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Nano-silicon coating on fruit crops: Review

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Abstract
In order to maintain the quality of food, edible coatings are employed, but they also have the potential to immobilise active substances on the food surface. Since the droplet size of nanoemulsions is reduced, the solubility, stability, and potential biological activity of lipophilic active substances are all increased when added in food matrix. The use of nano-silicon based coatings as carriers of functional compounds like antimicrobial component, antioxidants, and texture stimulators as well as significantly enhancing quality of fruits and vegetables are discussed in this review of recent developments for the maintenance of the quality and safety of fresh-cut fruits and vegetables. Nanoemulsion characterization and its preparation as low energy and high energy methods has also been reviewed.

Keywords: Nano silicon, nanoemulsion, shelf-life, decay rate

Introduction

Freshly cut fruit are rich source of biologically active substances and micronutrients that have antioxidants, minerals, fibres, anti-inflammatory, anti-allergic, anti-cancer, and anti-genotoxic properties (Gupta *et al.*, 2021) [13]. Due to changing lifestyles and customer considered as significant part, the demand for such advantages has grown significantly over time. Fruits and vegetables are crucial parts of the human diet (Chen *et al.*, 2020) [3]. Cutting, washing, or peeling fresh fruit and vegetables alters the quality of the product by injuring the tissues and modified enzymatic activities. These processes have negative impacts on the products' quality, including surface browning, unusual flavours, water loss, and texture degradation (Ramos *et al.*, 2021) [31]. As a result, these problems reduce the fresh-cut fruit and vegetable shelf life, raising manufacturing prices and lowering consumer acceptance (Yousuf *et al.*, 2021) [45].

According to report of Ministry of Agriculture, co-operation, and Farmers, 40% of fruits and vegetables are contaminated and degraded as a result of improper shelf-life extension techniques (Corato *et al.*, 2020) [5]. Consequently, extending the shelf life of fruits and vegetables has become a crucial concern in the food industry. Therefore, novel technologies like controlled atmosphere packaging (Wang *et al.*, 2021) [40], modified atmosphere packaging (Garavito *et al.*, 2022) [11], and edible coatings (Saleem *et al.*, 2021, Gioushy *et al.*, 2022) [33, 8] and edible coating and film (ECF) (Sultan *et al.*, 2021) [37] are recommended as potential options for preserving the quality of agricultural produce during storage and shelf life (Xing *et al.*, 2019) [44]. The development of microbial pathogens poses a serious risk to the quality of fruit and vegetable as well as human health, which has prompted substantial study into the joint use of edible coatings and nano-biocomposites (Adiletta *et al.*, 2021) [1].

Recent advancements in nanotechnology have enabled the development of coatings based on emulsions with enhanced characteristics and functionalities. Nanomaterials are substances with at least one structural dimension smaller than 100 nm of oil water emulsion which is more common (Saleh *et al.*, 2020) [34]. As materials change their state from the macroscopic to the nanoscale, a variety of different characteristics, such as barrier and optical properties, etc., emerge that are distinct from their macroscopic condition (Liu *et al.*, 2022) [25]. Additionally lowering moisture migration, gas exchange, oxidative reactions, inhibiting microbiological development (microorganisms), product degradation, and improving control of physiological disorders, this alters the coating's physical qualities (Felicia *et al.*, 2022) [9]. Furthermore, coatings formed on nanoemulsions have demonstrated promise as carriers for a variety of active substances, including oil-soluble vitamins, antimicrobials, flavours, and nutraceuticals, that might help to maintain the qualitative qualities of food products (Kiss 2020) [18]. Nano-level detection technologies have captured the attention of researchers in the area of fruits and vegetables storage because they can include a better knowledge of the features and can be used to demonstrate the causes of changes in food qualities during storage and processing (Liu *et al.*, 2020) [24].

Nanomaterials can be thought of as a viable option to counter the drawbacks of conventional preservation approaches because of the advantageous unique qualities such as greater surface-to-volume ratio, broad-spectrum antimicrobial activities, and high-efficiency barrier properties (Chua *et al.*, 2020) [4].

Nanoemulsion Technology

A nanoemulsion is a heterogeneous system composed of at least two immiscible liquids, one of which is distributed into the other in minute droplets varying in size from 10 to 1000 nm (Kumar *et al.*, 2021) [22]. Nanoemulsions having a radius of less than 100 nm provide physical stability to active compounds that are encapsulated because of their subcellular size. Additionally, they offer additional benefits including enhanced bioactivity due to higher diffusion and a diminished impact on the organoleptic qualities of food products (Pandiselvam *et al.*, 2021) [27]. Oil-in-water or water-in-oil emulsions classified as nanoemulsions assist in enhancing the physicochemical characteristics of edible coatings on a range of food commodities (Kumar *et al.*, 2022) [21]. An aqueous phase, an oil phase, and an emulsifier are the common components of a nanoemulsion (Felipe *et al.*, 2022) [6]. Water is the primary component of the aqueous phase, but it can likewise be created with other polar substances, such as co-solvents (simple alcohols and polyols), carbohydrates, proteins, minerals, acids, and bases (Basak *et al.*, 2018) [2]. The oil phase can be created by manufacturing a variety of nonpolar substances, including free fatty acids, essential oils, mineral oils, waxes, weighing agents, vitamins, and lipophilic compounds (Hasan *et al.*, 2020) [14]. Because they are simple to integrate with food substances and give additional opportunity for scaling up in the food industries employing the high-pressure homogenization method, oil-in-water emulsion nanoemulsions are being developed as the latest generation of edible coatings (Tripathi *et al.*, 2021) [39]. The water barrier, optical and microstructural mechanical characteristics, as well as the antimicrobial and antioxidant activities, are the key modifications driven on by the usage of nanosystems in nanocomposite coatings (Jafarzadeh *et al.*, 2021) [15]. When antimicrobial or antioxidant compounds are included in coatings, nanoparticles in the coatings enhance these actions by allowing their steady and regulated release over the course of fruit storage, perhaps under varying storage conditions, enhancing the bioavailability of these substances over period (Pateiro *et al*., 2021) [28].

Production of nanoemulsion

On the base of energy input, two methods—low energy and high energy—may be used to create nanoemulsions. Spontaneous emulsification (Thirumalaisam *et al*., 2022) [38] phase inversion composition (Zhang *et al.*, 2020) [47], and phase inversion temperature are examples of low-energy techniques, whereas high-energy techniques involve ultrasonication (Paudel *et al*., 2019) [30], high-pressure homogenization (Patrignani *et al.*, 2020) [29], and homogenization in microfluidizers (Wiseva *et al*., 2021) [42]. For the production of nanoemulsions, low-energy techniques are highly productive and efficient compared to high-energy techniques, although not all oils and emulsifiers can be produced using low-energy techniques (Safaya *et al*., 2020) [32]. Nanoemulsions are kinetically stable but thermodynamically unstable. Furthermore, time-dependent modifications may lead in aggregation, coalescence, flocculation, Oswald's ripening, and gravity sedimentation, among other destabilising impacts (Zaragoza *et al*., 2018) [46].

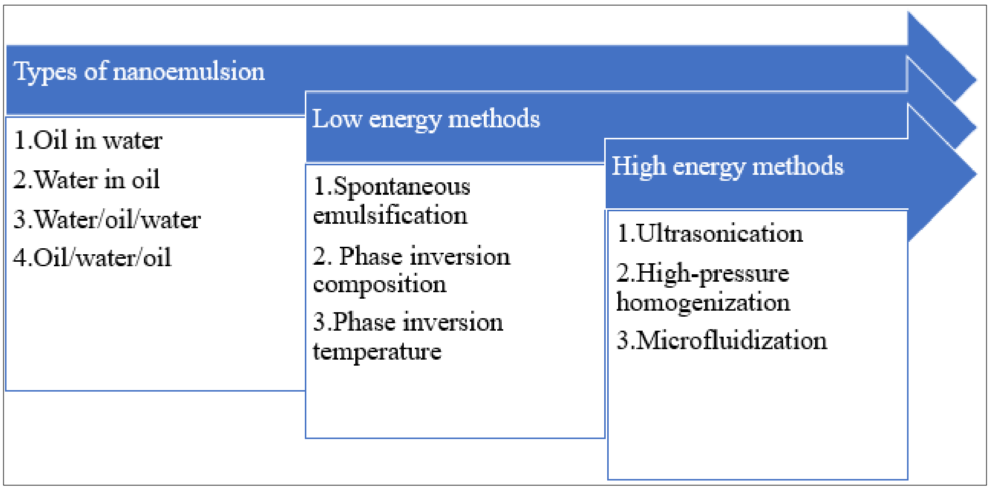

Fig 1: Methods and types of nanoemulsion.

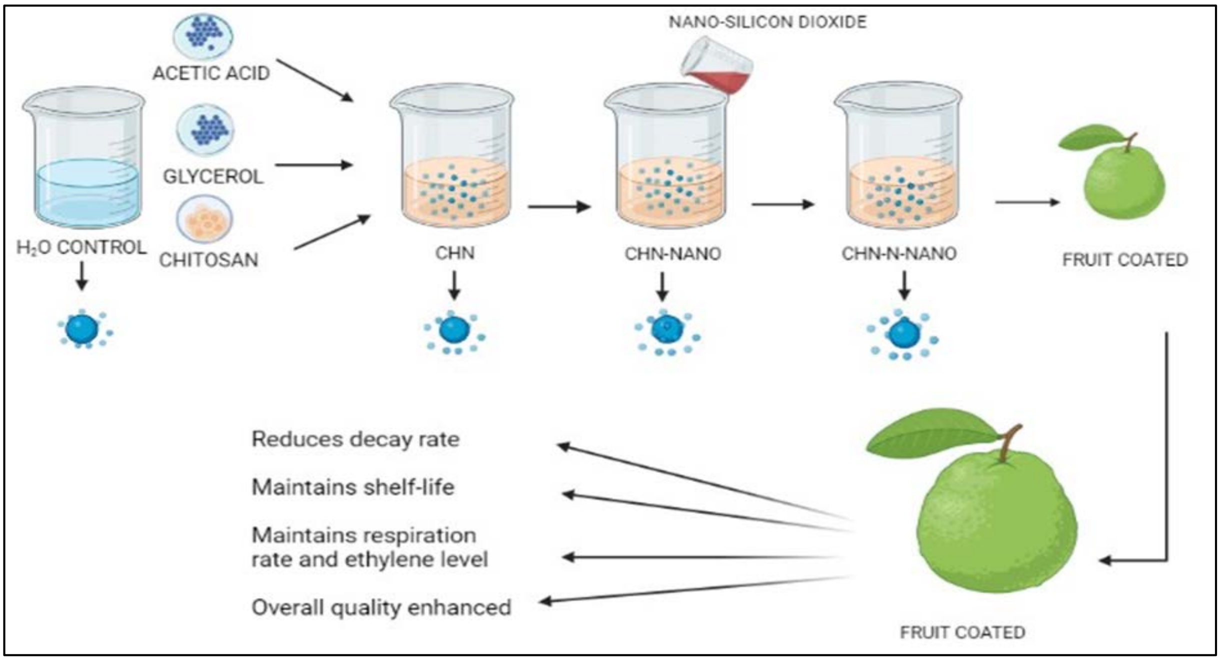

Fig 2: Coating procedure and benefits on coating on fruit

Impact of nano-silicon dioxide coating on shelf life

There have been numerous research studies on the use of nanoemulsions to extend the shelf life and quality of fruits and vegetables. Colour, firmness, respiration, water loss, TSS, acidity are major factors that determine shelf life of fruits and vegetables. In a study conducted by Sami *et al.*, (2021) [35] nano-silicon and nano-chitosan on fresh-cut cantaloupe and were stored for 8 days at 4 °C. They concluded that pH (5.67–5.99), vitamin C (22.29 mg/100 g) was maintained, TSS was increased at the end of storage period. Nano-silicon (2%) incorporated with nano-chitosan (0.5%) were coated on canino apricot fruits and were stored at 1°C and 90-95% (RH) and Kamil *et al.*, (2019) [16] revealed that the coating-maintained firmness of fruits, acidity and vitamin C content as compared to control fruits. This treatment also increased TSS content but decreased decay rate. Sami *et al.*, (2021) [36] treated button mushrooms with nano-silicon incorporated with nisin and chitosan and stored at 4°C for 12 days. They revealed that, this treatment led to lowest respiration rate (0.005 mg $CO2$ kg^{-1} s^{-1}) values, MDA content was increased both in treated (0.81 to 1.63 µmol kg^{-1}) and control (0.81 to 4.08 µmol kg^{-10}). Eldib *et al.*, (2020) [7] synthesized nano-silicon dioxide (1%) with chitosan, nisin (1%) on blueberry fruits for eight days at ambient temperature. At the end of storage period, Vitamin C (7.34 mg/100 g) and polyphenol oxidase (PPO) (558.03 U min^{-1} $\cdot g^{-1}$) were retained. Reduced weight loss was also seen and nano-layers were the reason behind this for preventing shrinkage. TA, SSC, SSC/TA were also maintained throughout the storage period. Zhang *et al.*, (2019) [48] synthesized nano-silicon, konjac glucomannan (KGM)/carrageenan (KC) coatings and applied on mushrooms. Nano-silicon was effective component to improve the properties of KGM and KC coating. It was also concluded that nano-silicon reduced the gas permeability of coatings. In another study, Zhu *et al.*, (2019) [20] synthesized nano-silicon and nano-chitosan coating on green tomatoes under ambient temperature stored for 15 days. Results revealed that, it led to less weight loss, firmness values were retained, TA gradually increased (30.3%) during first few days but decreased (26.1%) at end of storage period. It was summarized that the coating treatment was beneficial for increasing shelf life of tomatoes. Kou *et al.*, (2019) [19] synthesized nano-silicon, abscisic acid, chitosan & sodium alginate coating on chinese winter jujube (*Zizyphus jujuba* Mill. cv. Dongzao) fruits. TSS, TA was maintained during the storage period.

Impact of nano-silicon dioxide coating on nutritional quality

Ascorbic acid, which is considered as a vital nutrient and an antioxidant that impairs reactive oxygen species in fruit tissues, has the particular property of delaying the senescence of harvested fruit. Kou *et al.*, (2019) [19] synthesized nano-silicon, abscisic acid, chitosan, and sodium alginate coating on Chinese winter jujube (*Zizyphus jujuba* Mill. cv. Dongzao) fruits and stored. The ascorbic acid concentration of the ABA-treated fruits declined to 118 mg/100 g, which is lesser than the control. In the ABA-treated and control fruits, the anthocyanin content first increased and subsequently declined, peaked on days 60 and 75, accordingly. Sami *et al.*, (2021) [35] treated button mushrooms with nano-silicon incorporated with nisin and chitosan stored at 4 °C for 12 days and evaluated antioxidant capacity. Results for (2,2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid)) ABTS radical scavenging improved during storage, peaked at (71.09 and 70.03%), and then began to decline. The maximum scavenging against (DPPH) 2, 2-diphenyl-1-picrylhydrazyl radicals was at 78.13%. Zhu *et al.*, (2019) [20] synthesized nano-silicon and nano-chitosan coating on green tomatoes under ambient temperature stored for 15 days. They concluded that, total phenol content increased during first 6 days, but decreased at the end of storage period. PAL and POD activity was also maintained throughout the storage. Kassem *et al.*, (2022) [17] incorporated chitosan and nano-silicon dioxide and coated on ‘Tommy Atkins’ mangoes which were stored at 13 ± 1 °C and 90-95% RH for 30 days, and then at 20 ± 2 °C and 70-75% RH for 5 days. It was concluded that the best coating for preserving the mango's quality throughout cold storage and marketing was produced up of 2% chitosan and 1% nano-silicon dioxide (Kassem *et al*., 2022) [17].

Impact of nano-silicon dioxide coating on post-harvest deterioration

Sami *et al*., (2021) [36] experimented on nano-silicon with nano-chitosan and applied on fresh-cut cantaloupe and were stored for 8 days at 4℃ and evaluated their microbial activity. At the end of storage, the microbial quality was 5.73 log CFU/g recorded. It was concluded that the treatment led to less microbial activity as compared to control. Eldib *et al.*, (2020) [7] synthesized nano-silicon dioxide (1%) with chitosan, nisin (1%) on blueberry fruits. They concluded that at the end of storage treatment that blueberries had decay rate of 8.61% which was very less as compared to control fruits. Coating also reduced the microbial populations for molds/yeast and mesophilics (3.60 and 2.73 log CFU/g). Zhu *et al*., (2019) [20] synthesized nano-silicon and nano-chitosan coating on green tomatoes under ambient temperature and showed the inhibition rates of NSCC (nano silicon and chitosan coating) solution against *Escherichia coli* and *Staphylococcus aureus* are substantially (p 0.05) greater at 42.88% and 37.85%, accordingly. Kassem *et al.*, (2022) [17] incorporated chitosan and nano-silicon dioxide and coated on ‘Tommy Atkins’ mangoes which were stored at 13 ± 1 °C and 90–95% RH for 30 days, and then at 20 ± 2 °C and 70–75% RH for 5 days. The mango fruits coated with chitosan 2% + nano-silicon dioxide 1% showed the lowest decay rate (8.04%) after 5 days. Furthermore, towards the ending of the marketing term for both seasons, the control fruits exhibited the highest deterioration (32.90%).

Table 1: Impact of nano-silicon dioxide coatings on different horticultural crops.

Crop	Scientific name	Edible coating	Impact	Reference
Tomato	*Solanum lycopersicum*	Nano silicon+ Nano chitosan	Maintained PAL and POD activity.	Zhu *et al.*, (2019) [20]
Jujube	*Ziziphus jujuba*	Nano-silicon, abscisic acid, chitosan, and sodium alginate	Maintained ascorbic acid and anthocyanin content.	Kou *et al.*, (2019) [19].
Canino apricot	*Prunus armeniaca*	Nano chitosan+ Nano silicon	Maintained the firmness, acidity, and vitamin C content.	Kamil *et al.*, (2019) [16].
Mushroom	*Agaricus bisporus*	Nano-silicon, konjac glucomannan (KGM)/ carrageenan (KC)	reduced the gas permeability of coatings and reduced weight loss	Zhang *et al.*, (2019) [48].
Blueberry	*Vaccinium sect. Cyanococcus*	Nano chitosan+ Nano silicon+ Nisin and Silicon (B/CH/Nano-SiO_2) and titanium (B/CH/Nano-TiO_2) dioxide	Inhibited growth of moulds & mesophilics and maintained vitamin C content PPO activity and reduced weight loss.	Eldib *et al.*, (2020) [7] and Rokayya *et al.*, (2021) [23].
Loquat	*Eriobotrya japonica*	Nano- silicon dioxide	Reduced decay rate and maintained ascorbic acid and antioxidant capacity.	Wang *et al.*, (2020) [41].
Cantaloupe	*Cucumis melo* var. *cantalupensis*	Nano silicon + Nano chitosan	Reduced microbial activity and maintained Ph, TSS, TA and vitamin C content.	Sami *et al.*, (2021) [35].
Mango	*Mangifera indica*	Nano silicon+ Nano chitosan	Reduced decay rate and maintained antioxidant capacity and TPC.	Kassem *et al.*, (2022) [17].

Conclusion

From above results it may be summarized that, combinations of nano-silicon including various coatings significantly increased the shelf life of fruits and vegetables. Additionally, we noticed that the use of nanoemulsions in coating-developed solutions offered several advantages, including improved antimicrobial activity, nutritional quality, and maintenance of overall fruit and vegetable quality.

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