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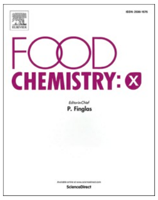

Green synthesized silver nanoparticles, a sustainable approach for fruit and vegetable preservation: An overview

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ABSTRACT

Nanotechnology in which silver nanoparticles (AgNPs) have received more interest in fruits and vegetables (FaV) preservation due to their anti-microorganism properties. There are various approaches to synthesizing AgNPs, in which biological reduction, especially plant extraction containing bioactive compounds, is considered non-toxic, eco-friendly, and economically viable. AgNPs can be applied for FaV preservation by immersing or incorporating AgNPs into the edible coating or wrapper film. Depending on the type of coating and the kind of FaV, choosing the coating components is necessary to ensure the anti-microorganism ability and improve preservation efficiency. This review highlights green-synthesized AgNPs for preserving FaV. The study covered the materials employed in the green synthesis of AgNPs, their effectiveness against microorganisms, the influence of AgNPs on film structure, safety properties, and various preservation strategies. Using plant or bacterial-synthesized AgNPs in edible coatings offers a sustainable approach to enhance safety, edibility, environmental friendliness, and FaV quality during storage.

1. Introduction

Food security remains a critical concern, drawing significant attention as the global demand for food rises annually. The number of undernourished people has tended to grow since 2015, and up to 768 million were reported in 2021; more than half (425 million) live in Asia, and more than one-third (278 million) live in Africa, while Latin America and the Caribbean accounts for close to 8% (57 million) (World Health Organization, 2022). A meta-analysis of the projected global was reported by Van Dijk et al. (2021) indicated that between 2010 and 2050, the total global food demand is expected to increase by 35% to 56%, while the population at risk of hunger is projected to shift by −91% to +8% during the same period. According to WHO, by 2030, it is estimated that almost 8% of the world population, which equals nearly 670 million people, will still struggle with hunger (World Health Organization, 2022). One of the essential daily food resources is fruit and vegetables. Between 2000 and 2020, global fruit production increased by 55%, while vegetable production grew by 65% (FAO, 2022). In 2021, worldwide fruit production reached 910 million tonnes (1.1% increase from 2020), and vegetable production reached 1.2 billion tonnes (1.4% increase) (FAO, 2022b). However, post-harvest losses cause significant losses in the yield of vegetables and fruits. Post-harvest losses are defined as losses occurring after the separation of the product from the site of immediate growth (harvest) to the moment it reaches the consumer (FAO, 2023). Besides, around 1.3 billion tonnes, roughly one-third of the total food produced, is wasted or lost within the supply chain (World Economic Forum, 2019). Therefore, ensuring food security and finding sustainable solutions are pressing matters.

Post-harvest losses in fruits and vegetables can result from various factors, including improper handling, lack of pre-cooling, inadequate storage temperature control, microbial pathogens, etc. Among these factors, microorganisms pose one of the greatest threats to the shelf life

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of fruits and vegetables (Dong et al., 2020; Wanjiku et al., 2020; Lieu & Dang, 2021; Wang et al., 2022; Gowda & Sriram, 2023; Lieu et al., 2024). Microbial factors causing damage to fruits and vegetables are diverse, including bacteria, yeasts, and molds (Wu et al., 2018; Ortiz-Duarte et al., 2019; Saravanakumar et al., 2020; Akyüz et al., 2023; Goh et al., 2023; Gowda & Sriram, 2023; Zhang et al., 2024). Apart from proper storage, controlling the growth of pathogens in damaged produce during storage is a critical concern to minimize post-harvest losses.

Various strategies exist for this purpose, including essential oil treatment, irradiation, modified atmosphere packaging, nanotechnology, etc. (Du Rand et al., 2010; Hernández et al., 2017; Arpaia et al., 2018; Lieu & Dang, 2021; Shankar et al., 2021; Lieu et al., 2024; Zhang et al., 2024). Among these approaches, nanotechnology has garnered significant interest. Nanotechnology promises to enhance food availability and create novel products with beneficial applications across agriculture, food, water, the environment, medicine, energy, and electronics (Neme et al., 2021). Nanotechnology has received more interest in fruit and vegetable preservation due to its antimicrobial properties. Using different types of nanomaterials as functional additives in food packaging has become commonplace. These nanomaterials include copper nanoparticles, gold nanoparticles, platinum nanoparticles, silver nanoparticles, and zinc oxide nanoparticles (Alamdari et al., 2022; Mahuwala et al., 2020; Nishanthi et al., 2019; Sportelli et al., 2019). Among these, silver nanoparticles (AgNPs) with green synthesis, high antimicrobial activity, and a simple process have emerged as a potential fruit and vegetable preservation approach. AgNPs showed relatively higher antibacterial activity against pathogenic bacteria (*Staphylococcus* sp., *Bacillus* sp., *Klebsiella* sp., and *Pseudomonas* sp.) than gold and platinum nanoparticles (Nishanthi et al., 2019). Furthermore, the antimicrobial ability of AgNPs when combined with films (cassava starch/agar) was higher than that of ZnO nanoparticles (Mahuwala et al., 2020). Besides, green synthesis AgNPs could be synthesized from many different sources such as agar, chitosan, laser ablation, plant extract, microorganisms, triethanolamine, etc. (Dolgaev et al., 2002; Orsuwan et al., 2016; Nguyen et al., 2020; Wei et al., 2020; Gowda & Sriram, 2023; Vijayakumar et al., 2023; Alharbi et al., 2024) with broad-spectrum antimicrobial effects including yeast, mold, both Gram-negative and positive, antibiofilm activity, resistant strains, potential antidiabetic effect, against cancer cells, etc. (Jayaprakash et al., 2017; Zhang et al., 2017; Patra et al., 2019; Kanikireddy et al., 2020; Nguyen et al., 2020; Baker et al., 2021; Juárez-Méndez et al., 2021; Shankar et al., 2021; Miškovská et al., 2022; Mansour et al., 2023; Alharbi et al., 2024), along with low toxicity (Cheng et al., 2021; Vijayakumar et al., 2023). Incorporating AgNPs into film or edible coatings has significantly enhanced the shelf life and quality of fruits and vegetables during storage (Jia et al., 2015; Becaro et al., 2016; Kanikireddy et al., 2020; Mahuwala et al., 2020; Gowda & Sriram, 2023; Goh et al., 2023; Alharbi et al., 2024; Zhang et al., 2024). These attributes position AgNPs as a promising approach to delivering robust antimicrobial effects, prolonging the shelf life of fruits and vegetables, and enhancing economic efficiency. However, there are still some important considerations to take into account, such as the choice of materials for synthesis, the influence of AgNPs on film structure, preservation effectiveness, consumer safety, and more, which have not been well-documented. This review focused on green synthesized AgNPs to preserve fruits and vegetables. The study focused on the materials utilized for green synthesis of AgNPs, their effectiveness against microorganisms, the influence of AgNPs on film structure, safety characteristics, and different preservation approaches. Additionally, the review covers the advantages and disadvantages of each preservation method and the potential approach for preserving fruits and vegetables.

2. Reducing agent source for AgNPs synthesis

There are various approaches to synthesizing AgNPs, in which the synthesis process was carried out through reducing agents to transfer $AgNO_3$ into AgNPs (Fig. 1). Many different reducing agents could be used to make AgNPs, including physical reduction such as laser ablation (Mafuné et al., 2000), UV radiation (Fernández et al., 2010), γ-irradiation (Sheikh et al., 2009), chemical reduction agents such as gallic acid (Jamróz et al., 2019), L-tyrosine (Shankar et al., 2021), sodium borohydride (Jiang et al., 2013; Das & Das, 2019), sodium citrate (Wang & Rhim, 2015), sodium nitroprusside dihydrate (Zhang et al., 2024), triethanolamine (Wei et al., 2020;), or biological reduction agents such as plant extracts (Alharbi et al., 2024; Goh et al., 2023; Nishanthi et al., 2019), microorganisms (Vijayakumar et al., 2023), chitosan (Jia et al., 2015), agar (Orsuwan et al., 2016) (Table 1). Besides, external aided conditions are often physical agents such as stirring, heating, sunlight, ultrasonication, microwave irradiation, and hydrothermal reaction (Gao et al., 2017; Ortiz-Duarte et al., 2019; Foujdar et al., 2021; Wei et al., 2020; Cheng et al., 2021; Ahmad et al., 2023; Gowda & Sriram, 2023; Alharbi et al., 2024) which were used to play an essential role in accelerating the process of reducing $AgNO_3$ into AgNPs. The different external aided conditions could create different antimicrobial activity in the same reducing agent. A study by Foujdar et al. (2021) indicated that ultrasonication-assisted showed better antibacterial activity at low concentrations (50 μg/mL) against both Gram-positive and Gram-negative bacteria than sunlight-assisted or microwave irradiation-assisted.

To synthesize AgNPs, a reducing agent is added to $AgNO_3$, and then the reaction is carried out with an assistant agent to accelerate the process (Fig. 1). The AgNPs synthesis is formed through a color change. The color of the mixture was observed to change to yellowish brown, indicating the reduction of the Ag ions for AgNPs. The efficiency of AgNPs synthesis is often evaluated through spectroscopic method with a maximum wavelength in the range of 300 to 500 nm, which is the typical absorption range of AgNPs (Orsuwan et al., 2016; Gao et al., 2017; Jayaprakash et al., 2017; Nishanthi et al., 2019; Shankar et al., 2021; Gowda & Sriram, 2023; Alharbi et al., 2024).

2.1. *Physical reduction*

In this approach, physical reduction such as laser ablation, UV radiation, γ-irradiating were used as reducing agents (Dolgaev et al., 2002; Fernández et al., 2010; Mafuné et al., 2000; Sheikh et al., 2009). A study by Fernández et al. (2010) demonstrated the production of AgNPs using UV radiation as a reducing agent, followed by heating at 170 °C for 120 min. Similarly, silver ions were reduced to AgNPs using 5 kGy doses of γ-rays at room temperature (Sheikh et al., 2009). Another method for producing AgNPs involves laser ablation of a silver metal plate in a liquid environment, such as ethanol, sodium dodecyl sulfate, or water, with the use of surfactants (Dolgaev et al., 2002; Mafuné et al., 2000). Advantages of physical methods include rapidity, avoidance of hazardous chemicals, and the use of radiation as a reducing agent, whereas limitations include low yield of nanoparticles, high energy consumption, solvent contamination, and poor size distribution (Aragaw et al., 2022). Therefore, to minimize the impact of physical agents and improve synthesized AgNPs effectiveness, physical agents were often used as external aided conditions (Cheng et al., 2021; Foujdar et al., 2021; Jayaprakash et al., 2017; Ortiz-Duarte et al., 2019; Wei et al., 2020).

2.2. *Chemical reduction*

Chemical methods utilize organic or inorganic solvents to synthesize AgNPs. The synthesis steps are based on reducing agents such as gallic acid, L-tyrosine, sodium borohydride, sodium citrate, triethanolamine, Tween 80, etc. (Das & Das, 2019; Jamróz et al., 2019; Wang & Rhim, 2015; Mazur et al., 2020; Wei et al., 2020; Shankar et al., 2021). The procedure includes mixing silver nitrate ($AgNO_3$) with chemicals such as reducing agents and reacting to create AgNPs (Fig. 1). The reaction to create AgNPs with chemical reducing agents could be easily carried out by stirring at room temperature (Das & Das, 2019; Mahuwala et al.,

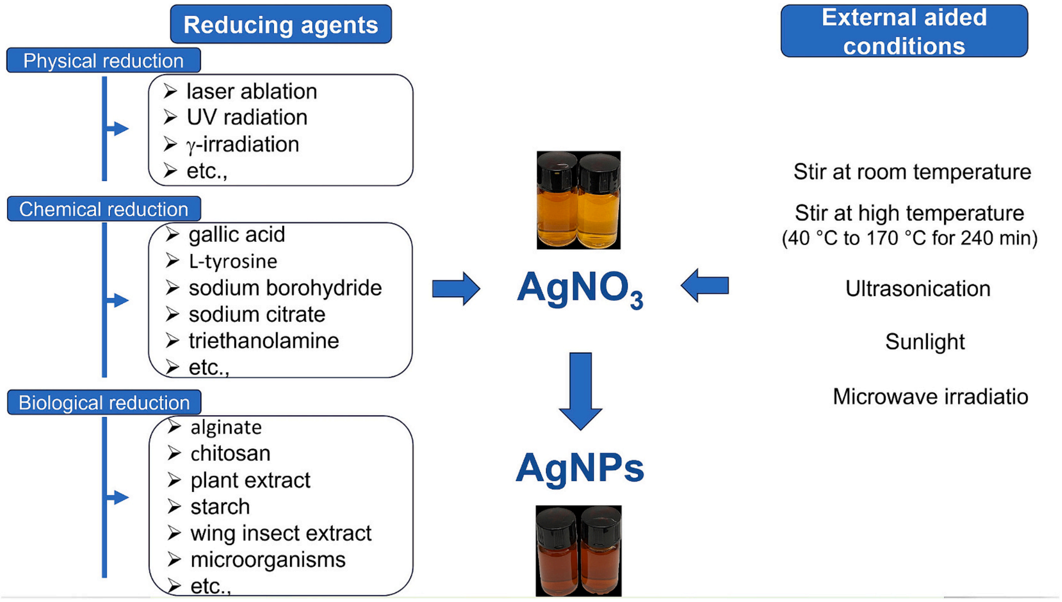

Fig. 1. Agent sources for AgNPs synthesis.

2020) or conducting a hydrothermal reaction at 160 °C for 2 h (Wei et al., 2020). Besides, external aided conditions such as microwave irradiation, heating treatment, etc., also showed effectiveness in producing AgNPs (Ortiz-Duarte et al., 2019; Shankar et al., 2021). Synthesis time by this approach is from 20 min to 72 h, depending on the chemical and external aided conditions. However, although using chemical reduction for producing AgNPs is advantageous due to their simplicity, high efficiency, and cost-effectiveness, this process often results in impure products with chemical residues on their surfaces (Hamed et al., 2022).

2.3. *Biological reduction*

This approach has received much concern and is considered non-toxic, eco-friendly, economically viable, and green synthesis (Jayaprakash et al., 2017; Gao et al., 2017; Hamelian et al., 2018; Wu et al., 2018; Nishanthi et al., 2019; Baker et al., 2021; Goh et al., 2022; Ahmad et al., 2023; Gowda & Sriram, 2023; Mansour et al., 2023). Generally, the synthesis of AgNPs is similar to the chemical method (Fig. 1), including a biological reducing agent mixed with $AgNO_3$. Then, the mixture would be reacted through external aided conditions such as stirring (Alharbi et al., 2024; Gao et al., 2017), heating (Alharbi et al., 2024), sunlight (Foujdar et al., 2021), ultrasonication (Cheng et al., 2021), microwave irradiation (Foujdar et al., 2021). The reducing agents for this synthesis approach are diverse, including alginate, algae (Salih et al., 2023), chitosan (Jia et al., 2015; Gowda & Sriram, 2023), essential oil (Gonfa et al., 2023), plant extract (Miškovská et al., 2022; Nejad et al., 2023; Nejad et al., 2024; Saravanakumar et al., 2020; Wunnoo et al., 2023), microorganism (Abdelwahab et al., 2021; Vijayakumar et al., 2023), starch (Kumar et al., 2020; Srikhao et al., 2021), wing insect extract (Jakinala et al., 2021). These reducing agent sources have been shown to produce AgNPs with effective antimicrobial activity. Notably, when synthesizing AgNPs using microorganisms as the reducing agent requires the time for microorganism culture and the time for fluid culture incubating with $AgNO_3$, which usually takes an additional 24 to 72 h (Saeed et al., 2020; Vijayakumar et al., 2023), significantly longer than the synthesis from other biological reducing agent sources. AgNPs synthesis with rind extract of *Garcinia mangostana* as a reducing agent showed that the formation time of AgNPs occurred within 10 min and peaked after 5–6 h of reaction (Nishanthi et al., 2019). Additionally, although using microorganisms as the reducing agent is gaining traction, only a select few bacterial strains are able to synthesize AgNPs. Saeed et al. (2020) reported that more than three hundred strains were tested, and only five showed positive results. Another potential reducing agent is plant extract, which contains many bioactive compounds that provide benefits such as antioxidants (Hamelian et al., 2018; Patra et al., 2019; Ojemaye et al., 2021; Alharbi et al., 2024), antimalarial activities (Ojemaye et al., 2021), potential antidiabetic (Patra et al., 2019), against cancer cells and antiviral (Alharbi et al., 2024). Ali et al. (2020) indicated that plant leaf extracts with bioactive secondary metabolites, especially flavonoids and other polyphenolic compounds, would ameliorate the toxicity induced via AgNPs in mice. Moreover, according to Saravanakumar et al. (2020), AgNPs synthesized using persimmon pedicel extracts in polyvinylpyrrolidone showed more antibacterial activities than the AgNPs synthesized by sodium borohydride, as evident by low minimal inhibitory concentration and minimal bactericidal concentration. These could be due to the plant extract with bioactive compounds, which positively impact and enhance anti-microbial. Therefore, the synthesis of AgNPs using the biological approach, which involves using reducing agents sourced from plant extracts, has shown promising results for the green approach.

3. Characteristics of AgNPs

Characteristics of AgNPs are essential in considering their applicability in fruit and vegetable preservation. One of these characteristics encompasses aspects such as size distribution, anti-microorganisms activity, the influence of combined materials in preservation applications, and considerations related to consumer safety.

3.1. *The size distribution of AgNPs*

The size distribution of AgNPs is a commonly considered criterion for evaluating the efficiency of synthesized AgNPs. Agnihotri et al. (2014) indicated that the average size (5–100 nm) of AgNPs impacted their antimicrobial activity in which 5 nm demonstrated the best results and mediated the fastest bactericidal activity against all the tested strains compared to AgNPs having 7 nm and 10 nm sizes at similar bacterial concentrations. Previous studies showed the size distribution of AgNPs was about 5–600 nm depending on the reducing agents, external aided conditions, reaction time, and composition of the combined film

Table 1
AgNPs synthesis sources and application for fruit and vegetable preservation.

Reducing agent	External aided conditions	Pathogen microorganisms inhibition	Fuits or vvegetable/ film material	Outcome	References
Immersing in AgNPs solution					
Fatsia japonica leaf extracts	Stir for 10 min and radiated by the white light for 100 min.	*Penicillium italicum, Escherichia coli, Staphylococcus aureus.*	Citrus fruits	The rotten rate decreased by about 50% at an AgNPs concentration of 100 μg/mL.	Zhang et al., 2017
Oolong tea extracts	Stir for 60 min at 20, 40, 60, 80, and 100 °C.	NS	Cherry tomatoes	The treated tomatoes have the highest healthy fruit rate, with a value of 2.4 times that of the untreated tomatoes after 15 days.	Gao et al., 2017
Wrapped film or Pad film					
UV radiation for subsequent four 5 min treatments	Heated at 170 °C for 120 min	*E. coli*	Fresh cut “Piel de Sapo” melon pieces Cellulose fibres pads	Increased the lag phases of the microbial growth curves. The addition of silver-loaded absorbent pads significantly improved the quality of melon cuts stored for ten days, reducing yeast counts, increasing juiciness, and lowering °Brix values.	Fernández et al., 2010
Sodium citrate (1%)	Stir	*Listeria monocytogenes, E. coli*	Potato Agar/alginate/collagen	Increased the tensile strength and decreased lightness of the film based on agar/alginate/ collagen. Prevent the greening and reduce weight loss of potatoes.	Wang & Rhim, 2015
Laponite nanodisk	Stir for 30 min at 70 °C.	*E. coli, S. aureus Aspergillus niger, P. citrinum*	Litchis Chitosan/Laponite	Litchis wrapped by Chitosan/ Laponite/AgNPs nano-films remained fresh compared to pure chitosan film with decay and grew with mycete after five days of storage.	Wu et al., 2018
Gallic acid	NS	*S. aureus (MRSA), E. coli.*	Mini kiwi fruits Furcellaran, gelatin	Nanocomposite films made of furcellaran, gelatin, and nanoselenium-AgNPs can extend the shelf life of kiwis by preventing fungal infection and weight loss	Jamróz et al., 2019
Mentha leaves extract	NS	*Bacillus subtilis, Salmonella typhe, Klebsiella pneumonia, Fusarium oxysporum, S. aureus, Candida albicans, Pseudomonas aeruginosa, Micrococcus liteus,*	Strawberries Carboxymethyl cellulose-Guar gum	Broad-spectrum microbial inhibition. AgNPs improved the tensile strength and modules of film, Reducing 30% of strawberries’ weight loss compared to unpacked samples.	Kanikireddy et al., 2020
Diospyros kaki L pedicel extracts	Put in the dark at room temperature	*Bacillus cereus, E. coli, P. aeruginosa, S. enteria subp. Enterica, S. aureus*	Fresh-cut bell pepper (FCP) Polyvinylpyrrolidone	Extending the shelf life of the red or yellow FCP for 12 d at 4 °C without causing any harm to cellular or physicochemical properties of FCP.	Saravanakumar et al., 2020
Mango peel extract	Ultrasound for 1 h and stirred for another 12 h	*E. coli* *S. aureus*	Strawberries Polylactic acid	The strawberries wrapped in the PLA film containing AgNPs did not show browning or mildew within the seven-day experimental period compared to PE, with browning occurring after three days of storage and mold growing after five days.	Cheng et al., 2021
L-tyrosine	Heating	*L. monocytogenes,* *S. enterica* serovar *E. coli* *A. niger*	Strawberries Chitosan	Enhancing anti-microorganisms activity, reducing decay, and retaining more phenolic compounds without influencing the weight loss, anthocyanin content, total soluble solids, firmness, and color parameters of the fruit.	Shankar et al., 2021
Edible coating					
$NaBH_4$ and polyvinylpyrrolidone	Stir	*Pseudomonas* *Yeasts* *Molds.*	shiitake mushroom (*Lentinus edodes*) Sodium alginate	The weight loss, softening, and browning of the alginate/nano Ag coating on the mushrooms were significantly reduced after 16 days of storage.	Jiang et al., 2013
Chitosan	Stir (95 °C)	*E. coli,* *S. choleraesuis,* *S. aureus,* *B. subtilis, and* *B. cinerea*	Blueberries Chitosan	Significant reduction in the number of *B. cinerea* spreading lesions on blueberries compared to the control group.	Jia et al., 2015

(*continued on next page*)

Table 1 (*continued*)

Reducing agent	External aided conditions	Pathogen microorganisms inhibition	Fuits or vvegetable/ film material	Outcome	References
$NaBH_4$ Red claw crayfish-extracted chitosan	Microwave irradiatio	*Mesophiles, Psychrophiles, Enterobacteria, yeasts, and molds*	Fresh-cut melon Chitosan	Reduced respiration and ethylene production, maintained total vitamin C content, contaminated microbial reduction.	Ortiz-Duarte et al., 2019
Banana peel extract	Incubating in a dark cabinet at 30 °C in 30 mins.	NS	Banana blocks Sodium carboxymethyl cellulose (SCC)	AgNPs incorporated into SCC coating prevent mold growth on banana blocks during the five-day storage period compared to the samples coated only by SCC with enlarged black spots that covered most surfaces.	Goh et al., 2023
Chitosan	Stir at 90 °C and then added 1 mL NaOH 0.4 M for 15 min of reaction	*Colletotrichum truncatum*	Chilli fruits Chitosan	Controlling seed-borne pathogens and increasing their productivity by enhancing the germination and growth of chilli seeds.	Gowda & Sriram, 2023
Egg white protein	NS	*Bipolaris sorokiniana, Fusarium culmorum, Fusarium graminearum, and Fusarium verticillioides*	Fresh cherries and apricots Locust bean gum	Most cherries and apricots in the control group were rotten on the fourth and fifth days, respectively. In contrast, the samples coated by LBG-AgNPs showed no considerable difference on their surface.	Akyüz et al., 2023
Pomegranate waste extract	Stir (150 rpm) for 20 min at 50 °C and pH 6.8.	*S. aureus, L. monocytogenes, Campylobacter jejuni, S. typhi and Candida*	Mandarin fruit Kidney peptide-Arabic gum (KPI/AG) Coating	KPI/AG/AgNPs 1% regulated the Vermont mandarin fruit's oxygen exposure, reducing H_2O_2 buildup and delaying the fruit's senescence.	Alharbi et al., 2024
Sodium nitroprusside dihydrate	Stirred for 18 h at room temperature in the dark	*B. cereus, S. aureus, L. monocytogenes, S. enterica, E. coli*	Banana Sodium alginate	Maintained the banana's appearance Slow down the ripening Reduce the weight loss Reduced total bacterial colonies in the banana peel and pulp Antibacterial activity against all tested bacterial pathogens	Zhang et al., 2024

NS: not showed.

(Fernández et al., 2010; Hanif et al., 2019; Mansour et al., 2023; Nejad et al., 2024; Orsuwan et al., 2016; Salih et al., 2023; Zhang et al., 2024). Transmission electron microscopy (TEM) analysis showed AgNPs made by different reducing agents (Fig. 2). A study by Fernández et al. (2010) indicated that UV radiation acted as a reducing agent and heated at 170 °C for 120 min, forming AgNPs with size distributions ranging from 5 to 35 nm. The mean value of AgNPs diameter with γ-irradiation as a reducing agent was 16.1 ± 4.9 nm (Sheikh et al., 2009). Using sodium nitroprusside dihydrate as a reducing agent (stirred for 18 h at room temperature in the dark condition) made the average diameter of the synthesized AgNPs approximately 400 nm (Zhang et al., 2024). Agnihotri et al. (2014) indicated that using sodium borohydride as a primary reductant at two different temperatures (60 °C and 90 °C) could control AgNPs average size about 5, 7, 10, 15, 20, 30, 50, 63, 85, and 100 nm.

Plant extracts used as reducing agents also showed differences in the size of AgNPs. A study by Jayaprakash et al. (2017) using *Tamarindus indica* fruit extract as a reducing agent showed that the size of the crystallites of AgNPs was calculated to be around 6–8 nm. The synthesized AgNPs by *Artemisia scoparia* or Mentha leaves extract had a size range of 12.0–23.3 nm (Hanif et al., 2019; Kanikireddy et al., 2020). Similarly, AgNPs synthesis with rind extract of *Garcinia mangostana* as a reducing agent showed that the average mean size of AgNP was about 23 nm and predominately spherical (Nishanthi et al., 2019). Tea leaf extracts were used to biologically synthesize silver nanoparticles that were observed to be highly crystalline, approximately spherical, and had a diameter ranging from 10 to 50 nm (Gao et al., 2017). AgNPs were synthesized using *Cassia fistula* fruit extract, resulting in spherical-shaped AgNPs with an average crystallite size of about 69 nm (Rashid et al., 2017). The synthesized AgNPs from pomegranate waste showed spherical particles ranging from 15 to 55 nm (Alharbi et al., 2024). A study by Zhang et al. (2017) indicated that concentrations of reacted agents such as *Fatsia japonica* leaf extracts, $AgNO_3$, and NaCl affected AgNP yields and particle sizes. Using algae as a reducing agent, such as *Noctiluca scintillans*, have particle sizes of AgNPs from 4.0 nm to 140 nm (Salih et al., 2023). These results suggested that particle sizes of AgNPs depend on the type of reducing agent and reaction conditions.

Previous studies also indicated that film materials significantly affected the AgNPs' diameter. The field emission scanning electron microscopy (SEM) showed that the AgNPs' diameter was 150–200 nm in a film containing only banana powder (4 g/150 distilled water) and 100 nm in a film containing 4 g of agar and banana powder (blending ratio 1:1), as reported by Orsuwan et al. (2016). The authors suggested that the phytochemicals in the banana powder acted as a reducing agent, facilitating the formation of AgNPs, and increasing the amount of banana powder led to faster and larger growth of AgNPs crystals without agglomeration (Orsuwan et al., 2016). Similarly, according to the TEM analysis, the hybrid nanoparticles composed of chitosan and silver were found to form spherical clusters with smooth surface morphology and were well dispersed with a diameter ranging from 100 to 200 nm (Jia et al., 2015). Orsuwan et al. (2016) indicated that the size and shape of nanoparticles depend on the concentration of reducing and capping agents. The AgNPs in polyvinyl alcohol/soluble starch films have a size distribution ranging from 8.80 nm to 20.88 nm, as Chen et al. (2021) reported. Besides, the composite film has been proven to reduce the diameter of AgNPs. Zhang et al. (2024) indicated that the synthesized AgNPs reduced by sodium nitroprusside dihydrate exhibited an average hydrodynamic size of 541.43 ± 15.19 nm, while incorporation in sodium alginate films resulted in an average size of 365.60 ± 30.75 nm. Chen et al. (2021) suggested that the interaction between AgNPs and film components (polyvinyl alcohol 10% *w/v* and starch 5% *w/v*) can prevent nanoparticle agglomeration. Additionally, Zhang et al. (2024) indicated that the smaller average size of AgNPs incorporated in sodium

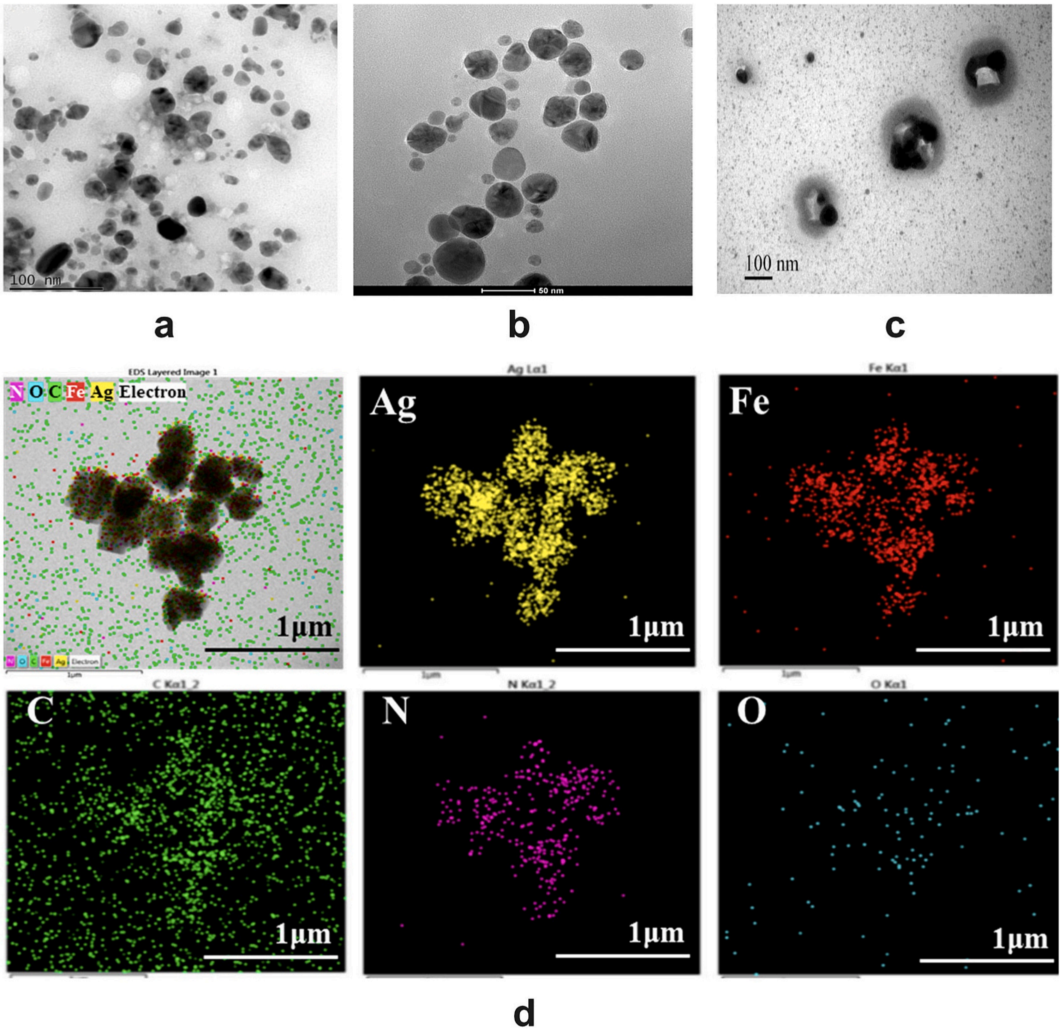

Fig. 2. TEM analysis of AgNPs synthesized with different reducing agents: a: probiotic bacterium (Vijayakumar et al., 2023); b: plant extract (Gao et al., 2017); c: chitosan Janus (Jia et al., 2015), and d: sodium nitroprusside dihydrate in which images of AgNPs (yellow), iron (red), carbon (green), nitrogen (purple), and oxygen (blue) (Zhang et al., 2024). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

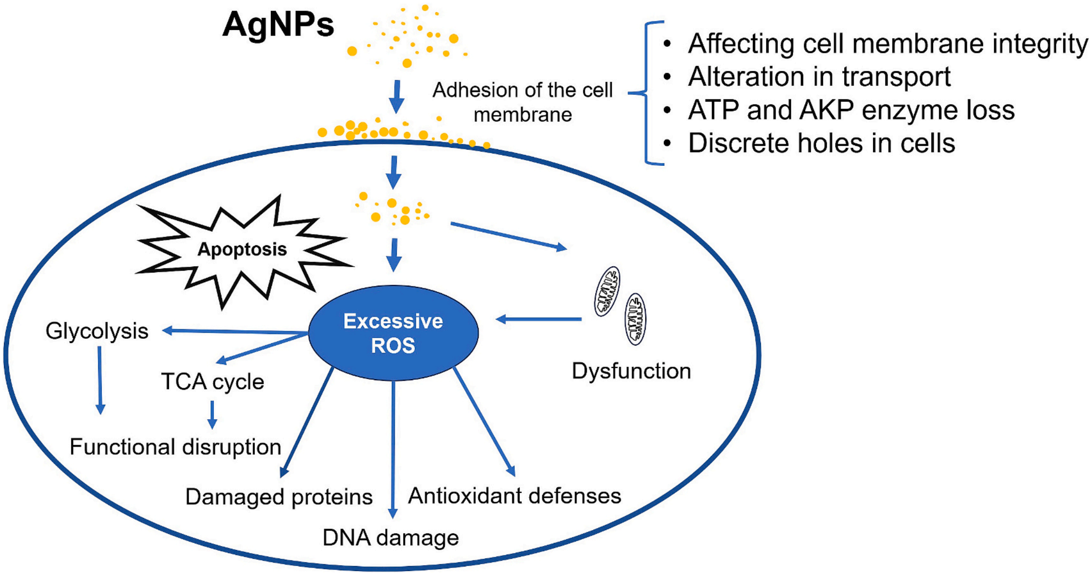

Fig. 3. Anti-microorganism activity of AgNPs.

alginate films is because sodium alginate coating on the surface of the nanoparticles limits the growth of the nanoparticles. Another study by Srikhao et al. (2021) reported that the particle size of AgNPs in polyvinyl alcohol (2.5% w/v) and cassava starch (2.5% w/v) film decreased from 44.35 nm to 23.75 nm, depending on the concentration of oregano essential oil (ranging from 0 to 5 wt%), which acted as a reducing agent. The SEM image revealed that the synthesized AgNPs from banana peel extract had agglomerated and adhered to each other, making it impossible to observe individual nanoparticles (Goh et al., 2023). Similarly, AgNPs were prepared using mango peel extract as a reducing agent in the polylactic acid film, having a particle size distribution of about 1.0–3.4 nm (Cheng et al., 2021). These show that the component of film material could prevent excessive agglomeration of AgNPs and reduce the particle size of AgNPs.

3.2. Anti-microorganism activity of AgNPs

AgNPs can combat pathogenic microorganisms through multiple pathways (Fig. 3). Antimicrobial activity initiates through the uptake process of AgNPs into the cell. The transport mechanisms of nanoparticles include (1) cellular internalization (endocytosis), (2) transcellular transport, (3) paracellular transport through tight junctions between cells, and (4) receptor-mediated transcytosis (Murugan et al., 2015). After entering cells, AgNPs cause changes that increase reactive oxygen species (ROS) (Sriram et al., 2012; Van Aerle et al., 2013; Khan et al., 2023). Most cellular and biochemical alterations in cells are caused by ROS-mediated toxicity, and several in vitro models have confirmed this (Van Aerle et al., 2013). The Excessive ROS generation induced by Ag-NPs influenced mitochondrial function, damaged cellular proteins, and antioxidant levels, ultimately leading to apoptosis in vitro (Sriram et al., 2012; Van Aerle et al., 2013). Besides, with these multiple combat pathways (Sriram et al., 2012; Moussa et al., 2013; Van Aerle et al., 2013; Zhang et al., 2017; Wei et al., 2020), AgNPs would slow down the adaptation and resistance of microorganism pathogens. Previous studies showed that AgNPs inhibited broad-spectrum microorganisms effectively, including molds (Dairi et al., 2019; Shankar et al., 2021; Akyüz et al., 2023; Gowda & Sriram, 2023), yeasts (Alharbi et al., 2024), Gram-negative and Gram-positive bacteria (Dairi et al., 2019; Shankar et al., 2021), Multi-Resistant *Staphylococcus aureus* (Jamróz et al., 2019), and antiviral (Alharbi et al., 2024).

The AgNP's impact on combating microorganisms varied depending on the specific type of bacteria or fungi involved. AgNPs provide antibacterial properties in bacteria cells with many different impacts, including causing discrete holes in cells and affecting cell membrane integrity (Jia et al., 2015), causing ultrastructural damage and increasing the cell membrane permeability (Vazquez-Muñoz et al., 2019), ATP and AKP enzyme loss (Wei et al., 2020), and dissolved cytoplasm (Zhang et al., 2017). In *E. coli* cells, Ag^+ primarily targets glycolysis and the oxidative branch of the TCA cycle (or pyruvate cycle) via functional disruption of the key enzymes (Wang et al., 2019). According to the TEM analysis, the *Escherichia coli* and cells that were not treated with AgNPs were intact, whereas the cells that were treated with AgNPs were deformed and had dissolved cytoplasm that ultimately led to the death of the bacteria (Zhang et al., 2017). The bacterial cell wall surfaces exhibited discrete holes and severe damage (Jia et al., 2015). Similarly, surface morphology analysis by field emission scanning electron microscopy revealed the formation of grooves/pits in the lysed cell membrane that eventually led to bacterial death (Rashid et al., 2017). Besides, ion interaction caused severe damage to the bacterial cell membrane, which led to the complete release of cell contents in the case of Ag/ZnO-Chitosan composite coating, which affected the synthesis of high molecular weight total protein and low molecular weight membrane protein (Wei et al., 2020). The authors also indicated that Ag/ZnO-chitosan coating increases the outer and inner membranes' permeability, content release, and ATP and AKP enzyme loss, leading to inhibition of the reproduction and growth of *Shewanella puterfaciens* and *Pseudomonas aeruginosa*.

The impact of AgNPs on bacteria also differs between Gram-negative and Gram-positive. It has been found that AgNPs are more effective in inhibiting Gram-negative bacteria than Gram-positive bacteria (Alharbi et al., 2024; Jamróz et al., 2019; Jia et al., 2015; Kumar et al., 2020; Nishanthi et al., 2019; Orsuwan et al., 2016). TEM image analysis (Fig. 4i) indicated that at the same concentration of AgNPs (with pomegranate waste as a reducing agent) shows that the impact on the cell membrane of Gram-negative bacteria is more severe than that of Gram-positive bacterial cells (Alharbi et al., 2024). Orsuwan et al. (2016) indicated that Gram-negative bacteria have a thin peptidoglycan layer with a negatively charged outer membrane, allowing AgNPs to enter the bacterial cell, while Gram-positive bacteria have a thicker peptidoglycan layer that makes it more challenging for AgNPs to penetrate. However, a study by Kanikireddy et al. (2020) found that a film made of carboxymethyl cellulose-Guar gum and AgNPs synthesized by Mentha leaves extract effectively inhibited both Gram-negative and Gram-positive bacteria, regardless of their Gram classification. Similar results were also reported by Zhang et al. (2024) regarding the synthesized AgNPs reduced by sodium nitroprusside dihydrate inhibited Gram-positive and Gram-negative, regardless of their Gram classification. Besides, Chen et al. (2021) indicated that the effect of AgNPs in polyvinyl alcohol/soluble starch films on Gram-positive bacteria (*Bacillus subtilis, Pseudomonas aeruginosa,* and *Staphylococcus aureus*) was more severe than that of gram-negative bacteria (*Salmonella* and *Escherichia coli*). Similarly, AgNPs from a film made with polyvinyl alcohol and cassava starch showed more significant antimicrobial activity against Gram-positive bacteria than Gram-negative bacteria (Srikhao et al., 2021). These results indicate that AgNPs can effectively inhibit both Gram-positive and Gram-negative bacteria, and the sensitivity of these bacteria is dependent on the microbial strain and the reducing agents used.

In the case of fungi cells, the inhibition tests and TEM analysis revealed that AgNPs caused cell deformation, cytoplasmic leakage, and, ultimately, cell death of *Penicillium italicum* (Zhang et al., 2017). The mycelial shape of *Botrytis cinerea* was altered when it was attacked by AgNPs combining chitosan coating, causing lysis in fungal hyphae, thinning and increased elasticity of cell walls, and loss of spores from the fungal conidiophore (Fig. 4iii; Moussa et al., 2013). AgNPs at concentrations of 10, 20, 40, and 80 μg/mL were found to inhibit the growth of Fusarium fungus mycelia and induce the destruction of the fungal hyphae, as reported by Nejad et al. (2023). A study by Zhang et al. (2017) showed that the AgNPs caused heavy deformation phenomena in *P. italicum* mycelium, the damaged cell membrane, and the cytoplasm, resulting in cell death. Similarly, Zhang et al. (2019) indicated that *A. niger* spores were destroyed or disintegrated, with some even disappearing, and a small number of AgNPs could be observed around the cell wall with treatment by molybdenum disulfide-chitosan-AgNPs (MoS-Cs-Ag) (Fig. 4iiii). Another study by Nejad et al. (2024) also indicated that AgNPs at 40 μg/mL completely inhibited the spore germination of *Alternaria alternata*, causing soft rot on sweet cherry fruits.

Moreover, incorporating AgNPs into the film material confers anti-microorganism pathogen properties to the film. Wei et al. (2020) indicated that adding AgNPs to the making process of ZnO-chitosan coating significantly improved its efficacy against both *Shewanella putrefaciens* and *Pseudomonas aeruginosa* compared to using chitosan or ZnO-chitosan coating alone. Gowda and Sriram (2023) suggested combining chitosan and AgNPs further increases its efficacy due to their synergistic activity, effectively controlling the seed-borne pathogens caused by *Colletotrichum truncatum*. Similarly, nanocomposite films, produced via solvent casting from aqueous solutions of furcellaran and gelatin with varying concentrations of nano selenium-AgNPs, exhibit potent antibacterial effects against *Staphylococcus aureus*, Multi Resistant *Staphylococcus aureus*, and *Escherichia coli* (Jamróz et al., 2019). These important highlights make AgNPs an object of great interest in

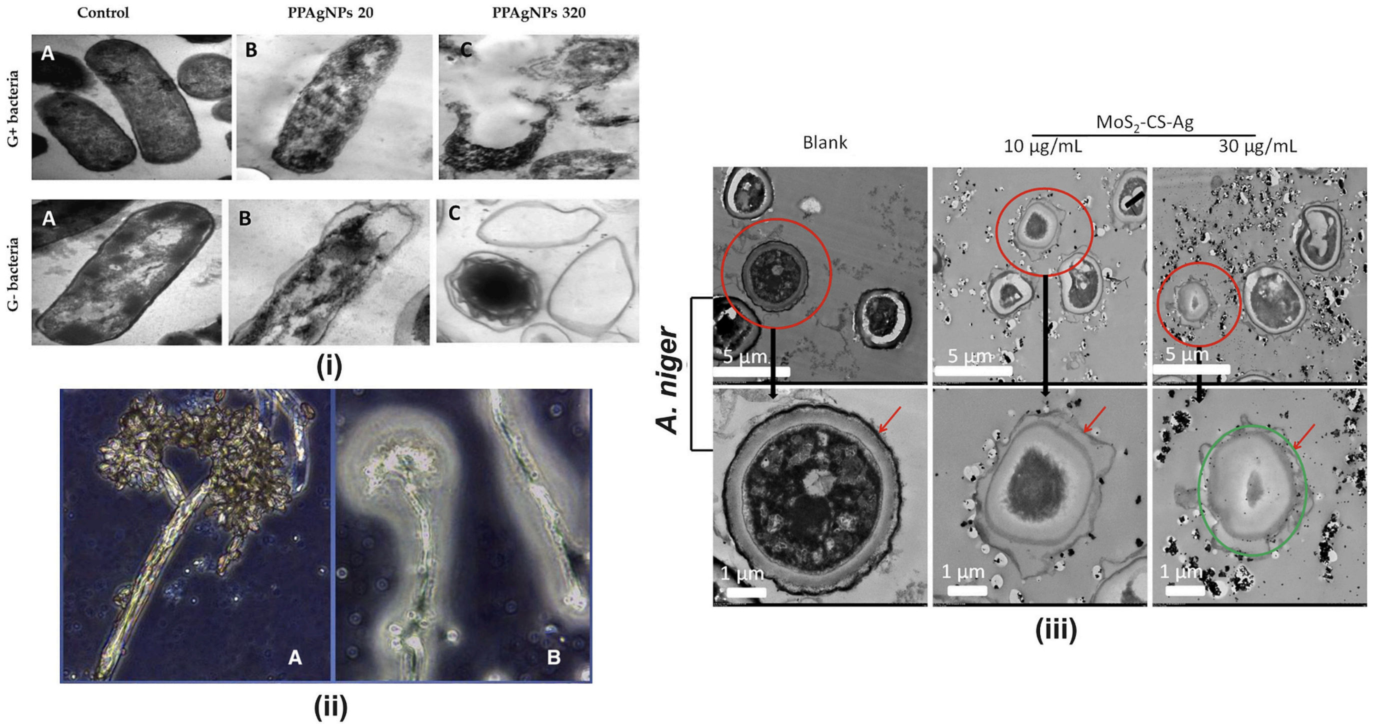

Fig. 4. TEM image about the anti-microorganism mechanism of AgNPs. Fig. 4i: AgNPs against pathogenic bacteria (A) control, (B) AgNPs interact with the membrane of bacteria, (C) AgNPs enter the inside cell and react with cell components (Alharbi et al., 2024). Fig. 4ii: AgNPs against *Botrytis cinerea* after different incubation periods at minimum inhibitory concentrations: (A) zero time, (B) after 24 h (Moussa et al., 2013). Fig. 4iii: Red arrows indicate the cell wall, and the red circle indicates the zoomed-in region. The green circles indicate Ag NPs around the cell wall (Zhang et al., 2019). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

anti-microorganism activity studies. With anti-microorganisms, AgNPs have become a potential approach for preserving agricultural products, particularly fruits and vegetables.

3.3. *Effect on film's structure*

In general, supplementing AgNPs to the film applied in food technology aims to enhance anti-microorganism ability. However, previous studies also demonstrated that adding synthesized AgNPs by different reducing agents would change the film properties (Fig. 5). In general, adding AgNPs into the film resulted in the film's surface being rough and unsmooth (Figs. 5i, 5ii, and 5iii). Therefore, the choice of coating components impacts the antimicrobial ability, influenced by factors such as coating type (film or edible) and the coating's adherence to the fruit or vegetable surface. Fruit and vegetable preservation applications consider film properties such as water vapor permeability, solubility, moisture content, thickness, tensile strength, surface color, and optical properties. These properties play a vital role in fruit and vegetable preservation, which enhances quality and shelf life by UV-blocking capacity, avoiding moisture migration from food to the environment, etc.

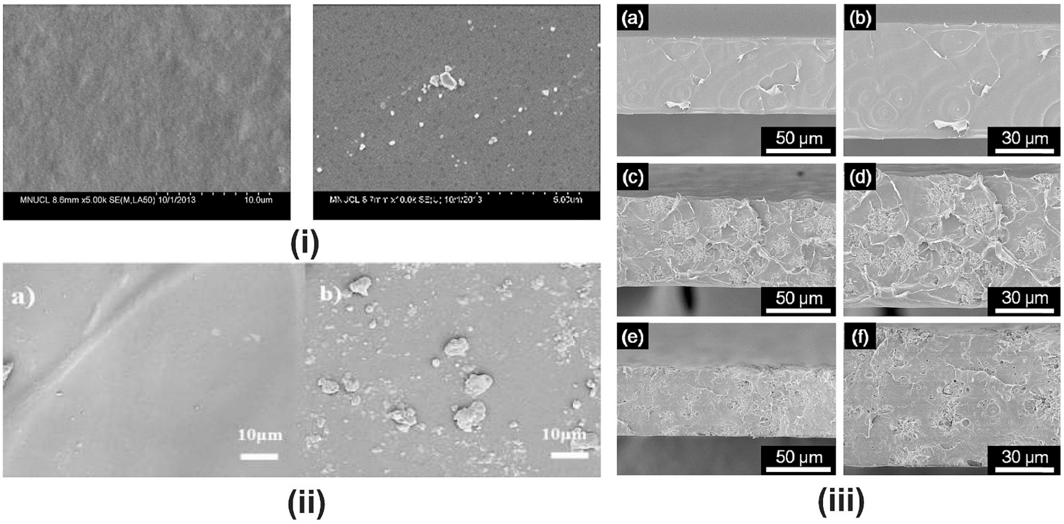

Fig. 5. SEM image of the film. Fig. 5i: agar/alginate/collagen ternary blend film with (right) and without AgNPs (left) (Wang et al., 2015). Figure 5ii: Carboxymethyl cellulose-guar gum film with (right) and without AgNPs (left) (Kanikireddy et al., 2020). Fig. 5iii: (a, b) Polylactic acid film, (c, d) Polylactic acid/ mango peel extract film, and (e, f) Polylactic acid/ mango peel extract/AgNPs film (Cheng et al., 2021).

Previous studies indicated that the addition of AgNPs to film reduces water vapor permeability, water solubility, and moisture content (Wang & Rhim, 2015; Kumar et al., 2020; Mahuwala et al., 2020; Chen et al., 2021). The film based on agar/alginate/collagen incorporated with AgNPs reduced the water vapor permeability and water solubility (Wang & Rhim, 2015). Incorporating AgNPs in the film-based cassava starch/agar or corn starch was found to reduce the moisture content, water solubility, and water vapor permeability with an increase in the concentration of AgNPs (Kumar et al., 2020; Mahuwala et al., 2020). However, Orsuwan et al. (2016) reported that agar/banana powder blend films with AgNPs reduced moisture content, but water solubility and water vapor permeability remained unchanged compared to those without AgNPs. In the case of hydroxypropyl methylcellulose containing 0.5% AgNPs, however, the moisture content increased by approximately 14% compared to control films (Vieira et al., 2020). These indicated that the film's water vapor permeability, water solubility, and moisture content values varied depending on its components and AgNP concentration.

Besides, incorporating AgNPs also affects the thickness of the film. Kumar et al. (2020) reported that cornstarch-based nanocomposite film thickness increased significantly upon adding AgNPs. Similarly, Orsuwan et al. (2016) found that adding AgNPs to agar/banana films increased the thickness by approximately 13% compared to films without AgNPs. In another study, Vieira et al. (2020) observed that an increase in the ratio of AgNPs (0.5% *w*/w) significantly increased the average thickness of hydroxypropyl methylcellulose-based films by 31.6%. Wang and Rhim (2015) suggested that the film thickness is related to the increased solid content of AgNPs. The presence of AgNPs impacted various properties of hydroxypropyl methylcellulose-based films, including thickness, morphology, moisture content, chemical bonds, crystalline structure, and thermal properties (Vieira et al., 2020). Besides, the study by Orsuwan et al. (2016) showed that the agar/banana powder ratio also significantly affected the thickness of films containing AgNPs. These suggested that AgNPs significantly impact the film thickness; additionally, the type of film material and the ratio of film-forming components also affect the film's thickness.

Previous studies also evaluated the impact of AgNPs on film's tensile strength. Kanikireddy et al. (2020) indicated that the inclusion of AgNPs in the carboxymethyl cellulose-Guar gum film results in enhanced mechanical properties in which the tensile strength (8.14 MPa) and modulus (21.41 MPa) of the composite film surpass those without AgNPs (5.29 MPa for tensile strength and 10.53 MPa for modulus). The tensile strength of agar/alginate/collagen film incorporated AgNPs was increased significantly compared with the control (Wang & Rhim, 2015). Similarly, the tensile strength of chitosan film increased after blending AgNPs into the film (Shankar et al., 2021). However, Orsuwan et al. (2016) indicated that adding AgNPs decreased the tensile strength of agar/banana powder blend films. These suggested that the tensile strength also depends on film components. Moreover, UV light-induced free radicals in food materials lead to color degradation, nutrient loss, and lipid damage, making UV protection a critical research focus for preserving fresh fruits, vegetables, and other food items. A study by Kumar et al. (2020) indicated that AgNPs incorporated into corn starch-based nanocomposite film created a UV-blocking capacity. Similarly, cellulose acetate/triethyl citrate film containing AgNPs (biosynthesized in situ the clay using *Curcuma longa* tuber extract) significantly improved the tensile properties, UV, and oxygen barrier ability (Dairi et al., 2019).

In fruit and vegetable preservation, the color and transparency of film or edible coating could affect the sensory property, especially in ready-to-eat products. The yellow color of AgNPs characteristic could change the film color and transparency. A study by Wang and Rhim (2015) incorporating AgNPs into agar/alginate/collagen (ratio of 1:1:1) film for tomato preservation showed that AgNPs affected the apparent color and optical properties of film with brown and translucent properties. Similarly, AgNPs significantly increased the yellow value of agar/banana powder blend films (Orsuwan et al., 2016). Kumar et al. (2020) indicated that AgNPs give corn starch-based nanocomposite film varied from colorless to yellowness due to pigment in the AgNPs and guava leaves extract solution. Besides, Orsuwan et al. (2016) suggested that the ratio of film components (agar/banana powder) also significantly affects films' surface color and optical properties. According to studies, adding AgNPs could alter the film properties of fruits and vegetables. Therefore, depending on the preservation aim, one should select the appropriate coating type (film or edible) and AgNPs concentration to achieve the desired anti-microorganism effect while maintaining the product's quality and sensory attributes.

3.4. *Safety properties of AgNPs*

Besides the practical anti-microorganism ability, the safety of AgNPs is always a concern when applied in fruit and vegetable preservation. The toxicity of AgNPs is an issue that is considered in food technology. In addition, finding safe, non-toxic approaches to green synthesizing AgNPs is regarded as a sustainable strategy for application in fruit and vegetable preservation.

Previous studies have shown that the toxicity of AgNPs is related to shape, size, and surface modification. A study conducted by Ali et al. (2020) found that when mice weighing between 20 and 25 g were exposed to powder form AgNPs obtained from Sigma-Aldrich CO. (at doses of 2.5 mg/mice) of different particle sizes (20 nm and 100 nm), they exhibited toxic effects. This was observed through changes in specific cellular biochemical parameters, genotoxicity, mutagenicity, and histopathological indices (Ali et al., 2020). Therefore, it is necessary to focus on reducing the toxicity of AgNPs to ensure consumer safety, while still benefiting from their anti-microbial properties.

Among the reducing agents used to make AgNPs, biological reducing agents from plant extracts, bacteria, and algae have emerged as a potential approach to making safe AgNPs. According to Alharbi et al. (2024), using biological reducing agents from plant extracts to synthesize AgNPs has advantages due to bioactive compounds, such as flavonoids and other polyphenolic compounds, which have no toxicity on liver and kidney tissues, making them a safe option for creating AgNPs (Fig. 6i). Plant leaf extracts (*Casimiroa edulis* and *Glycosmis pentaphylla*) were proven to ameliorate the toxicity induced by AgNPs in mice with doses of 2.5 mg/mice (20–25 g of weighing) (Ali et al., 2020). Vijayakumar et al. (2023) indicated that green synthesis of AgNPs using probiotic bacteria at various doses (20, 40, 60, 80, and 100 μL/mL) had moderate to low cytotoxicity to fibroblast cells. Similarly, AgNPs were prepared by using mango peel extract as a reducing agent at a concentration of 1 wt% based on the polylactic acid film, which exhibited over 80% viability in the L02 cell line, making them a non-cytotoxic biological material (Fig. 6ii) (Cheng et al., 2021).

Besides, synthesized AgNPs by biological reducing agents have also been shown to have positive effects. AgNPs synthesized from *Ananas comosus* fruit peel extract demonstrated potential antidiabetic effects, increased cytotoxicity against $HepG_2$ cancer cells in a dose-dependent manner, and exhibited moderate antioxidant and antibacterial activity (Das et al., 2019). Mansour et al. (2023) demonstrated that AgNPs synthesized using olive leaf extract were non-toxic to normal cells while exhibiting significant anticancer effects on HCT-116 cells, modulating the expression of TNF-α and Cox. A study by Alharbi et al. (2024) showed that administering pomegranate waste-mediated AgNPs (particles ranging from 15 to 55 nm) to rats at 160 μg/kg in their diet had several positive effects, including improved growth performance, normal liver and kidney parameters (with *p*-values ranging from 0.029 to 0.038), reduced lipid profile, malondialdehyde, and increased glutathione reduced, and total protein. Additionally, the authors observed a decrease in gene expression of Interleukin 6 (IL-6) and Tumor necrosis factor alpha (TNFα) in the serum of albino rats, suggesting an anti-inflammatory effect of AgNPs (Alharbi et al., 2024). Salih et al. (2023) indicated that the breast cancer xenograft model significantly

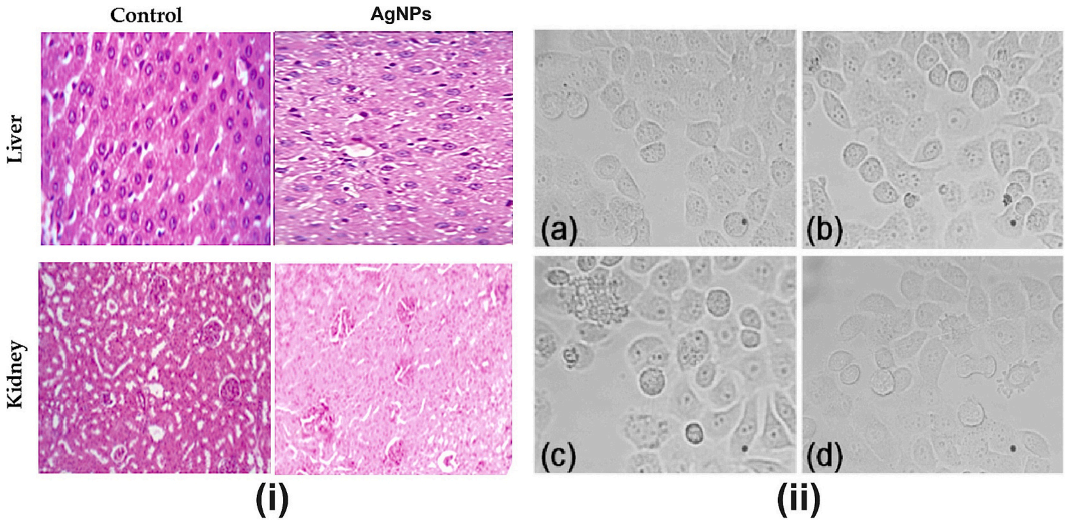

Fig. 6. Effect of AgNPs on liver, kidney, and L02 cell. Fig. 6i: Histology of liver and kidney tissue of albino rats fed dietary pomegranate waste-mediated AgNPs as a medicine for stress in 30 days. All images showed normal liver and kidney tissues under the tested AgNPs (320 μg/kg) with no differences in control (Alharbi et al., 2024). Fig. 6ii: Cell toxicity of the thin films, (a) Blank group, (b) polylactic acid film, (c) polylactic acid/mango peel extract film, and (d) polylactic acid/mango peel extract-mediated AgNPs film. The dashed line marks 80% of L02 cell viability (Cheng et al., 2021).

reduced tumor growth in mice treated with the green synthesized AgNPs (400 μg/mL, particle sizes ranging from 4.0 nm to 140 nm) capped with *Noctiluca scintillans* algae extract. Alharbi et al. (2024) also showed that AgNPs (320 μg/mL) impeded the development of breast and colon cancer cell lines by 80% and 78%, increased the activity of apoptosis marker caspase 3, and inhibited 82% of COVID-19. The synthesized AgNPs reduced by persimmon pedicel extracts in polyvinylpyrrolidone coating did not cause any roundworm toxicity, while the uncoated fresh-cut bell pepper juice induced cellular damage and death (Saravanakumar et al., 2020).

In fruit and vegetable preservation, AgNPs are often incorporated into a wrapper film or edible coating to create a cover layer on the product. With these approaches, the AgNPs content on the fruit and vegetable surface would be low. Jayaprakash et al. (2017) indicated that the advantage of this green synthesis method is that the AgNPs formed are stable without any oxide formation for more than six months. Besides, Wu et al. (2018) showed that only 5.6% of AgNPs were released from films based on Chitosan/Laponite/AgNPs, which hardly showed cell toxicity but exhibited promising antimicrobial activity. Green synthesized AgNPs by *Noctiluca scintillans* algae have been proven to selectively trigger apoptosis in cancer cells without affecting normal cells, as reported by Salih et al. (2023). Another study by Chen et al. (2021) indicated that the amount of Ag+ released from the polyvinyl alcohol/soluble starch film was 20.82 mg/g after soaking in water for five days, which had low toxicity when packing fruits and vegetables. Similarly, the values of silver ion release from polyvinyl alcohol/ cassava starch film were 7.48 to 24.51%, which were lower than the OML reported by European Standard EN 1186–1:2002 (Srikhao et al., 2021). AgNPs incorporated in sodium alginate films reduce the toxicity of AgNPs to mouse fibroblast cell lines, with no toxicity observed at concentrations ranging from 1.9 μg/mL to 62.5 μg/mL, where cell viability was maintained above 90% (Zhang et al., 2024). Studies on AgNPs application in fruit preservation were not only on fruit peels but also coating directly on ready-to-eat fruit such as fresh blueberries, fresh-cut melons, banana blocks, etc. (Goh et al., 2023; Jia et al., 2015; Ortiz-Duarte et al., 2019). These showed that AgNPs safety was increasingly recognized and showed the potential for application in fruit and vegetable preservation.

4. Green synthesized AgNPs application for fruit and vegetable preservation

Due to their broad-spectrum antimicrobial activity, AgNPs are interested in many applied studies preserving fruits and vegetables (Orsuwan et al., 2016; Wu et al., 2018; Kanikireddy et al., 2020; Bizymis et al., 2023; Gowda & Sriram, 2023; Alharbi et al., 2024). AgNPs can be applied for fruit and vegetable preservation by immersing or incorporating AgNPs into wrapper film or edible coating (Figs. 7 and Table 1). The key concerns in applying AgNPs to preserve fruits and vegetables include enhancing antimicrobial properties and maintaining overall quality during storage.

In immersing treatment (Fig. 7i), synthesized AgNPs by tea leaf extracts reduced the weight loss of the tomatoes, as well as changes in their total soluble solids, vitamin C, and titratable acid contents (Gao et al., 2017). Additionally, the rotten rate of citrus fruits decreased by about 50% in the treatment with AgNPs synthesized by *Fatsia japonica* leaf extracts at a concentration of 100 μg/mL (Zhang et al., 2017). Gao et al. (2017) indicated that tomatoes treated with synthesized AgNPs by Oolong tea had a healthy fruit rate that was 2.4 times higher than untreated tomatoes after 15 days. Moreover, bananas treated with 0.01% AgNPs by dipping process effectively controlled ripeness, curbing morphological changes and ethylene production, as Nayab and Akhtar (2023) reported. However, to enhance the anti-microorganism activity and improve the fruit and vegetable quality during storage, AgNPs have been incorporated into other materials to extend the product's shelf life.

AgNPs were incorporated into film material used in fruit and vegetable preservation in two main approaches (Fig. 7ii): 1. Incorporated into film used to wrap products. With this approach, the film could not entirely cover fruits and vegetables. When the wrapped fruits or vegetables are used, the AgNP-containing film layer is removed; 2. AgNPs were incorporated into edible coating to coat fruits and vegetables directly. This approach exposes the entire fruit surface to the edible coating, which could be consumed directly in ready-to-eat products. Regarding preservation effectiveness, incorporating AgNPs into wrapped films (or edible coating) has two things that are often of concern: firstly, the anti-microorganism activity during storage; secondly, the impact of AgNPs on fruit and vegetable quality (such as slowing down the ripening, reducing the weight loss, etc.,).

The advantage of incorporating AgNPs into the film layer minimized the possibility of AgNPs entering the fruit peels compared to edible

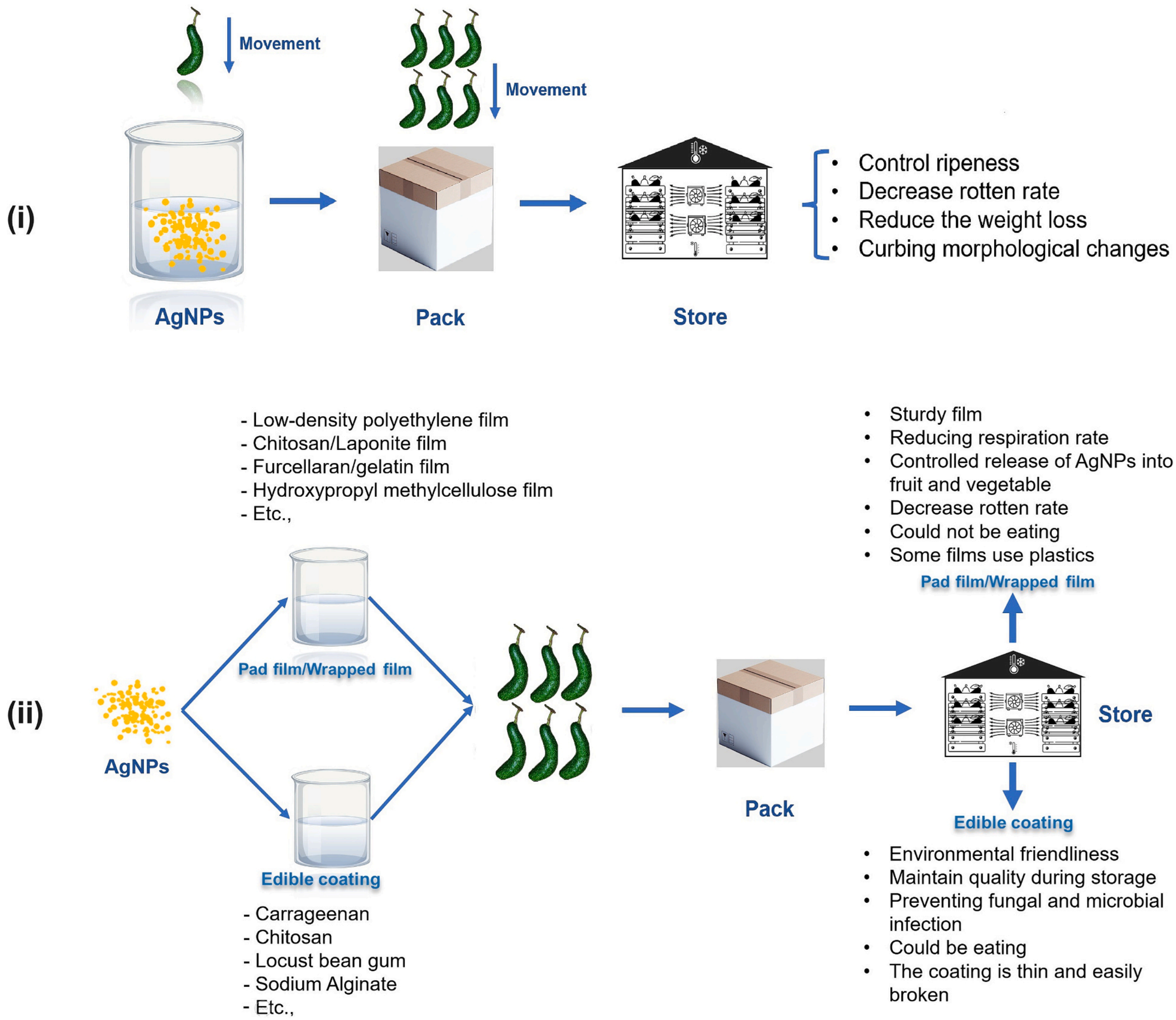

Fig. 7. The fruit and vegetable preservation application is achieved by immersing in AgNP solution (i) and incorporating AgNPs into film or edible coating (ii).

coatings. A study by Becaro et al. (2016) indicated that incorporating AgNPs into low-density polyethylene film for packaging fresh-cut carrots showed no silver traces (below ten ppb). The gradual release of AgNPs would maintain anti-microorganism effectiveness during storage with safety. A study by Wu et al. (2018) showed that the release level of AgNPs from films impacted antimicrobial activity efficiency against *S. aureus*, *E. coli*, *A. niger*, and *P. citrinum*, in which the high release have high antimicrobial activity. Similarly, films containing AgNPs were efficient as active packaging for sliced carrots, especially when AgNP was employed at low concentrations, showing higher antimicrobial activity probably due to the optimized contact area between the AgNP and the microorganism (Becaro et al., 2016). Fernández et al. (2010) indicated that AgNPs also increased the lag phases of the microbial growth curves (total mesophilic aerobic counts, psychrotrophic microorganisms, total yeast counts) in fresh-cut melon pieces during ten days, indicating delayed spoilage. Hydroxypropyl methylcellulose containing 0.25% of AgNPs effectively inhibited and prevented *C. gloeosporioides* growth, extending the shelf life of papaya with no presence of *C. gloeosporioides* was detected after 14 days of storage at 20 °C (Vieira et al., 2020). The AgNPs incorporated into cellulose pads could improve the quality and shelf-life of fresh-cut melon pieces, which suppressed and slowed the growth of spoilage microorganisms, especially yeasts (Fernández et al., 2010).

Besides the incorporated AgNPs wrapped film layer, AgNPs incorporated into edible coating are also receiving much attention. The edible coating has many advantages, such as biodegradation, safety, environmental friendliness, etc. Therefore, the incorporation of AgNPs into edible coatings in the preservation of fruits and vegetables is considered a green approach that enhances the effectiveness of anti-microorganism activity and extends the shelf life (Ortiz-Duarte et al., 2019; Goh et al., 2022; Akyüz et al., 2023; Bizymis et al., 2023; Zhang et al., 2024). Edible coating materials include alginate, agar, carrageenan, chitosan, locust bean gum, etc. The preservation effectiveness of edible coating would depend on the coating layer's properties, ability to combine and disperse AgNPs, adhesive ability with peel and mesocarp of fruit and vegetable, etc. Among edible coating materials, chitosan has emerged as a coating material with preservation effects simple process. Gowda and Sriram (2023) showed that the AgNPs incorporated into chitosan suppress *Colletotrichum truncatum* conidial germination, resulting in 100% inhibition of spore germination and enhancing the germination and growth of chilli seeds. The *Botrytis cinerea* spreading lesions on blueberries were significantly reduced by AgNPs incorporated into chitosan Janus nanoparticles coating compared to the control samples (Jia et al., 2015). Similarly, AgNPs incorporated into the chitosan coating completely inhibited the growth of *B. cinerea* infecting strawberries (10^4 spore/mL) compared to the damage rate of the control samples was 30% after four days of storage (Moussa et al., 2013). Strawberries coated by AgNPs incorporated irradiated chitosan also showed that fungal decay appeared at 10% compared to 90% in control samples by the end of the storage period of 7 days (Moussa et al., 2013). Gowda and Sriram (2023) indicated that coating chill fruits with chitosan-AgNPs notably reduced the pathogenicity of the *Colletotrichum truncatum* conidia and increased chill fruit shelf-life. The edible coating based on red claw crayfish extracted Ag-chitosan nanocomposites induced a microbicidal reduction (0.6 log units) from days 10 to 13 during fresh-cut melon preservation (Ortiz-Duarte et al., 2019). The cherry properties, such as hardness retention, weight loss reduction, and total microbial load reduction, have been reached by chitosan-cellulose nanocrystals-beta cyclodextrin-AgNPs edible coating (Bizymis et al., 2023). Another material coating made by sodium carboxymethyl cellulose combined with AgNPs exhibited superior preservation of Banana blocks as no mold growth was detected during the five-day storage period, whereas banana blocks coated with only Na-CMC showed mold growth starting on the third day (Goh et al., 2023). Also, in treating bananas with AgNPs incorporated in sodium alginate coating, total bacterial colonies in the banana peel and pulp were as low as 1.13×10^3 and 51 CFU/g on the ninth day of storage compared to uncoated samples with 8.96×10^5 and 3×10^3 CFU/g respectively (Zhang et al., 2024). Besides, synthesized AgNPs using plant extracts as a reducing agent exhibited more effective preservation than those synthesized using chemical reducing agents. According to Saravanakumar et al. (2020), fresh-cut yellow and red bell peppers, when coated with silver nanoparticles (AgNPs) synthesized using persimmon pedicel extracts in polyvinylpyrrolidone, exhibited better texture compared to those coated with AgNPs synthesized by $NaBH_4$ in polyvinylpyrrolidone and control samples. Additionally, the authors observed that the AgNPs synthesized by persimmon pedicel extracts effectively prevented colonization by grey mold, whereas the AgNPs synthesized by $NaBH_4$ and the uncoated control showed grey mold colonization after 15 days of storage at 15 °C (Saravanakumar et al., 2020). These could be due to the plant extract with bioactive compounds, which positively impact and enhance antimicrobial during storage.

The quality of fruits and vegetables is essential when considering consumer purchasing decisions. Quality parameters such as weight loss, anthocyanin content, total soluble solids, firmness, color, etc. are often considered. During storage, internal metabolic processes (metabolism, respiration, etc.) and the impact of external factors (storage conditions, microorganism pathogens attack, etc.) significantly affect fruit and vegetable quality. Using AgNPs in combination with film (or edible coating) has many advantages in which AgNPs limit the attack of microorganism pathogens, while the film layer (or edible coating) would be a barrier that limits the metabolism of fruit and vegetables with the environment, thereby maintaining the quality during storage.

AgNPs incorporated into chitosan film combined with γ-irradiation permitted the retain more phenolic compounds and did not influence the weight loss, anthocyanin content, total soluble solids, firmness, and color parameters of strawberries during storage (Shankar et al., 2021). Cheng et al. (2021) indicated that strawberries wrapped in polylactic acid film containing AgNPs prepared by mango peel extract have a low oxygen transmission rate, high mechanical strength, and potent antibacterial activity, which extended shelf life without browning or mildew (Fig. 8i). Similarly, strawberries packed in a film containing carboxymethyl cellulose, guar gum, and synthesized AgNPs by Mentha leaves exhibit reduced weight loss due to the antioxidant properties of Mentha leaf extract and the antimicrobial properties of AgNPs, which slow the aging process and inhibit decay development (Kanikireddy et al., 2020). Besides, the presence of AgNPs has not significantly influenced the pH and firmness values of fresh-cut carrots packaged in plastic films containing AgNPs (Becaro et al., 2016). According to Jamróz et al. (2019), nanocomposite films made of furcellaran, gelatin, and nanoselenium-AgNPs can extend the shelf life of kiwis by preventing fungal infection and weight loss. Wu et al. (2018) indicated that chitosan/Laponite/AgNPs nano-films exhibited low cell toxicity, good antimicrobial activity, and effectively extended the shelf life of litchis.

Similar to the wrapped film layer, the edible coating has been proven to improve the fruits and vegetables during storage. Research on mushroom preservation demonstrated that applying an AgNPs-Alginate coating positively affected the physico-chemical and physiological quality, reduced microbial counts, and enhanced preservation qualities for shiitake mushrooms during extended storage (Jiang et al., 2013). Besides, the treatment of bananas with AgNPs incorporated in sodium alginate coating maintained the banana's appearance compared to uncoated samples with more black senescent spots after nine days of storage at 25 °C (Zhang et al., 2024) (Fig. 8ii). Jiang et al. (2013) also indicated that an alginate coating treatment inhibited the respiration rate of shiitake mushrooms, and the inspiration rate decreased with the addition of AgNPs during four days of storage at 4 °C. In contrast to whole fresh fruits, ready-to-eat fruits containing pulp cells are particularly vulnerable to spoilage caused by microorganisms and environmental factors. These adverse effects can detrimentally affect their quality during storage. Previous research has indicated that the use of edible coatings can have a positive impact on the preservation of both fruits and vegetables. Ortiz-Duarte et al. (2019) showed that the edible coating based on red claw crayfish-extracted chitosan incorporated AgNPs showed the highest total vitamin C content after 13 days at 5 °C compared to control samples during fresh-cut melon preservation. The authors also indicated that fresh-cut melon's respiration rate and ethylene production were reduced after coating treatments with

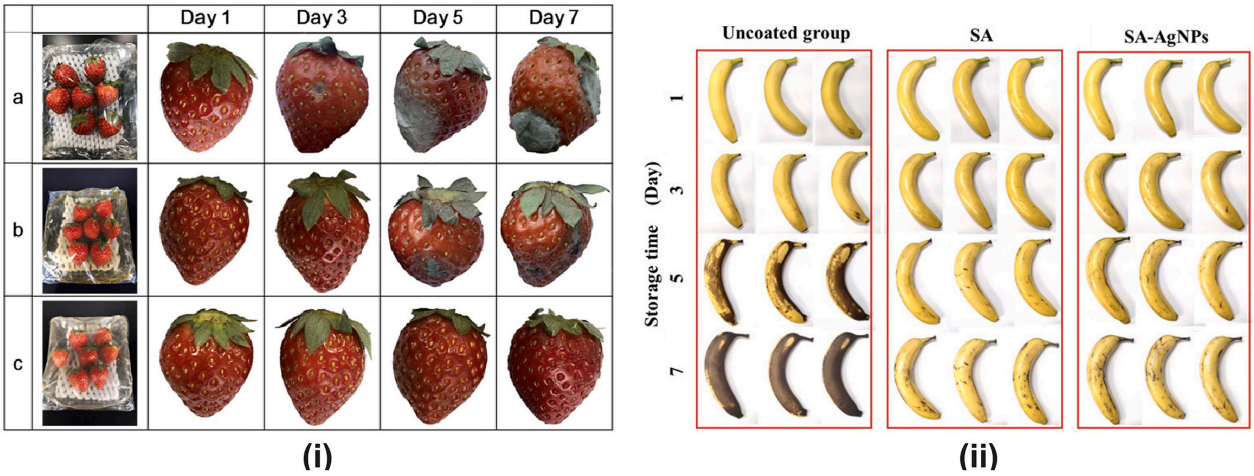

Fig. 8. The effect of the wrapped film and edible coating on strawberries and banana. Fig. 8i: (a) Polylactic acid film, (b) Polylactic acid/ mango peel extract film, and (c) Polylactic acid/mango peel extract-mediated AgNPs film (Cheng et al., 2021). Fig. 8ii: SA: sodium alginate coating (Zhang et al., 2024).

chitosan (Ortiz-Duarte et al., 2019). Calcium alginate coating containing AgNPs significantly improved the shelf life of strawberries and loquats by reducing weight loss, acidity loss, soluble solid content loss, microbial growth, and quality decay (Hanif et al., 2019). Also, the sensory qualities like taste, smell, and appearance in uncoated strawberry fruit decreased value from 5 to 1 after three days of storage compared to a value of 4 in the case of calcium alginate coating containing AgNP (Hanif et al., 2019). Alharbi et al. (2024) indicated that white kidney peptide-Arabic gum coating contained AgNPs (using pomegranate waste-mediated as a reducing agent) regulated the *Vermont mandarin* fruit's oxygen exposure, reducing H_2O_2 buildup and delaying the fruit's senescence. These results indicated that AgNPs can effectively preserve fruits and vegetables by immersing or incorporating them into edible coatings or wrapper films. Combining AgNPs and film is necessary to extend the shelf life of fruits and vegetables. Choose the appropriate preservation approaches depending on the type of film (wrapped film or edible coating) and type of fruit and vegetable.

5. Conclusion

AgNPs have garnered increased attention for fruit and vegetable preservation, primarily due to their anti-microorganism properties. Various approaches to synthesizing AgNPs include physical, chemical, and biological reduction. The synthesis of AgNPs through biological reduction, especially plant extraction, which contains numerous bioactive compounds, is considered non-toxic, eco-friendly, economically viable, and environmentally friendly. The size distribution of AgNPs was about 5–600 nm depending on the reducing agents, external aided conditions, reaction time, and composition of the combined film. AgNPs could combat pathogenic microorganisms through multiple pathways. Incorporated AgNPs into film properties such as water vapor permeability, solubility, moisture content, thickness, tensile strength, surface color, and optical properties are considered. AgNPs can be applied for fruit and vegetable preservation by immersing or incorporating AgNPs into the edible coating or wrapper film. Depending on the type of coating (wrapped film or edible coating) and the kind of fruit or vegetable (especially the adhering ability of the coating to the fruit or vegetable surface), choosing the coating components ensures the anti-microorganism ability and improves preservation efficiency. Integrating AgNPs synthesized by plant extracts or by probiotic bacterium into edible coatings would become a sustainable method for improving safety, being eatable, being environmentally friendly, preventing fungal and microbial infections, and preserving the quality of fruits and vegetables, especially ready-to-eat and fresh-cut fruit, during storage.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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