf-life, (ii) on packaging with antimicrobial activity enhanced with physical barrier properties, and (iii) additionally with sensors capable of indicating ripening stage and internal quality of fruits and vegetables. The main objective of this article was to review recent advances in the application of nanotechnology for the development of technologies capable of contributing to reduce post-harvest losses of fresh fruits and vegetables.

Keywords Nanoemulsions · Edible coatings · Nanoparticles · Nanosensors

1 Introduction

Fresh fruits and vegetables are an important source of fibers, vitamins, minerals, and bioactive compounds such as carotenoids, anthocyanins, and vitamin C, essential for human well-being. However, they are perishable live products that require coordinated activities by producers, storage operators, processors, and retailers to maintain quality and reduce post-harvest losses [1]. Significant post-harvest losses, ~40% in developing countries, occur in fresh vegetables during supply chain, and the main cause is post-harvest deterioration, mainly due to rot, that compromises the quality and durability of fruits and vegetables [2, 3]. Major causes are non-application of continuous cold chain, combined with intensive handling [3]. It is important do highlight that food losses causes economic, social and environmental impacts. Natural resources, fertilizers and labor are also indirectly disposable, that unfortunately were not used to feed people,

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but urban dumps, with gas emition and water contamination, among other hazards [4].

Consequently, there is a huge demand for alternative postharvest technologies that should offer protection against diseases and physiological disorders, in addition to delaying senescence, and thereby improving the handling and maintenance of the quality of fresh fruits and vegetables [5].

In recent years, nanotechnology has been introduced as a new opportunity to develop new technologies to increase shelf life of fresh fruits and vegetables [6]. Its submicron size offers a new way to improve the properties of materials to food conservation such as improving gas exchange, mechanical and optical features, water barrier, and also functionality with greater sensitivity to antioxidant and antimicrobial activity [6].

Therefore, nanotechnology has been used in the area of fruit and vegetables postharvest technologies for i) the development of new coating materials (nanocomposite or nanoemulsion coatings) with better physical and antimicrobial properties [7–9], ii) polymeric packaging with nanoparticles with antimicrobial activity for the conservation of fruits and vegetables [10], and iii) development of nanosensors with high sensitivity for detecting volatile compounds such as ethylene capable of indicating the ripeness of fruits and vegetables [11]. The main objective of this review was to report the recent advances in the application of nanotechnology for the development of technologies capable of contributing to the reduction of losses of fresh fruits and vegetables.

2 Nanotechnology: an Overview

Nanotechnology is defined as the science and technology that is involved in the synthesis, characterization, and application of materials and devices at the nanoscale (generally in the range of 1–100 nm) [12], having several applications for food industry. Particles in the 10^{-9} m size range have unique characteristics that alter the properties of molecules and their subsequent effects [13].

Nanoscale materials have better properties such as high transparency, good mechanical strength, improved antimicrobial properties, and others [14]. Nanomaterials can be found in the form of nanosheets, nanoemulsions, nanotubes, nanofibers, nanoparticles, and nanowhiskers [15].

The application of nanotechnology in the food area preservation can occur in two opposite approaches "from the top-down" or "from the bottom-up." The first one is achieved through physical methods, and is currently the most used, where nanoscale materials are synthesized by breaking a larger portion of the material into nanoparticles, using techniques such as milling and nanolithography [16]. In the bottom-up technique, nanomaterials are synthesized from individual atoms or molecules [5]. Nanomaterials must have a larger specific surface area to present functionality. The top-down and bottom-up approaches to producing nanomaterials are shown in Fig. 1.

3 Nano-Edible Coatings for Fruits and Vegetables

A significant challenge in applying nanotechnology to conserve and prevent fruits and vegetables loss is to maintain quality, or at least to assure that there are no negative alterations in their functional and nutritional properties [18]. One of the most efficient technologies that can be used to ensure the maintenance of quality features are edible coatings, a thin edible layer formed on the surface of the

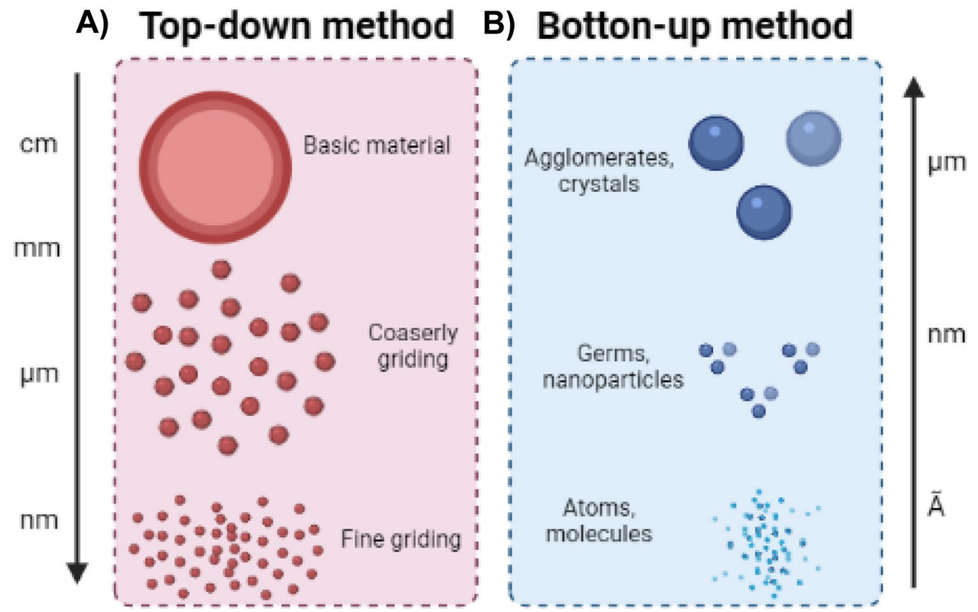

Fig. 1 Schematic **a** top-down and **b** bottom-up approaches for making nanoparticles. Adapted from Roohinejad and Greiner [17]

fruit or vegetable, which guarantees the extension of its shelf- life [19].

The main mechanism of action of edible coatings (Fig. 2) involves the retention of CO_2 (produced during respiration) by the edible layer, and consequently O_2 reduction. In this way, less O_2 is required by the respiration process, which triggers a series of metabolic processes, such as lower ethylene production, lower water loss, maintenance of firmness, and, consequently, an extension of the shelf life of fruits and vegetables [20]. For this mechanism of action to occur, the edible coating must have some specific properties, depending mainly on its molecular structure, such as: being water and mechanically resistant, covering the product properly, not eliminating totally the O_2 inside the formed layer, improving appearance, drying easily and not melting at higher temperatures, having a certain degree of transparency to light and, above all, being economically viable [21].

One of the ways to further improve the properties of edible coatings and, consequently, their effects on coated food, involves the use of nanotechnology: incorporating nano-sized components into the coating can bring numerous advantages due to their greater surface area, which enhances their biological activity and their stability in the medium [19]. Nano-edible coatings have improved structural properties and manage to further restrict the transfer of gases and moisture, preventing weight loss and slowing down the respiratory metabolic process of the coated fruit. In addition, nanoparticles or nanosystems can improve the visual appearance and impart antioxidant and antimicrobial properties to the edible coatings [19, 22–24].

There are different types of nanostructured systems that can be applied as nano-edible coatings, each with its particular characteristics, advantages and disadvantages; among the most common systems are as follows: polymeric nanoparticles (which have non-toxicity, biodegradability, ability to form films and better mechanical properties as advantages), solid lipid nanoparticles (also known as SLN, potential suppliers of bioactive compounds to the coating), inorganic/organic nanocomposites (with improved mechanical and barrier properties), nanotubes and nanofibers (with high crystallinity and negative charge, which allow a better association with the food surface), and nano-emulsions (delivery channels of nanostructured lipophilic active components, such as essential oils) [25, 26]. Table 1 provides some recent examples of different systems that have been applied as nano-edible coatings in fruits and vegetables and their effects on improving quality conservation.

Edible coatings, regardless of their composition, can be applied by different methods to the surface of fruits and vegetables; among the most traditional deposition methods are dipping, spraying, and brushing [18]. More recent technological methods for applying edible coatings, used for years in other applications in the food and pharmaceutical sectors, for example, are fluidized bed processing and panning. In relation to nanostructured coatings, even more advanced and robust techniques have been put into practice to guarantee uniform distribution of the coatings on the surface of foods; one of them involves the use of micro-sprays and electro-sprays, in which the deposition solution passes through a capillary nozzle, maintained at high-electric potential, and forms droplets ranging from tens of nanometers to hundreds of micrometers. Even more innovative, the atomic layer deposition (ALD) technique can deposit ultra-thin films one atomic layer at a time, in sequential cycles that allow controlling the thickness of the formed films [38, 39].

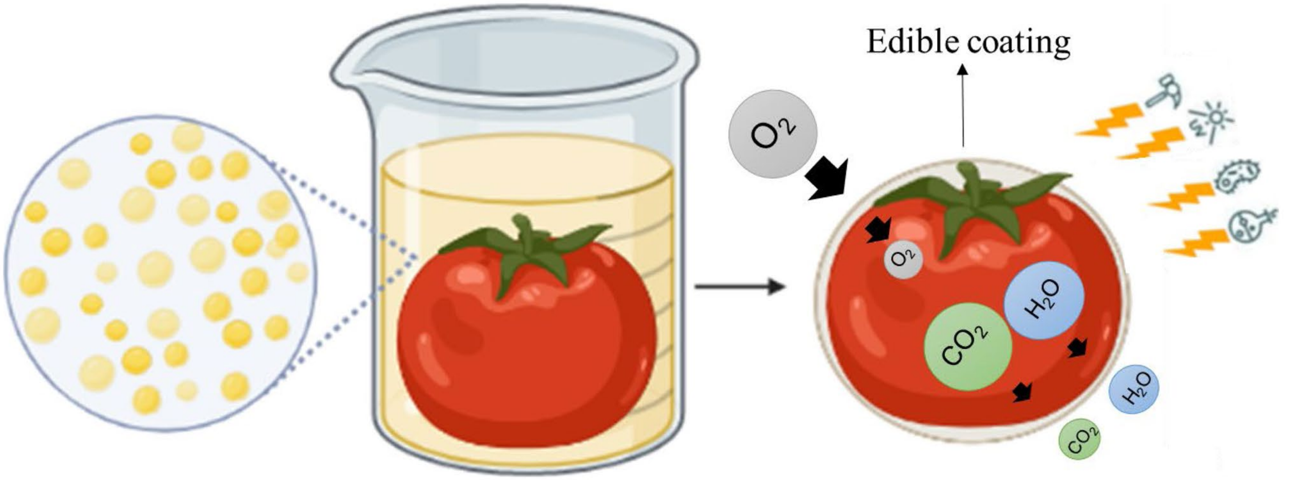

Fig. 2 Main functions of edible coatings on fruits and vegetables. Adaptated Braga et al. [22]

Table 1 Recent examples of different systems that have been applied as nano-edible coatings, and their effects on the quality of food products

Nano-edible coating system	Components	Food product coated	Beneficial effects	Reference
Polymeric nanoparticles	Chitosan	Bananas	Delay in the ripening process, with lower *MaACS1* and *MaACO* gene expression for the coated bananas	[27]
	Chitosan	Table grapes	Delay in the ripening process, with reduction in weight loss, soluble solids, and sugar contents	[28]
	Chitosan	Fresh-cut bell pepper	Maintenance of weight and sensory quality of peppers for 12 days at 5 °C	[7]
Solid lipid nanoparticles (SLN)	Candeuba® wax and xanthan gum	Guavas	Reduction in O_2 and CO_2 permeability, retention in ascorbic acid and total phenols content	[29]
	Candeuba® wax and xanthan gum	Tomatoes	Maintenance of firmness and lycopene concentration over time	[30]
	Beeswax, xanthan gum and propylene glycol	Strawberry	Decrease in weight loss, decay index and loss of firmness	[31]
Nanocomposites	Chitosan, alginate and ZnO nanoparticles	Guavas	Extension in guavas shelf-life for up to 20 days (versus 7 days of uncoated guavas)	[8]
	Cassava-starch and starch nanocrystals	Pears	Maintenance of the color, texture, permeability, and inhibition of peroxidase (POD) and polyphenol oxidase (PPO) activities	[32]
	Chitosan and ZnO nanoparticles	Fresh-cut papaya	Suppression in the microbial contamination of papayas in relation to the control, with a visible reduction on day 4 of storage	[33]
Nanofibers	Cellulose	Strawberry	Restriction in respiratory process and delay in strawberry senescence	[34]
	Cellulose	Grapes	Decrease in weight loss and water vapor permeability, improvement in mechanical characteristics	[9]
	Whey protein isolate nanofibers, glycerol, and carvacrol	Salted duck egg yolk	Decrease in weight loss rate in a hardness increase rate	[11]
Nanoemulsions	Alginate and basil oil	Okra	Maintenance of textural, color, and overall acceptance; prevention of fungal infections during prolonged storage	[35]
	Chitosan, carboxymethyl cellulose and citral	Fresh-cut melons	Up to a 5-log reduction in microbial contaminations and up to 13 days of shelf-life extension	[36]
	Sodium alginate and sweet orange essential oil	Tomatoes	Increase in total acceptance of the tomatoes, increase in firmness, and decrease in total mesophilic bacteria and in weight loss	[37]
	Carnauba wax	'Nova' mandarins and 'Unique' tangors	Less water loss, conferred gloss, and caused less ethanol production than shellac	[23]
	Carnauba wax	Papaya	Reduce weight loss, delay ripening and decreasing ethylene production	[24]

From a technological point of view, a recent technique that has shown promising results with the use of nano-edible coatings is encapsulation; the main objectives of encapsulating a compound are to protect it from external interactions and/or to release it in a controlled manner to the medium, in this case, the coated food. Substances such as vitamins, antioxidants and antimicrobials compounds, fatty acids, pre and probiotics can be packed into nanometric capsules. Their food release will be controlled under specific conditions, such as heat, humidity, and pressure [40]. Among the nano-edible coatings systems mentioned above, the most commonly applied as encapsulation systems are the nano-emulsions, which have a high delivery/encapsulation ability [18].

Another current line of investigation regarding nano-edible coatings, in addition to their method of application, concerns the evaluation of their biological potential (as the anti-cancer property), combining the issue of post-harvest losses with the active properties that the edible coating can provide when ingested. Joshy et al. [40] developed carboxymethylcellulose hybrid nanodispersions containing stearic acid, polyethylene glycol, and sesame oil, with curcumin as the encapsulated bioactive compound. Coatings were applied to apples and tomatoes, showing promising results of anti-cancer activity in vitro, with a significant reduction in fibroblast proliferation and changes in cell morphology.

From what was discussed, it can be concluded that the development and use of nano-edible coatings are one of the most efficient ways to associate nanotechnology with the conservation of fruits and vegetables; much has been developed, from a technological and biological point of view, but some limitations of this technique still need to be improved, so that better and more comprehensive results are achieved. In this case, nanotechnology can be an important factor in edible coatings developing, Generally Recognized as Safe—GRAS, from organic particles, such as plant origin, with new properties [22]. There has been a high demand for green products, and nanotechnology can make one differential. One example is the carnauba wax, a very well-known coating component, which one of the main features is maintaining fruit water moisture. Furthermore, by nanoemulsion, gas exchange properties can be added, extending considerably shelf life [23].

Among the main limitations associated with the use of nano-edible coatings are metabolic fruit disorders related to the excessive restriction of the coatings internal atmosphere, allergic reactions arising from one or more coating components (such as nuts, fish, dairy, etc.), cost of operating conditions necessary to produce the coatings, and lack and/or cost of efficient machinery for their large-scale application [19].

4 Packaging with Nanoparticle Additives for Quality Preservation of Fruits and Vegetables

Packaging efficiently protects food products from chemical, physical, and biological contaminants, maintaining the sensory characteristics. Additionally, has a fundamental function in quality and food safety, extending shelf life, and waste-reducing [41–44].

Over the years, microorganisms have been considered responsible for various food diseases, making them one of the leading food safety concerns in the world. According to World Health Organization (WHO), there are about 250 food hazards, and every year 600 million people are affected by foodborne diseases [41]. In the production chain, food contamination can occur from post-harvest to processing and distribution until the final consumer at the market. Thus, strict protocols are necessary to reduce the risk of microbiological diseases, making packaging essentials for this chain [41, 42, 44].

Polymers, particularly polyethylene and their blends, are commonly used for fruit and vegetable packaging, attributed to non-toxicity, high durability, and molding properties [45, 46]. The usual polymeric materials in this type of packaging are polyethylene terephthalate (PET), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), high-density polyethylene (HDPE), low-density polyethylene (LDPE), and linear low-density polyethylene (LLDPE). These polymers can be molded as bottles, trays, bowls, bags, films, pouches, and others, enabling protection according to the food characteristics [46].

Technologies denominated as active packaging help maintain food quality and safety and increase shelf life by inserting antimicrobial agents in the polymeric structure [41–43, 45]. The molecular interaction between antimicrobial agents and polymeric chains predominate Van der Waals and electrostatic attractions, allowing the additive-free to transfer from the polymeric medium to the surface of the package and enabling direct contact to the microbial cell membrane [44].

Among the studied materials in food packaging, nanoparticles are one the most promising actives showing elevated surface/volume ratio and reactivity, attributed by smaller size compared to the macroscale [47–50]. Typical nanostructures used are metallic silver Ag [51], oxides such as titanium (TiO_2) [52], copper (CuO) [53], zinc (ZnO) [54], silicon (SiO_2) [55], clays [56]. magnesium hydroxide (Mg(OH)) [57], and cellulose [58]. Metallic silver is one of the most usual materials concerning nanoparticles due to its intense antimicrobial activity and its additional properties as higher thermal stability and chemical compatibility with polymer matrices [42, 59, 60]. However, oxides (ZnO and CuO) have been available due to antimicrobial activity, low cost and accessibility [53, 58, 59, 61].

As well the protection against direct contact of fruits and vegetables with hazardous microorganisms, nanoparticles in packaging act as a barrier to external factors that can modify the internal environment, contributing to degradation and simultaneous microorganism growth [47]. The main external factors are the radiation permeation, gases and water vapor [53, 62–66]. Thus, nanoparticles provide superior physical, chemical, optical, and biological properties in packaging, maintaining quality and increasing shelf life.

In Table 2, some examples of different nanoparticles present in packaging films that allow for more significant shelf-time gain by preserving the fruits from external environment. In this way, fruits showed maintenance of their textural properties, minimizing losses, correlated with the mass of solids and water, in addition to the reduction of oxidative processes linked to degradation [67].

Modifications in the internal atmosphere, such as gases as O_2 and H_2O vapors, allow more favorable conditions for the growth of microorganisms and oxidation of organic compounds, accelerating the natural process of degradation of fruits and vegetables [59]. The permeability of gases and water vapor are crucial parameters for the choice of packaging; controlling these variables allows the maintenance of freshness and preservation, minimizing spoilage and decomposition of packaged foods [66]. The addition of nanoparticles (oxides, clays and cellulose) in packaging can promote the filling of polymer chains, making it difficult for molecules to diffuse into their matrix, and thus consequently decreasing the vapor permeability [62–64]. Additionally, the presence of reinforced particles influences the hydrophobicity characteristics of film and the affinity gases, blocking the passage to the internal package [68].

One result of fruit and vegetable degradations due to oxidation from organic molecules is the generation of gases such as CO_2. In addition, the production of CO_2 molecules is associated with the metabolic process of microorganism respiration [72]. However, food packaging with CO_2 enriched atmosphere has evidenced better preservation attributed to lacking metabolism of molecules such as chlorophyll and anthocyanin, essentials to fruit coloration [73, 74].

Another essential gas correlated with fruits and vegetables preservation is ethylene, a phytohormone that regulates the growth and ripening. In the case of ethylene, nanoparticles as TiO_2 can act as photocatalysts degradation, avoiding the gases accumulation and blocking the ethylene binding to receptors in plant cells, minimizing the fresh-fruit maturation [71, 75]. Semiconductors such as oxides (TiO_2, CuO, ZnO) show differences in energy values between the valence (the highest energy level occupied by electrons) and conduction bands (the lowest energy level unoccupied by electrons) [76]. Therefore, the electron can be transferred between the oxide bands from the light incidence with appropriate energy (bandgap). This electron excitation generates an electron–hole pair that leads to the formation of highly reactive radicals that can degrade organic molecules such as ethylene in the photocatalytic process [77, 78].

These oxide nanoparticles may also minimize oxidative stress in organic compounds, fruits, and vegetables by radiation action [79, 80]. For example, radiation from sunlight

Table 2 Advanced investigations about packaging films reinforced with nanoparticles and protection of fruits and vegetables

Nanoparticles	Polymeric packaging	Fruits / vegetables	Beneficial effects	Reference
Ag	Polyvinyl chloride	Papaya	Fruits with delay in ripening, lower loss of soluble solids, and mass	[65]
Ag/SiO_2 and Ag/TiO_2	Polyethylene	Carrots	Carrots with lower soluble solids, weight loss, and conserved values of ascorbic acid	[10]
Ag	Cellulose	Pumpkin and Tomato	A decrease in microbial growth and a longer shelf life	[66]
Ag and ZnO	Chitosan/starch	Peach	The lower degree of microbial development on the surface of the peach	[67]
ZnO	Carrageenan	Mango	A lower degree of degradation after 33 days of storage	[68]
ZnO	Chitosan/cellulose acetate phytate	Black Grapes	Better fruit preservation during 9 days of storage	[67]
Cu	Polyethylene	Pear and Apple	Provide superior textural aspects due to the smaller amount of microorganisms present	[69]
TiO_2	Poly(butylene adipate-co-terephthalate) and thermoplastic starch	Banana	Preservation of the fruit during the 12 days of storage attributed a superior barrier to the passage of O_2 and CO_2	[70]
	Chitosan	Cherry Tomatoes	Photodegradation of ethylene after exposure to UV radiation that preserved during 20 days of storage,	[71]
	Polyethylene	Apples and Grapes	Control of weight loss, fruit browning, and lower microbial growth	[66]
Cellulose	Gum Arabic	Strawberry	Stored strawberries had a lower mass loss of about 23.8%	[58]

or lamps when coming into contact with food surfaces can degrade compounds, leading to the oxidation process. In addition, nanoparticles in packaging can act as a barrier against radiation (ultraviolet–visible spectrum) from light absorption [81]. In this way, radiation is blocked by the nanoparticle present in the package, protecting the contact with the surface of the packaged food.

External microorganisms can permeate through the packaging, contaminating and accelerating degradation. Antimicrobial nanoparticles (Ag, CuO, ZnO) on the outer surface of the package act as contact antimicrobial agents leading to death and decreasing internal contact with food [43]. The action mechanism of nanoparticles in the cell microorganisms may be related to the morphological and permeability alterations of the microbial membrane, intracellular damage, such as the interruption of enzymes in the respiratory chain, and DNA replication, in addition to oxidative stress [66]. These disturbances in different ways lead to loss of maintenance of metabolic activities until cell death. The action forms of nanoparticles can be carried out from their nature (solid) and from the oxides solubilization to ions [42].

The use of nanoparticulate additives in fruit and vegetables packaging demonstrates better control of the internal atmosphere and promotes protection against external environmental (gases, humidity, radiation, and microorganisms). As a result, it avoids the incidence of foodborne illnesses, microorganisms growth, and alterations of physicochemical properties. Thus, nanoparticles as reinforced materials allow a delay in the degradation of organic compounds, contributing to an increase in the fruit and vegetable shelf life.

5 Nanosensors for Monitoring Fruits and Vegetables Quality

Nanomaterials are applied to maintain the quality and, mainly, food safety intended for consumption. A wide range of techniques is employed to detect compounds that compromise quality and safety [82].

However, the vast majority of experimental techniques for detecting compounds of interest cannot provide ideal conditions for their application in industry, where they often present a high cost despite of proved efficiency [83]. In this sense, recent research invests in the synthesis of detection methods of high sensitivity and low cost, enabling their application on a large scale, for example, using hybrid materials of polymeric matrices based on carbon structures [82].

Thus, the detection of compounds of interest can be broady. From volatile bacterial biomarkers emited by harmfurl bacterias applied on the medical area [84] to potatos storage. For potatoes, Sagjan et al. [85] reported volatile organic compounds (VOCs) that can be associated to potato storage bacterias and fungus, such as Soft rot pathogen, *Pectobacterium carotovorum* subsp. *Carotovorum* and *Pythium ultimum*, respectively. Similar studies were reported by Tietel et al. [86].

On the food area, chemical sensors are commonly used, a device that transforms chemical information, such as the concentration of an analyte of interest, into a useful analytical signal [87]. Among those sensors, important to mention the electronic tongue and electronic nose, which are global sensors used in the assessment of food quality and which are based on reading the "fingerprint" of the sample that can be related to the taste for the electronic tongue or aroma for the electronic nose [88, 89]. The composition of these sensors is made by a transducer based on metallic or semiconductor electrodes, which can be superficially modified using organic, inorganic, or hybrid nanostructured materials. When these materials come into contact with the analyte of interest, there is a change in the pattern response (which can be electrical, optical, biological, etc.). Then, computational tools, such as artificial intelligence, translate this signal.

Nanosensors applied to food packaging to monitor the quality during the logistical process stages and ensure the quality of the product to the final consumer is a potential technology for the current market [90]. One of the features of the nanosensor is its use for gas detection, specifically ethylene gas, which is a plant hormone that controls a large number of physiological processes that occur with fruits. In climacteric fruits, adverse effects can occur during storage leading to loss of fruit quality [91].

In nanosensors for ethylene capture, the adsorption of gas (adsorbate) occurs on the surface of the solid material (adsorbent). The amount of material adsorbed will depend on the temperature, pressure, and adsorbate concentration.

5.1 Colorimetric Nanosensors

Some platforms for ethylene capture have an oxidizing agent adsorbed on their surface, which provides an oxidation–reduction reaction when in contact with ethylene, causing a color change in the nanosensor. Currently, colorimetric platforms for ethylene capture are based on different capture mechanisms, supports, and even color variations depending on the compounds used [92].

Among the technologies currently used, many of the alternatives are based on metallic compounds for gas oxidation. Polymolybdate (IV), for example, is used as an oxidizing agent together with a palladium sulfate catalyst to capture exogenous ethylene. Gas is captured from the ethylene oxidation, which, in turn, causes a change in the coordination of the molybdenum metal center from Mo(VI) to Mo(V), causing visible changes that alter the color of the light yellow compound to dark blue. Lang et al. [92] also point out that the sensor sensitivity can be modified by changing the pH of the ammonium molybdate solution used.

Compounds involving metallic ions from group 10 (platinum and palladium) are also used to oxidize gases such as ethylene, represented by a characteristic color change from yellow to brown. The main advantage of these materials for application as colorimetric sensors is, in addition to their good ability to oxidize ethylene, the high selectivity [93] that these compounds have against gases present in the environment, enabling the capture only of the gas of interest instead of other compounds eliminated by the fruits, for example.

However, the main problem with using metals to prolong the shelf life of fruits is the possible poisoning with high concentrations of metals that are toxic to the body, limiting their applications as sensors. Furthermore, the high cost of some metallic compounds also prevents their application on a large scale. Potassium permanganate ($KMnO_4$), in turn, is one of the most used alternatives as an oxidizing material for ethylene—not only as a focus of research but also for application in commercial products in order to extend the shelf life of fruits while maintaining their characteristics desirable from the capture of exogenous ethylene [94]. The visual change due to oxidation is shown as the purple color gradually converting to brown due to the formation of MnO_2, with the ethylene being oxidized to form ethylene glycol or acetic acid, which can be oxidized again to CO_2 and H_2O. Martinez-Romero et al. [95] showed that the platform based on potassium permanganate supported on activated carbon exhibits an excellent ethylene adsorption capacity, with 80% using granular activated carbon, 70% using powder, and 40% using carbon fibers. This capacity was not affected by the temperature range of 2-20ºC. Furthermore, it has widely accessible raw material and can be made from lignocellulosic materials. On the other hand, Spricigo et al. [96] proposed monitoring ethylene concentrations platforms based on silica (SiO_2) and alumina (Al_2O_3) nanoparticles impregnated with potassium permanganate ($KMnO_4$), which color variation indicating concentration changes.

However, the biggest obstacle to using $KMnO_4$ is its reaction with other organic compounds such as alcohols and aldehydes. The high oxidation capacity of the compound results in a low selectivity, which can compromise the amount of adsorbed ethylene due to the presence of gases prone to oxidation, which also compromises the range of materials that can be used support [97, 98].

5.2 Other Materials

Some materials that can be used as adsorbents are activated carbon, zeolites, and silica. The titanium dioxide nanoparticle platform supported on activated carbon shows great potential as titanium is a relatively inexpensive material, is photostable and clean, does not interfere with relative humidity, and ethylene can be removed at room temperature. However, UV light is necessary for its functioning since it is the photocatalytic reaction of TiO_2 that decomposes the ethylene molecule and does not present a color change [91]. Another alternative is to use cobalt oxide on nanoporous carbon, in which some studies also point to the use of cobalt oxide dispersed on substrates to capture the ethylene released by fruits. For example, the dispersion of cobalt oxide powder on the nanoporous carbon surface is able to carry out the adsorption of olefins after thermal treatment of the substrate and support. The method, however, has limited applications as the adsorption of ethylene on the substrate surface occurs more efficiently at higher temperatures, although its application at lower temperatures is still possible to preserve the shelf life of the fruits [92]. Research in recent years has focused on using zeolites and nanoclays as a material for ethylene capture, which is based on the high porosity of these materials and the variety of their chemical composition, with variable efficiency. Often, these compounds of natural origin are used as support for oxidizing materials capable of capturing the released ethylene and which are fixed in the mineral structure through chemical or physical interactions, thus becoming ideal inert support for the process of capture. Potassium permanganate impregnated in the structure of zeolites was shown to be an efficient way to capture ethylene following the principle described above, in addition to allowing its application as a colorimetric sensor due to the color change of potassium permanganate from purple to brown, as well as several studies in literature employ different materials in the cavities of these minerals with the same purpose. Furthermore, zeolites and nanoclays can also be used as additives that modify the materials properties from their incorporation in the synthesis process, for example, modifying the mechanical strength of plastic films [92, 93, 99].

Therefore, in the context of porous supports for the impregnation of colorimetric sensors, zeolites, and activated carbon, proved to be a promising alternative in acting as an adsorbent for oxidizing materials. The idea behind the use of porous materials is that the high surface area allows a high amount of oxidizing material to be impregnated not only on the surface but also inside of the support [92, 99].

Other approaches present divergent paths from those presented above, which depend on inert supports or coordinated bonds of metallic compounds for adsorption. For example, plastic films have drawn attention due to their attractive properties (e.g. adhesion to surfaces, high malleability, absence of inert support) that can favor application in certain situations. Some works in the literature focused on the use of tetrazine films for ethylene capture and application as a colorimetric sensor. Basically, the method consists of forming plastic tetrazine films on hydrophobic plastic materials without -OH groups (silicon polycarbonates, polystyrenes, polyethylene, propylene). The platform functioning is based on the interaction of ethylene with tetrazine, which changes from pink to brown when it becomes saturated with ethylene. Thus, it is possible to use this platform as a colorimetric sensor. However, in addition to the need for a hydrophobic film due to the instability of tetrazine in the presence of water, there is also little data in the literature regarding this platform [99, 100].

6 Final Considerations and Future Perspectives

Nanotechnology is a promising tool for developing technologies to reduce post-harvest losses of fruits and vegetables. Different nanomaterials showed significant potential in postharvest technology management. Several investigations support nanotechnology-based edible coating materials (nanocomposite coatings or nanoemulsions) with better physical and antimicrobial properties than traditional coatings. In addition, these new materials have very beneficial effects in maintaining physicochemical, microbiological, and physiological quality compared to other coating materials.

Polymeric packaging with nanoparticles is an innovative concept in active food packaging. The incorporation of nanomaterials such as Ag, TiO_2, copper, ZnO, SiO_2, and others in polymeric packages has been shown to improve the physical, mechanical, optical, and antimicrobial properties of these packages, which has contributed to an improvement in their ability to prolong quality and shelf life of fruits and vegetables. However, future studies should be carried out under different storage conditions to assess whether the migration of these nanoparticles is taking place within limits established by safety authorities.

Strategies based on the use of nanosensors applied in packaging to monitor or preserve the quality of fruits and vegetables during stages of the logistical process to guarantee the quality of the product to the final consumer proved to be one of the biggest bets of nanotechnology for the current market of fruits and vegetables. The promising results observed in several investigations using different platforms have made this technology attractive. However, future studies are needed to improve this nanosensor technology. This way includes possibly developing applications that will help consumers accurately interpret color changes of colorimetric nanosensors using smartphone cameras to avoid dubious interpretations based on user perceptions.

The major concern of nanomaterials is their safety issues. This issue was reported in a recent review by Neme et al. [101]. According to the authors, some nanomaterials can induce health risks due to easy penetration through the cell for adverse reactions in various human and animal organs, as well as plant parts. Such risks due to nanoparticles or nanocomposites can be controlled in future research through the use of greener syntheses and the search for easy and inexpensive protocols for degradation and removal of existing nanomaterials from the sites of attack.

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