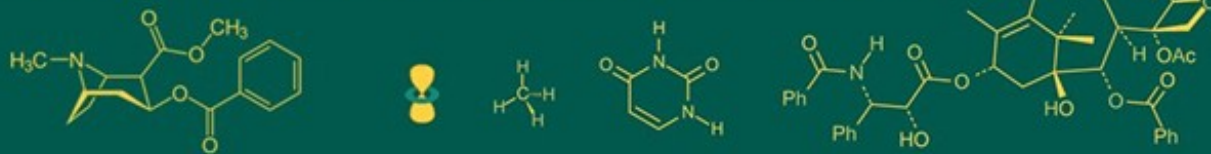


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Sushank

Department of Horticulture,
 CCS Haryana Agricultural
 University, Hisar (Haryana) -
 125004, India

Vinita Rajput

Krishi Vigyan Kendra (Sirsa),
 CCS Haryana Agricultural
 University, Hisar (Haryana) -
 125004, India

Garima

Department of Horticulture,
 CCS Haryana Agricultural
 University, Hisar (Haryana) -
 125004, India

Satpal Baloda

Department of Horticulture,
 CCS Haryana Agricultural
 University, Hisar (Haryana) -
 125004, India

Edible coatings and nanotechnology: Emerging strategies for extending fruit shelf-life and enhancing postharvest

Sushank¹, Vinita Rajput², Garima³, Satpal Baloda⁴, Vikas Kumar Sharma⁵, Saksham⁶,
 Akshay Mehta⁷, Bharti⁸, Mukesh Kumar⁹

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ABSTRACT

Postharvest losses for fruits are a major problem in horticultural production systems worldwide, especially in the developing countries and underdeveloped because of insufficient infrastructure, particularly storage and transportation facilities which results rapid quality loss. Since fruits are high-water-content plant parts and have a high respiratory rate and rapid tissue breakdown, hence they are perishable commodities. Edible Coatings and Nanotechnology have recently appeared as economical, environmentally friendly solutions available today to prolong storage of fresh fruits. Such edible coatings are thin layers of natural biopolymers [polysaccharides (e.g., chitosan, starch and alginate), proteins (gelatin (G)) or whey protein and lipids]. These coatings act as semi-permeable membranes that regulate gas exchange, and reduce moisture loss and ripening, improving fruit quality. Nanomaterials contained in the coatings also play a crucial role by providing better antimicrobial properties with the help of silver nanoparticles or maintaining barriers using nano emulsions among others. The latter allows the controlled release of bioactive compounds, which improve their efficiency as preservatives over long periods of fruit postharvest storage. Thus, these new coating technologies offer significant opportunities to lower postharvest loss and retain the nutritional and sensorial quality (e.g., aroma) of fruits as well as facilitate the marketing process.

Keywords: Antimicrobial, Biopolymers, Nanocomposite coatings, Polysaccharides and post-harvest fruits

Introduction

Fruits are an important part of human diet, being a great supplier of energy, dietary fiber and essential micronutrients (including vitamins, minerals, flavonoids and other bioactive phytochemicals) (Mares-Perlman *et al.*, 2002) [1]. Besides their nutritional importance, fruits supply digestible carbohydrates and minerals providing high contributions to daily energy requirements (Vicente *et al.*, 2022) [2]. Yet, the growing number of fresh fruits demanded worldwide has generated considerable challenges for food scientists and the processing industry that must evolve towards innovative approaches in regards to maintaining freshness while simultaneously improving quality, shelf-life, and safety. Thus, in this scenario the use of natural, edible and biodegradable polymers has been strongly considered as a sustainable option (Tahir *et al.*, 2019) [3]. Globally, postharvest losses of fruits constitute an important threat as almost one third of the total food produced is lost along the supply chain and this has a high impact on food security and environmental sustainability aspects (Blanckenberg *et al.*, 2022) [4]. In response to these obstacles, newly developed technologies including nanotechnology have come into play. Nanoparticles are known for their promising applications in several fields such as; medical therapeutics, energy (solar and fuel cell applications), cosmetics and textile products. (Hasan, 2015) [5].

Nanotechnology in Food Sector- A Promising Approach to Extend Shelf Life of Perishable Commodities at Low cost. Nanoscale materials demonstrate distinct physicochemical characteristics compared to their bulk counterparts, enhancing their functional performance in food preservation systems (Onyeaka *et al.*, 2022) [6]. Presentation Quality and Shelf Life of Fruits The postharvest quality and shelf life of the fruits are influenced by the intrinsic as well as extrinsic attributes. Intrinsic factors are species and cultivar variance, and growth conditions; while extrinsic factors include environmental conditions (temperature, O₂, CO₂ and ethylene concentration), as well as other stress conditions (Kluge *et al.*, 2002) [7]. The challenges of preserving food quality and safety are partly addressed with edible coatings that can be applied to fresh and minimally processed fruits. These coatings are semi-permeable barriers that decrease moisture loss, control the migration of solutes, gas exchange, and respiration or oxidative processes (Shuang *et al.*, 2019).

In addition, physiological activity of fruit is very important in postharvest management. Climacteric fruits are harvested before reaching maturity, remain fit for limited periods only and continue to ripen after harvest, thus being subject either to microbial invasion or wilting (Jafarzadeh *et al.*, 2021) [8]. Fresh fruits and

Corresponding Author:
Garima

Department of
 Horticulture, CCS Haryana
 Agricultural University,
 Hisar (Haryana) - 125004,
 India

vegetables experience senescence that leads to progressive deterioration, which is usually accompanied with increased respiration rates, heightened susceptibility to pathogen infections and serious sensory changes such as color of ripening stages (Umeohia *et al.*, 2024). Nanotechnology shows promise for the extension of the shelf-life of horticultural produce in this context. It is able to prevent microbial growth, help formation of modern packaging products such as nanos-

structured films and coatings, and protect food products from adverse environmental conditions including ultraviolet radiation (Yadollahi *et al.*, 2010) [9]. In this sense, combining nanotechnology with edible coatings may also serve as a useful tool to enhance the postharvest quality and reduce losses while assuring food safety in new food systems.

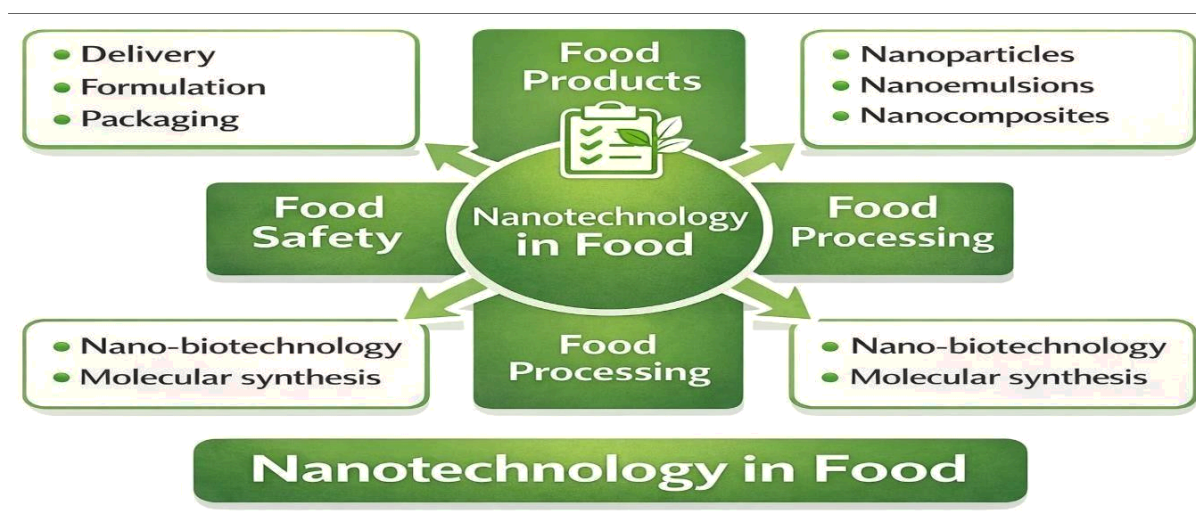


Figure 1. Nanotechnology applications in food industry

Edible coatings, mainly cellulose gums, have been shown to delay ripening in a variety of climacteric fruits such as mango, papaya and banana, while effectively controlling enzymatic browning in minimally processed foods such as sliced mushrooms (Salehi, 2020) [10]. These coatings serve as semi-permeable barriers to control the exchange of gases (O_2 and CO_2) and moisture from the fruit surface to its environment. This regulation causes a decline in respiration, delayed maturation, and minimizes the loss of volatile compounds responsible for flavor and aroma (Jama *et al.*, 2026) [11]. The edible films work by creating a barrier that reduces gas diffusion and water vapour transmission, maintaining quality as well as textural and sensory properties (Olivas *et al.*, 2008) [12]. In the past few years, antimicrobial agents have been incorporated into edible films because they can reduce microbial contamination and shelf life extension for fresh-cut fruits and vegetables (Yu *et al.*, 2025) [13]. Nanotechnology has activated a great capacity in food packaging systems, resulting in applications in edible nano-coatings containing both organic. Nanomaterials are characterized by particle dimensions in the nanometer to sub-micrometer scale, and exhibit unique physicochemical properties (Wang *et al.*, 2025) [14]. In coatings, such nanoscale materials can improve functional performance (e.g., barrier properties, antimicrobial activity, and mechanical strength). Ethylene also is an important regulator in fruit ripening of climacteric fruits, but its uncontrolled or excessive production could enhance senescence which often leads to huge pre- and post-harvest losses (Tipu *et al.*, 2024) [15]. Consequently, it is critical to regulate ethylene activity in order to prolong the postharvest life of fruit. Nanotechnology-Based Systems to Preserve Food. The proper extension of postharvest shelf life relies primarily on three factors:

- (i) Minimizing moisture loss,
- (ii) Slowing physiological processes such as ripening and senescence
- (iii) Inhibiting microbial growth (Sharma *et al.*, 2006) [16].

Edible coatings are very important for achieving all these goals and they can be defined as a thin (10-100 μm), edible, and continuous layer applied to the surface of food products (Summo *et al.*, 2022) [17]. We added that nanotechnology also plays a role in shelf-life extension through antimicrobial to reduce microbial growth and improve packaging efficiency and to counteract environmental stressors such as radiation (Yadollahi *et al.*, 2010) [9]. This trend is reflected in the global size of the edible packaging market, valued at around \$697 million (around 538 billion rupees) in 2016 with an estimated market size of \$1097 million (around ₹830 billion) in 2023, growing at a CAGR of 6.81% during the forecast period. Additionally, the use food-grade additives in edible coatings can minimize undesirable biochemical changes and improve the stabilization of products (Rojas-Graü *et al.*, 2009) [18]. Edible coatings can successfully reduce moisture loss from the sliced fruits, keep them firm and their internal quality well preserved during storage (Hazarika *et al.*, 2023) [19]. Edible coatings are generally developed on the data of three main groups of ingredients such as polysaccharides (pectin, starch, gums, alginate, chitosan and cellulose), proteins (gelatin, egg albumin, wheat gluten, zein, whey protein soy protein) and lipids (fatty acids and waxes) (Aaqil *et al.*, 2024) [20]. However, retaining fruits and vegetables still face a lot of challenges to preserve them for an extended period because they have relatively low shelf life due to their high moisture content (75–95%) that aids early decay, predisposes them to microbial spoilage and loss of aesthetic properties (Poonam *et al.*, 2022) [21].

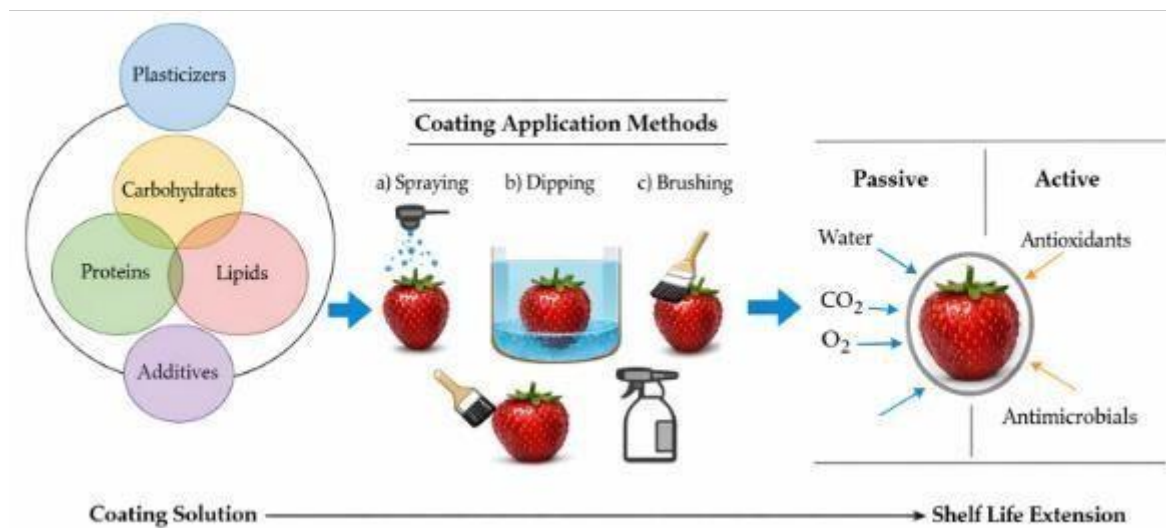


Figure 2. Main components of edible coatings and application methods on fruits.

Nanoparticles show much different physical and chemical properties as compared to the bulk counterpart due mainly to surface area effects, mass transfer rates and aggregate properties. With respect to these properties, higher penetration along with increased chemical and biochemical reactivity, enzymatic activation resulted in favorable catalytic behavior with unique quantum effects (Biswas *et al.*, 2022) [22]. But in terms of post-harvest preservation and respiration rates, OP (O₂ permeability) must be reduced sufficiently to slow down the rates but not so much that anaerobic conditions are created resulting in off flavors/ ethanol build up. In addition, coating materials must have enough physical and mechanical strength to survive the rigors of handling, transportation, and storage. High antimicrobial activity is also required to control the growth of spoilage and pathogenic microorganisms (Jafarzadeh *et al.*, 2021) [8]. In the subsequent first half, an overview regarding post-harvest challenges has been depicted followed by a detailed review of recent research on design and application of edible coatings and nanocomposite films to different fresh fruits and vegetables listing their benefits as well as constraints (Ashfaq *et al.*, 2022) [23].

Synthesis of nano particles and its parts

The nanoparticle-producing process can either be intracellular or extracellular depending on the location of their generation. (Hulkoti *et al.*, 2014) [24]. Biological methods of nanoparticles synthesis using microorganisms (Hasan, 2015) [5], or enzymes (Willner *et al.*, 2006) [25], fungus (Vigneshwaran *et al.*, 2007) [26], and plant extracts (Shankar *et al.*, 2004) [27].

1. Physical Methods

Work done in past

Author name	Study
Pols <i>et al.</i> , 2022	He reported that exposure of fruits and vegetables to small concentrations of nitric oxide significantly slows down their respiration rate. This treatment also reduces ethylene production, a key plant hormone responsible for ripening, thereby delaying the overall ripening process and extending shelf life.

Author name	Study
Raj <i>et al.</i> , 2016	Demonstrated the effectiveness of potassium permanganate (KMnO ₄) as an ethylene absorbent. The application of KMnO ₄ helps in scavenging ethylene from the storage environment, thereby delaying ripening and prolonging the storage life of horticultural produce.
Shankar <i>et al.</i> , 2020	Highlighted a breakthrough in genetic engineering, where Flavr Savr tomato was developed in 1994 by Calgene (Monsanto, UK). This transgenic tomato was engineered using an antisense strategy targeting the polygalacturonase enzyme responsible for cell wall degradation. The modification resulted in delayed softening, extended shelf life, and reduced ripening rate in tomatoes.
Mari <i>et al.</i> , 2024	Developed an innovative edible coating derived from marine microalgae and chitosan. This biodegradable coating has been shown to significantly extend the shelf life of perishable fruits such as tomatoes, strawberries, and bananas. Their research emphasizes sustainable approaches to reduce post-harvest losses while maintaining fruit quality.
Sabir <i>et al.</i> , 2023	Investigated the use of <i>Aloe vera gel</i> as a natural preservative. The study demonstrated that <i>Aloe vera</i> coating effectively preserves the functional and nutritional properties of grapes, while also delaying spoilage and extending shelf life.

A) Mechanical method

Even mechanical methods in various forms have recently gained attention to create nanoparticles because they are simple, scalable and inexpensive (Pei *et al.*, 2026) [28]. In these, mechanical milling is a frequently used technology to produce nanoscale materials from bulk materials through repeated deformations, fractures and cold weldings (McHugh *et al.*, 2000) [29]. Usually, this procedure is performed under an inert atmosphere to avoid oxidation and contamination during the synthesis process. Mechanical milling was also employed as a post-annealing technique to improve the structural and functional characteristics of nanoparticles (Sharma *et al.*, 2025) [30].

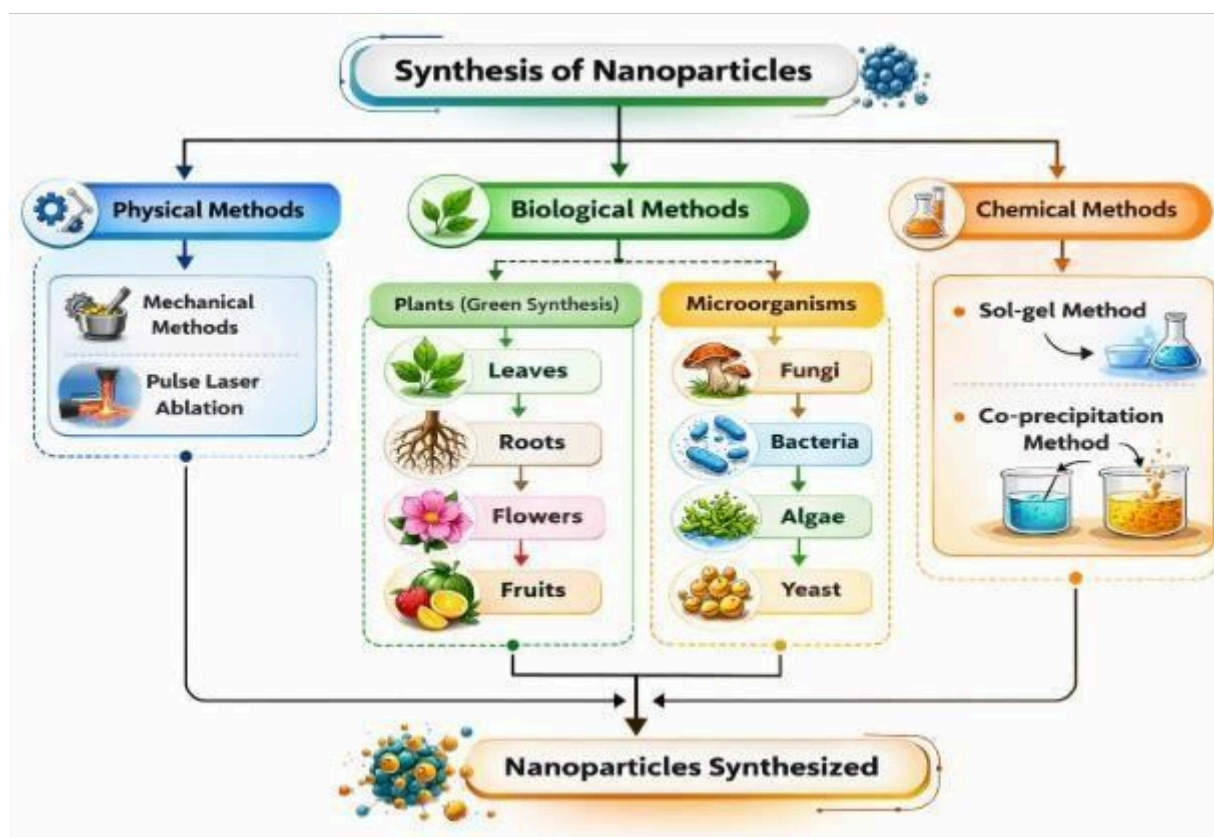


Figure 3. Showing each method for synthesis of Nano-Particle.

B) Ball milling

Among these methods, ball milling is one of the most widely used mechanical method for nanoparticles synthesis. This approach uses high-energy ball impacts and confines the material to be ground in a rotating milling chamber (Fig. 4). Nanoparticle formation is also highly dependent on operational parameters, such as milling speed, milling time, ball-to-powder ratio, and temperature. Of these, the milling parameters such as speed and duration primarily affect properties of the final particles (i.e. particle size, morphology). These parameters should be optimized to achieve nanoparticles with narrow size distribution and appropriate properties (Konrad *et al.*, 2001) [31].

C) Melt mixing

Melt mixing is one of the most common techniques for preparing nanoparticles, especially metal and ceramic systems. In this technique, multiple precursor materials are heated to a molten state and mixed at an appropriate temperature under controlled conditions for effective dispersion and reaction. An example of such a reaction is formed when a stream comprising Cu-B in molten form interacts with another heated stream consisting of titanium (Ti), giving rise to TiB₂ nanoparticles. This approach allows to obtain nanoparticles with a tunable composition and improved structural properties, as the high-temperature homogeneous mixing (Rastogi, 2017) [32].

D) Pulsed laser ablation

The pulsed laser ablation is a sophisticated physical method used for the preparation of nanoparticles in liquid or gas phase [Dikusar *et al.*, 2009 [33], Patscheider, 2003 [34]]. The nanoparticles are synthesized by irradiating a high-energy pulsed laser at a target material, causing the ablation of that target and, hence, production of the nanoparticles. Process parameters such as the type of laser, pulse duration, number

of pulses, solvent medium and pulsing interval play a notable role on the characteristics of synthesized nanoparticles. Plus, variations among these parameters may change particle size, morphology and distribution; thus can affect the total quality of nanoparticles (Patil *et al.*, 2021) [35]. Thus, control of experimental parameters is required to achieve desired properties of the nanoparticle (Ponon *et al.*, 2015) [36].



Figure 4. Ball Milling

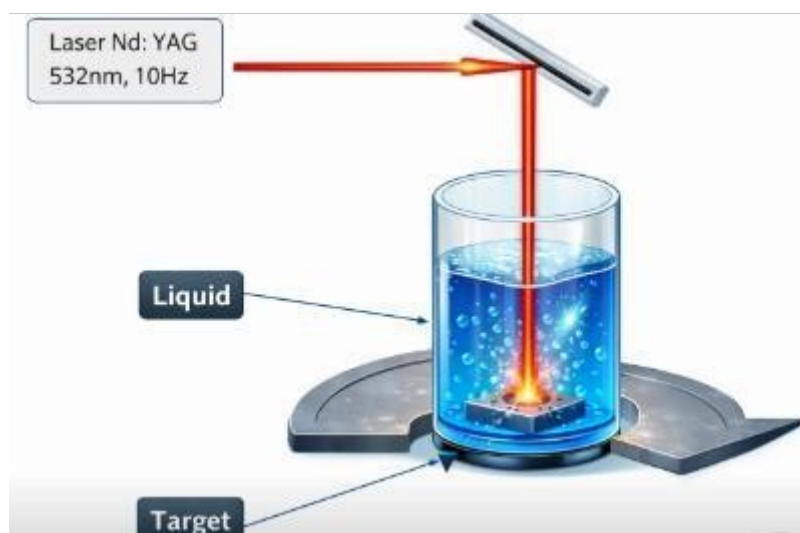


Figure 5. Pulse Laser Ablation technique

2. Biological methods

Biological approaches for the synthesis of nanoparticles have recently received a lot of attention because they are environmental friendly, economical and sustainable. These are biogenic methods because microorganisms and plant extracts are applied to synthesize nanoparticles at mild conditions without the use of toxic chemicals.

A) Synthesis using microorganisms

Nanoparticles have been biosynthesized from a variety of microorganisms where microbial cells act as the key player in this feature; these cells can synthesize NPs extracellularly and intracellularly. Extracellular synthesis occurs when microorganisms secrete enzymes or biomolecules that reduce metal ions in the external medium to nanoparticles. Alternatively, through intracellular synthesis metal ions are taken up into the microbial cell and enzymatic reduction and accumulation in the cell matrix occurs. Fungi have received significant attention for nanoparticle synthesis from different microorganisms because of their high metal tolerance, efficient bioaccumulation capac-

ity, and secretion of considerable amounts of extracellular enzymes and proteins. These factors also provide fungal systems as an excellent system for mass production of nanoparticles (Manjula *et al.*, 2023) [37].

B) Synthesis using plant extracts

In recent years, the use of plants for the synthesis of nanoparticles (green synthesis) has proven to be a viable alternative to microbiological processes. Plant extracts have many different bioactive compounds like phenolics, flavonoids, alkaloids, and proteins and serve as natural reducing agent or stabilizing agents during nanoparticle synthesis configuration. Plant extracts have several advantages over other microorganisms (e.g., fungi, bacteria) due to the faster rate of synthesis, simple handling, and no requirement for maintaining sterile conditions. Moreover, plant-mediated synthesis is comparatively safer and more viable for applications in large scales in industries. It has been proven efficient and convenient since some of the plant extracts can reduce metal ions in a matter of minutes or even seconds (Iravani, 2011) [38].

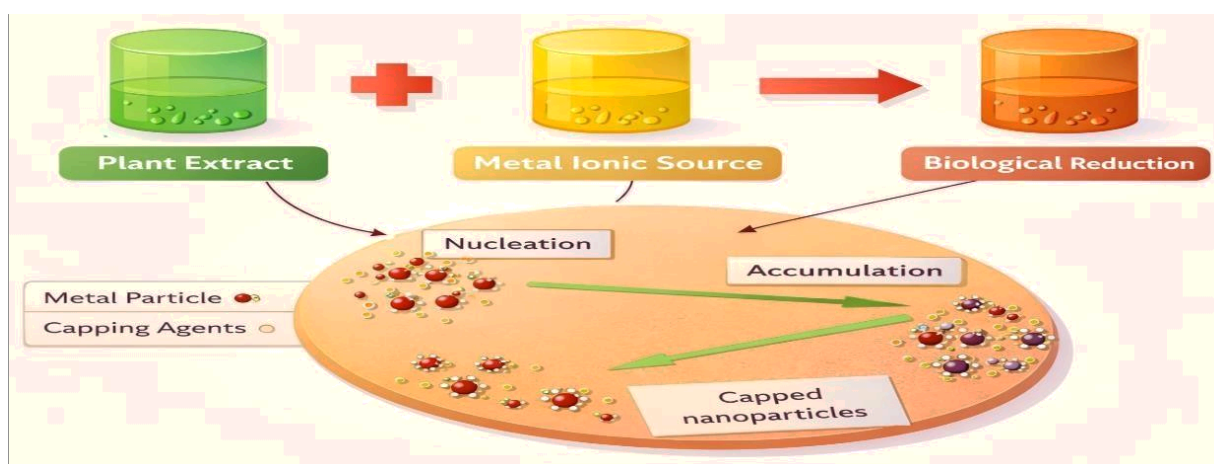


Figure 6. Synthesis using plant extract

3. Chemical methods for nanoparticle synthesis

A) Sol-gel method

The most common chemical process that is used for nanoparticle synthesis is a sol-gel method. The word "sol-gel" derives from the transition of a solution (sol) to a gel by means of hydrolysis and polycondensation reactions [Kessler and Seisenbaeva, 2023 [39]]. Elimination of unstable intermediates occurs during this transformation to give nanoparticles. It has several merits including ease of fabrication, low

thermal process and accurate artificial manipulation of particle size and morphology. The sol-gel technique is one of the most used methods for nanoparticle synthesis due to its versatility and ability to synthesize different types of nanomaterials (Ealias *et al.*, 2017) [40].

B) Co-precipitation method

One more frequently used chemical method for the preparation of nanoparticles is co-precipitation technology. This approach involves mixing the polymer with a non-solvent phase which offers instant diffusion of the solvent to a non-solvent medium.

Causing super saturation that results in the precipitation of nanoparticles. Nucleation and particle growth is primarily driven by interfacial tension between the two phases, leading to formation of nanoparti-

cles. The simplicity, cost-effectiveness and the control over the size and composition of nanoparticles are some of the advantages of this approach (Patil *et al.*, 2021) [35].

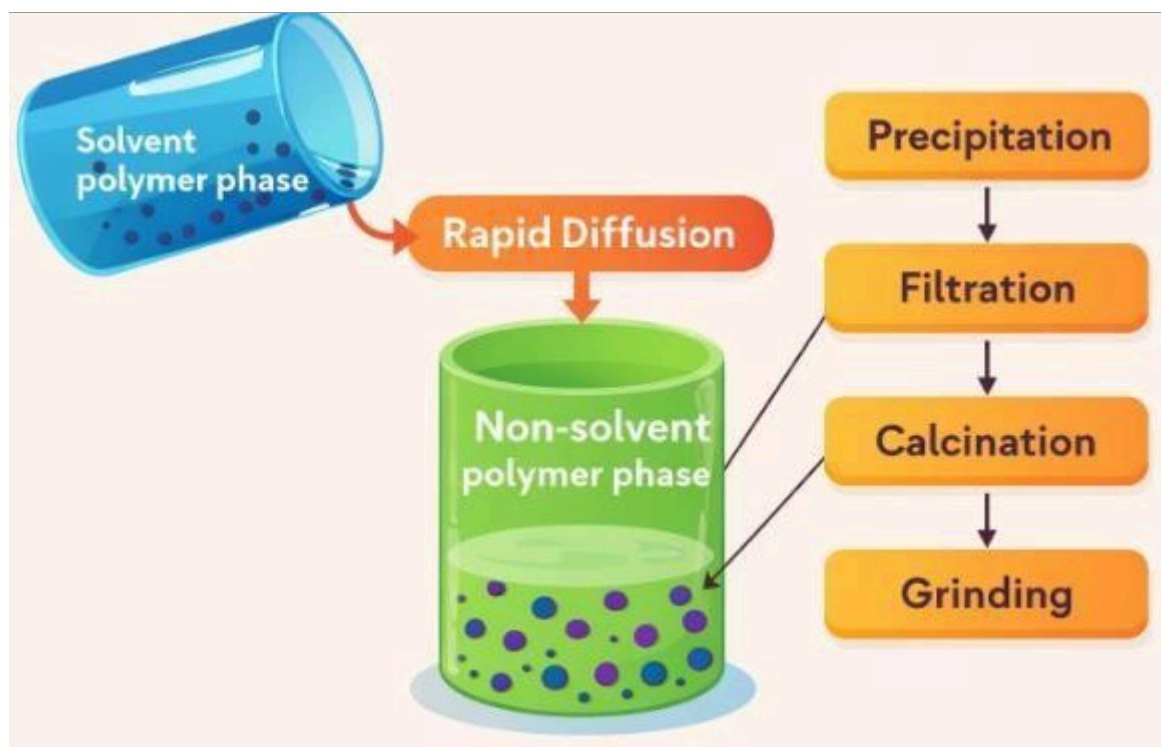


Figure 7. Co-precipitation technique

Nano-edible coatings

Edible Coatings: The edible coatings are a layer of either biological or chemical constituents that form up as monolayer or multilayer films which become applied on the food surfaces (Das *et al.*, 2016) [41]. These coatings are semi-permeable barriers and influence moisture, oxygen, and solute transference, thus increasing the quality of fruits during storage and their lifespan (McHugh *et al.*, 2000) [29]. Furthermore, edible coatings are important to keep phytonutrients (like antioxidants, phenolic compounds and natural pigments) and some essential physicochemical properties such as respiration rate, weight loss and total soluble solids (TSS) and pH during storage (Wang *et al.*, 2017). Recently, edible coating technologies have been known as potential solutions for prolonging postharvest life of fruits (Hazarika *et al.*, 2023) [19]. They act as substitutes or complements to natural wax coatings, resulting in greater storage stability and lower metabolic deterioration. Moreover, sanitation during harvesting and postharvest treatments and control of water activity, enzyme activity temperature and relative humidity are complementary measures for extending the shelf life (Qureshi *et al.*, 2023) [42].

Postharvest Application: Other PH treatments like heat treatment (HT) in combination with cold storage conditions (e. g. 14 °C) have been reported to increase quality parameters such as titratable acidity (TA), and total soluble solids compared to untreated fruits (Lu *et al.*, 2010) [43]. Calcium chloride is also present in edible coatings since it can improve film-forming properties and decrease moisture loss and gas exchange, which helps the efficiency of coatings (El-Gioushy *et al.*, 2022) [44]. Even though traditional technologies (e.g., refrigeration and modified atmosphere packaging (MAP) can maintain postharvest quality, they are mainly accountable for temperature control and consume a lot of energy. On the other hand, nano-edible coatings provide a cheaper and more multiplex alternative through superior barrier properties and they enhance preservation efficiency with

minimum postharvest losses and improved shelf life (Elik *et al.*, 2019) [45].

Edible coatings are widely used in fruits to extend shelf life and maintain quality because they modify the internal atmosphere, providing a barrier against respiration. These coatings behave like semi-permeable membranes that control the exchange of gases including oxygen (O₂) and carbon dioxide (CO₂), resulting in a reduced respiration rate, while downregulating ripening. The inteles of edible coatings also keep the texture and structural integrity of fruits by reducing moisture loss and maintaining firmness during storage and handling. They aid in long-distance transportation by stabilizing physiological processes and preventing rapid deterioration, thereby minimizing post-harvest losses. Edible coatings on fruits also give a significant increase in the overall market value by improving their quality and shelf life. These coatings also bear significance in providing carriers of functional additive such as antimicrobial and antioxidant agents, nutraceutical compounds, color and flavor enhancers etc. Incorporation of such compounds reduces microbial load, leads to delay in oxidative reactions and discoloration, enhancing the safety and sensory characteristics of fruits (Rooney, 2005) [46].

Key functions

1. Act as a semi-permeable barrier to regulate O₂ and CO₂ exchange.
2. Maintain fruit texture and structural integrity by reducing moisture loss.
3. Support long-distance transportation by stabilizing physiological processes.
4. Enhance market value through improved quality and shelf life.

Serve as carriers of functional ingredients such as antimicrobials, antioxidants, nutraceuticals and flavoring agents to improve safety and quality (Rooney, 2005) [46].

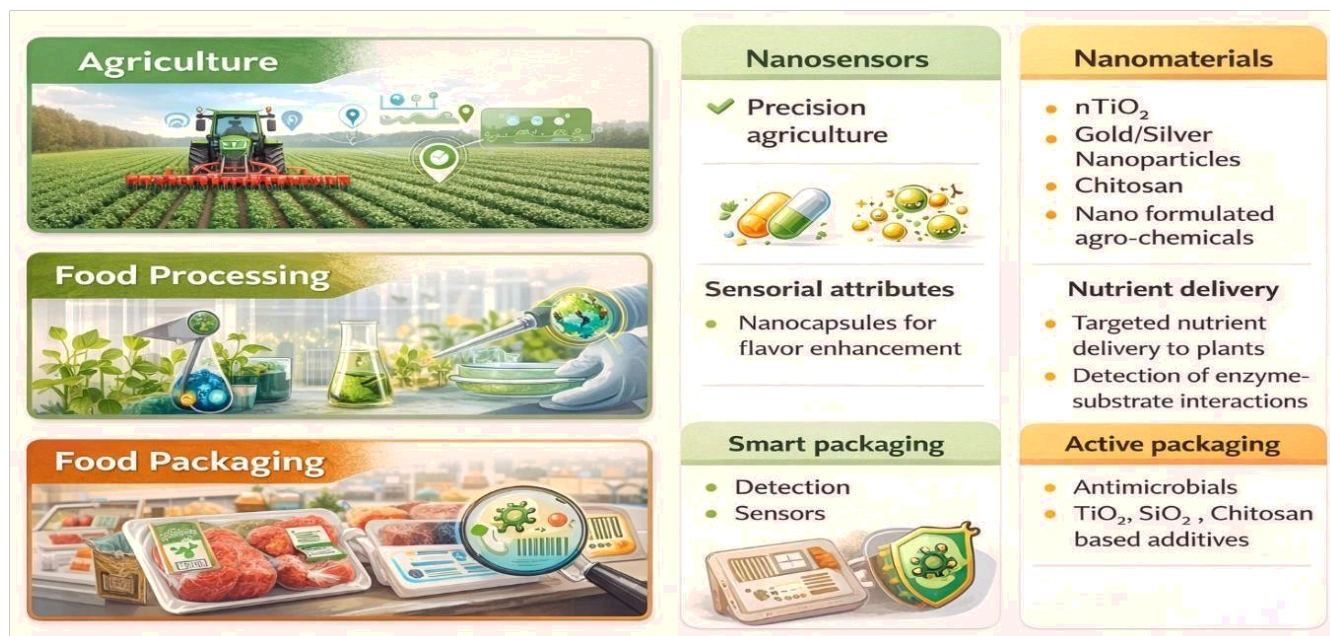


Figure 8. Applications for nanotechnology in agriculture, food processing, and packaging.

Types of nano-edible coatings

Another One uses antibacterial silver Nano-particle Coatings to Prevent the bacteria of fungi from Growing in on the outer surface of fruit (Durán *et al.*, 2016) [47]. In addition, fruit color and nutritional value are protected from oxidative processes through the use of antioxidant rich nanoparticles as food nano-coatings (Kanwar *et al.*, 2024) [48].

Chitosan nano-coatings

Chitosan based nano-coatings represent an innovative and improved alternative to the conventional chitosan (CS) coatings, since these nanostructured systems offer superior physicochemical and functional properties. The addition of chitosan nanoparticles to food wrappers increases their barrier properties (lower permeability for gases and moisture) due to the increased surface area and greater adhesion on the fruit surface concerned (Gardesh *et al.*, 2016) [49]. Furthermore, chitosan has intrinsic antimicrobial action and great film-forming properties (No *et al.*, 2007) [50]. In practice, however, chitosan coatings are usually placed in conjunction with additional physical treatments such as during some short-time heat treatment or gas fumigation and even modified atmosphere packaging to improve the overall effectiveness against targeted microorganisms. Both these integrated approaches have proved, to a certain degree independently and synergistically, suitable in augmenting the shelf life and quality of post-harvested produce. Several horticultural commodities such as strawberries, apples, apricots, mandarins, pomegranates and guava have proven the effectiveness of chitosan nano-coatings (Sharma *et al.*, 2025) [30]. Such coatings when applied on the fruit surface create a semi-permeable barrier as it controls gas exchange, minimize transpiration loss and moisture loss. Thereby they assist in keeping the firmness, delaying maturation and inhibit microbial colonization avoiding postharvest losses by more than 40% (Alvarez *et al.*, 2022) [51].

Silver nanoparticles (AgNPs) coatings

In recent years, silver nanoparticles (AgNPs) have attracted great interest due to their unique physicochemical properties and are widely used in food science, agriculture and nanotechnology (Aadil *et al.*, 2018) [52]. The strong antimicrobial and preservation properties they exhibit are due to their nanoscale size, high surface area-to-volume ratio, and their enhanced reactivity. AgNPs coating has great potential in the postharvest management of fruits, successfully prolonging the shelf life of these products for long periods through inhibition of growth by spoilage-causing microorganisms and pathogenic agents. The antimicrobial properties contribute to reducing postharvest

losses, fruit quality and food waste (Bruna *et al.*, 2021) [53]. The antimicrobial action of AgNPs is mainly due to cell membrane disruption, generation of reactive oxygen species and accumulation damaging the cellular metabolic processes. AgNPs are also very potent disinfectants and are used in food storage food packaging, sterilization of surface. Making their way into food packaging materials, storage containers and coatings has improved their role in maintaining cleanliness and quality control. Nano-silver-based storage boxes, colloidal silver solutions, and nano-silver integrated packaging systems as antimicrobial and preservative agents are used in various commercial and experimental applications (Dholariya *et al.*, 2021) [54]. The role of AgNPs as food additives has also been implemented in previous studies focused on their antimicrobial effectiveness (Zorraquín-Peña *et al.*, 2020) [55]. For instance, Chandirika *et al.* (2018) [56] discovered that tomatoes coated with AgNPs and kept under ambient conditions had an extended shelf life of 21 days compared to uncoated controls, which was attributed to its postharvest preservative quality. In addition to this, green synthesis of silver nanoparticles has been employed from plant extracts. Plant species have been successfully employed to perform the biosynthesis of AgNPs while utilising *Azadirachta indica*, *Capsicum annum* and *Carica papaya* which provide a quick, cheap, sustainable and greener alternative for chemical synthesis methods. AgNP-based coatings as a marketable tech for postharvest quality improvement, shelf-life extension and food safety validation. However, additional research is needed to assess the longterm safety, legal status and potential effects on human beings and planet Earth.

Zinc oxide (ZnO) nanoparticles coatings

As one of the novel nanomaterials, Zinc oxide (ZnO) NPs has drawn a lot of attention as the most promising medicine anticancer agent because of their unique physicochemical properties, yielding in low-cost, highly biocompatible and pro-biological activity among others type of metal oxides nanoparticles (Mohammed *et al.*, 2025) [57]. The effective incorporation of ZnO NPs within edible coating has been researched to greatly improve their barrier, mechanical and structural characteristics as compared to primitive edible coatings (Gandhi *et al.*, 2025) [58]. As coatings or as postharvest treatments, ZnO NPs help keep fruits safe for later consumption and delay their degradation by lowering microbial contamination (Sirelkhatim *et al.*, 2015) [59]. Due to their high antimicrobial activity, they are fit for food preservative and edible coating functionalisation. Studies showed that ZnO NP-based coatings enhance postharvest quality for strawberries, bananas, and other perishable commodities. Furthermore, Hmam *et*

al., 2023 [60], stated that alginate-based coating incorporated with ZnO nanoparticles resulted in a significant extending shelf life of fresh strawberries during cold storage and may have great implication in postharvest management systems.

Polysaccharide-based coatings

Natural biopolymers such as alginate, chitosan, cellulose, pectin and starch are very promising edible coatings in preserving the postharvest quality [Dai *et al.*, 2025 [61]]. The most common from these is that chitosan shows strong *anti*-micro hosting property. The study shows that for example chitosan coated strawberries had less microbial spoilage, and fungal growth was on the delayed as the effect of general antimicrobial action of chitosan (Hafids *et al.*, 2025) [62]. Apart from that, edible coatings serve as semi-permeable membrane barriers to gas exchange and moisture transfer ensuring the retention of some degree of internal moisture within the coated produce (Kester *et al.*, 1986) [63].

Protein-based coatings

Edible coatings based on proteins have attracted much attention because of their suitable film-forming properties, and ability to incorporate bioactive substances such as antioxidant and antimicrobial compounds due to the large number of functional amino acid groups (Chen *et al.*, 2019) [64]. The coatings are usually prepared with the help of solvents or carriers, which can be water, ethanol or their mixtures (Zorraquin-Peña *et al.*, 2020) [55]. Based on their structure and solubility, edible coatings proteins can be divided into two significant groups. Fibrous proteins are mainly of animal origin and include casein, whey protein, collagen, gelatin and keratin — they are relatively insoluble in water. However, on the other hand compared to fibrous proteins that can be purified as marginally soluble protein aggregates or fibers and particularly where most globular proteins are denatured as water soluble molecules in aqueous solutions of acid, base or salt and are often extracted from plant material like wheat gluten, soy protein, peanut protein, corn zein and cottonseed protein. This classifica-

tion is significant as it modifies functional properties and application possibilities of protein-based coatings in food preservation systems.

Lipid-based coatings

Lipid edible coating formats have been acknowledged for their moisture barrier but exhibit poor gas permeability, which may promote anaerobic respiration in covered produce if not properly designed and applied (Devi *et al.*, 2024) [65]. As such, lipid-based coatings have been used for over 800 years (Hardenburg, 1967) [66], in applications ranging from fruit waxing to confectionery coating (~October 2023).

Impact of nano-coatings on quality traits

Shipping delays would even see these bodegas up-charging them for 400% often How do ramps grow respect the farm-to-table model is preserving fruits? For instance, Li *et al.* (2020) [67] explored food industry applications using nano-coatings to extend postharvest quality preservation. Similarly, Barik *et al.*, 2024; Mokhtari *et al.* (2024) [68, 69] found that strawberries coated with edible chitosan-based nano-coatings showed reduced moisture loss and colour changes during cold storage ensuring better content of major quality attributes. Furthermore (Shah *et al.*, 2020) [70], The results of a research carried out by Begum *et al.* (2023) [71] based on the combined use of chitosan and aloe vera gel to prolong the shelf life of mango fruits, intensified show that postharvest deterioration was reduced while delaying ripening.

Application methods of edible coatings

This has driven the development of fruit preservation technology that should be compliant with consumers and environmentally sustainable, while significantly improving product quality content and safety without loss of sensory properties or nutritional value (Ju *et al.*, 2019) [72]. Fluidized bed processing and foaming approaches have been studied as well, but their use has generally been limited to laboratory research facilities rather than the commercial scale (Zhang *et al.*, (2020) [73].

Sr.no	Fruits	Edible coating used	Results	References
1.	Guava (<i>Psidium guajava</i> L.)	SLN (solid lipid nanoparticles) — carnauba wax and candelilla wax, with Poloxamer 407	The potential use of SLNs in edible coatings could be applied easily to minimize the senescence of several products	Eurobarometer, 2008
2.	Apple (<i>Malus domestica</i>)	Nano-SiO ₂	Edible coating prepared by ultrasonic processing and incorporated into an SPI matrix decreased the respiration rate, maintained firmness, and extended shelf life	Liu <i>et al.</i> , 2017
3.	Citrus (Citrus sp.)	Silver nanoparticles (AgNPs)	AgNPs caused cell deformation, cytoplasmic leakage, and cell death of <i>P. italicum</i> . They also showed significant activity against <i>E. coli</i> and <i>S. aureus</i> , with beneficial effects for citrus fruit preservation	Liu <i>et al.</i> , 2017
4.	Strawberry (<i>Fragaria</i> sp.)	Limonene (liposomes)	Limonene liposomes showed significantly lower fungal growth compared to the control on the 14th day of storage	Dhital <i>et al.</i> , 2017
5.	Pomegranate (<i>Punica granatum</i>)	Nano edible coating with zinc oxide and pomegranate peel phenols	Prolonged pomegranate shelf life by reducing microbial growth, enhancing physicochemical stability, and preserving quality attributes	Anean <i>et al.</i> , 2023
6.	Pomegranate (<i>Punica granatum</i>)	Chitosan-based edible coating enriched with 24-epibrassinolide	Effectively maintained pomegranate ("Wonderful") fruit quality and enhanced shelf life and quality	Mwelase <i>et al.</i> , 2022

Problems associated with edible coatings

The internal atmosphere modification from edible coating application may also lead to the development of physiological disorders associated with elevated carbon dioxide or lowered oxygen concentrations (Ben-Yehoshua, 1969) [74].

Future thrust

The growth and development of spoilage microorganisms, such as bacteria and molds on fresh fruits is an important factor affecting their postharvest quality and shelf life (Wang *et al.*, 2017). This is made worse by the fact that microbial contamination quickly accelerates spoilage, incurring losses in both quality and marketability. Accordingly, edible coatings have been successfully introduced as an efficient means for prolonging the storage shelf-life fruits. For instance, Alvarez *et al.*, (2022) [51] showed that pectin-beeswax coatings with the content of eugenol form a promising method for commercial applications to enhance postharvest quality and reduce losses in citrus fruits. However, large-scale production, storage stability and the practical implementation of edible coatings still face many challenges, in spite of these advantages. Consumer acceptance, food safety, nutritional feeds mistruth and shelf-life extension information of preservation by convection remain a constant problem (Kumar *et al.*, (2023) [75]. Moreover, edible films based on polysaccharides and proteins frequently have poor water vapour and gas barrier functionality (Hmam *et al.*, 2023) [60]. In order to explain these drawbacks, the addition of plasticizers, emulsifiers and other functional additives is crucial to its mechanical properties than was previously thought (Abdullah *et al.*, (2022) [76]. Thus, overcoming these technical and commercial challenges will require advances in material development, increased consumer awareness of existing products and the introduction of relevant regulatory regimes. To drive up widespread acceptance of edible packaging, it is also important to promote its potential environmental and health benefits (Duguma, 2022) [77].

Conclusion

Edible coatings are a potential and versatile means for sustaining maintaining the quality of perishable crops in most postharvest storage situations. Knowledge of incorporeal elements/microelements (physicochemical traits) of biopolymer is an obligatory duty when choose the coating adornment suiting to peculiar sorts whatsoever fruit. Due to their carrying capacity, the biopolymers allow adding functional additives, such as bioactive compounds (antimicrobial and antioxidant), probiotics or antagonistic microbes. The use of edible coatings fortified with active agents can act as a barrier against pathogen development while also modulating fruit physiological and biochemical processes altering the shelf life after-harvest quality attributes. Nanotechnology-based materials such as zinc oxide, silver nanoparticles, and chitosan nanoparticles have attracted more attention recently due to their efficacy in improving post-harvest quality and population of microorganisms. The mode of application also has a decisive effect on the edible coating. Choosing the right application method requires the previous knowledge of both coating matrix and fruit surface characteristics. The application of nanotechnology has made it possible for edible coatings to add even more functionality, including natural flavors and colors (natural variations of food based on place), as well as essential nutrients. It provides avenues for value addition, like fortification with vitamins and enhancement of their sensory appeal. Edible coatings based on nanotechnology are leading the way for a new era of sustainable and efficient preservation of fruits. Nevertheless, despite all advancements, this field is still in its infancy when it comes to safety, scalability and long-term consumer acceptance research. Hence, more studies are needed to design novel coating systems with greater functionality and safety but better sensory performance.

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Authors

Vikas Kumar Sharma

Department of Horticulture, CCS Haryana Agricultural University, Hisar (Haryana) - 125004, India

Saksham

Department of Horticulture, Maharana Pratap Horticultural University, Karnal, Haryana, India

Akshay Mehta

Department of Horticulture, CCS Haryana Agricultural University, Hisar (Haryana) - 125004, India

Bharti

Department of Horticulture, CCS Haryana Agricultural University, Hisar (Haryana) - 125004, India

Mukesh Kumar

Department of Horticulture, CCS Haryana Agricultural University, Hisar (Haryana) - 125004, India