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Harnessing Plant Power: A Review of Green-Biosynthesized Silver Nanoparticles for Improving Orange Postharvest Quality and Green Mold Resistance

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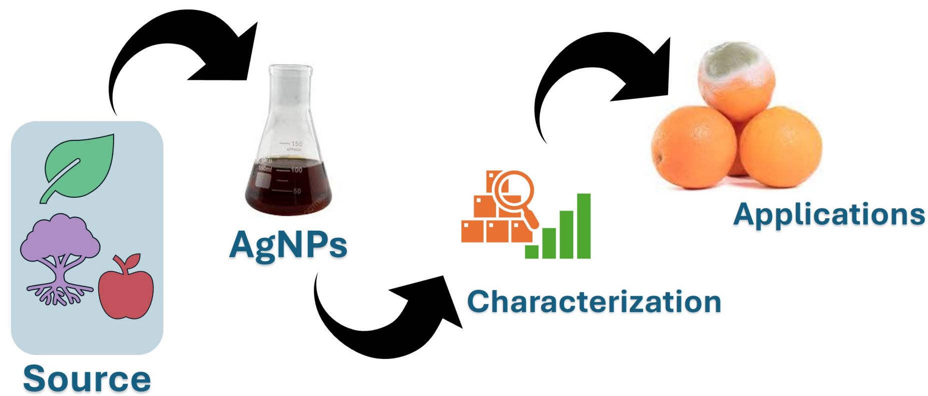
Abstract

The increasing demand for fresh, organic produce has prompted the exploration of innovative methods to enhance postharvest quality and combat diseases in fruits, particularly citrus. This review focuses on the green synthesis of silver nanoparticles (AgNPs) using plant extracts, which serve as both reducing and stabilizing agents, as a sustainable alternative to traditional chemical fungicides. The nanoparticles are characterized in terms of their size, morphology, and stability using techniques such as UV-Vis spectroscopy, X-ray diffraction (XRD), Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM). The green-synthesized AgNPs have considerable antifungal efficacy against the green mold pathogen *Penicillium digitatum*. It prolongs the shelf life of oranges without compromising their aesthetic and nutritional quality. These AgNPs exhibit long-term stability and efficacy, minimizing fruit weight loss and enhancing key quality metrics, including ascorbic acid concentration and titratable acidity. Despite thorough research, the mechanism of action of AgNPs and their molecular interactions with pathogens remains inadequately elucidated. This study emphasizes the necessity for additional research to unravel these mechanisms and assess the environmental safety of AgNPs. The prospective application of these AgNPs in various crops should also be investigated. Ultimately, this study aims to contribute to sustainable agricultural practices by integrating eco-friendly solutions into postharvest management strategies.

Keywords: Green synthesis, silver nanoparticles, citrus, post-harvest, green mold

Graphical Abstract:



1. Introduction

The demand for fresh and healthy food is increasing due to changes in lifestyle and eating habits. Organic agriculture is based on environmentally friendly, socially and economically sustainable methods or processes. Apart from being a source of biodiversity, organic foods have high antioxidants content and other essential nutrients in more significant quantities [1]. Because of sustainable processes like the use of organic waste and renewable feedstocks, organic chemistry reactions in the presence of a catalyst are increasingly preferred in organic synthesis [2]. In this biotechnological era of organic chemistry, silver or gold nanoparticles are prepared by plants, fungi, bacteria, and yeast using the secondary metabolites of these organisms [3]. The plants have alkaloids and flavonoids, which are green reducing agents that reduce metal ions. Then the metal ions are converted into nanoparticles or clusters (size less than 100 nm) by this green chemistry method [4]. Among the metallic nanoparticles, silver nanoparticles are used in foods to improve their shelf life[5].

Nanotechnology has the potential to revolutionize agriculture and food systems [6]. Organic farming is a system that avoids or excludes synthetic pesticides or fertilizers and emphasizes the use of living organisms in producing and handling food [7]. The increasing demand for organic fruits creates new markets for these agricultural products. On the other hand, the presence of fungi during the post-harvest stage often forces producers to submit fruit to antifungal treatment, which is not accepted by consumers [8]. To meet the consumer demand for organic fruits, the challenge for producers is not only to combat diseases after harvesting, prevent human illness and extend the shelf life of these products but also to be able to do this without synthetic additives [9, 10].

1.1. Background and Rationale

Consumption and production of orange fruits have been suffering from the green mold disease caused by *Penicillium digitatum* during the postharvest stage, which is commonly controlled by synthetic fungicides [11]. However, the potential risk posed by these fungicides, shown by the long-term safety for humans and the environment during continuous utilization, raised consumers' concerns and strictly limited the international movement of these fruits [12, 13]. Here we have reported a green method to fabricate silver nanoparticles with antimicrobial activities against *P. digitatum* by using lemongrass extract as reducing and stabilizing capping agents instead of synthetic ones [14]. The biosynthesized ice white color of silver nanoparticles was in a size range of 10.02–14.7 nm. It was stable in distilled water over a period of 30 days, whereas it exhibited stable antifungal activities over 10 days [15]. Furthermore, the silver nanoparticles were able to maintain the overall postharvest quality of orange fruits by decreasing the incidence of chilling injury, delaying fruit color, weight loss, and respiration rate, thereby increasing titratable acidity and ascorbic acid contents [16].

Orange is consistently one of the most popular fruits due to its abundant nutritional elements, including vitamin C, dietary fiber, carotenoids, etc [17]. However, postharvest losses due to *P. digitatum* result in the quality deterioration of this fruits during its worldwide handling and marketing [18]. Nowadays, the disease is generally controlled by using synthetic fungicides, which pose potential risks to human health and environmental safety [11]. To decrease these potential risks, more and safer naturally occurring compounds with fewer side effects are commonly used to replace synthetic fungicides [8]. Lemongrass-mediated silver nanoparticles were reported to exhibit an efficient lethal effect not only in vitro but also on diseased oranges by prolonging their shelf lives [19]. This method provides a simple and cost-effective biosynthesis approach without utilizing stabilizing or capping agents and has a higher yield using lemongrass, which presents a potential anti-*P. digitatum* management strategy, thus facilitating their safe postharvest treatments [19].

1.2. Importance of Post-Harvest Quality and Green Mold Disease Management

Fruit is a natural, readily available, and delicious source of essential vitamins, minerals, and dietary fiber, which play an important role in preventing chronic diseases, boosting energy, rejuvenating skin, and regulating body functions [20]. Citrus fruits are major contributors to both local and international fruit markets [21]. Oranges serve as an indicator of the citrus industry because of their abundant, perishable, and easily decayed characteristics [22]. Fungal pathogens such as green mold and blue mold of oranges cause severe economic losses by reducing the fruit's post-harvest quality and shelf life [11, 23]. Generally, several compounds are used in the post-harvest treatment of citrus fruits to control diseases, which have the potential to leave residues in the fruits [24]. In addition, with the increasing vegan and public awareness of the harm of chemical residues in fruits, clean, green, and low-toxicity substances that potentially degrade into non-toxic by-products are preferred to reduce or eliminate the use of synthetic chemical fungicides in fruits [23, 25].

Managing postharvest infections in fruits is crucial both before and after harvest [26]. Pre-harvest and postharvest diseases are closely related and affected by the selection of fungicides, postharvest treatments, and the rise of fungicide-resistant pathogen strains [26, 27]. The management of postharvest diseases varies from conventional fungicides and differs among various fruits [27, 28]. Injury, washing, and post-harvest storage conditions of fruit are factors that affect the post-harvest quality of fruit, especially the occurrence of water-soaked diseases in fruit [29, 30]. Green mold, caused by *Penicillium digitatum*, is the most important post-harvest disease in citrus fruits, especially in oranges [11, 31, 32]. Most strains of *P. digitatum* are tolerant to chemical fungicides, which results in fruit decay during storage and transportation [11]. The resistance of these strains to chemical fungicides has been ascribed to a combination of the frequent use of synthetic chemical fungicides and the genetic ability of citrus strain adaptation [33]. As a result, the selection of chemical fungicides diminishes post-harvest disease management [34, 35]. The control of green mold caused by *P. digitatum* is crucial in the commercial fruit industry [11, 36]. The reduction in the effect of chemical fungicides can be tackled by the application of alternative and eco-friendly methods [35].

2. Silver Nanoparticles (AgNPs): Synthesis and Properties

Silver nanoparticles have shown much promise for the food industry owing to their antimicrobial activity, largely due to localized surface plasmon resonance-induced heating [37, 38]. However, chemical synthesis methods have restricted the direct use of AgNPs in food production due to the toxicity they may cause [39, 40]. Both traditional methods and green synthesis have been suggested for large-scale AgNPs production [40]. However, the latter provides numerous advantages, including the use of safe materials, the feasibility of large-scale production, and the reduction of the cleaning process[37, 41]. Recently, significant experimental attention has been paid to the exploration of reduced toxicity and increased efficacy of green synthesized AgNPs[37].

The synthesis of silver nanoparticles applies green chemistry methods using plant extracts [42], fungi [43], and microorganisms, including bacteria, as reducing agents to produce extremely stable and mostly mono-dispersed AgNPs of various morphologies, including spherical, plate-like, and rod-like [44]. For the synthesis of plant extracts, plant-contributing secondary metabolites such as polyphenols, alkaloids, terpenoids, and flavonoids play a crucial role as natural stabilizing agents, capping agents, or reducing agents [45]. While synthesizing AgNPs via fungi, the high content of carbohydrates in the fungal cell wall is important to the phytochemical synopsis, reduces silver ions, and stabilizes AgNPs [43, 46]. During the callus as a reducing agent, the phenolic compounds or flavonoids released by the green cell asphyxiate silver ions, whereas part of the nontoxic element obtained in the reaction promotes the nanoparticles without breakage during plant cell destruction [46, 47]. The (bio)molecules, mostly polyols, released from the reduced process have dual roles, acting as both the reducing and capping agents [48]. These *in situ*-formed bio-reducing agents bind to reduced metal, acting as steric and electric stabilization [48].

2.1. Green Synthesis Methods

Over the years, considerable efforts have been made to develop eco-friendly techniques in the synthesis of silver nanoparticles due to the potential hazards associated with different synthetic procedures [49]. Among various synthetic methods, the usage of plant-derived materials and microorganisms has received a great deal of attention in producing metal nanoparticles [50]. Green-synthesized silver nanoparticle production involves the reduction of silver ions to silver nanoparticles using various plant biomasses like fruits, leaves, seeds, and other parts of the plants, as well as microorganisms like bacteria and fungi [51]. These green reducing agents contain bioactive compounds that are very useful in metal reduction [51, 52]. This method, aside from being time-saving and cost-effective, offers the advantages of efficiency, biomedical compatibility, and nontoxicity [53]. The utilization of environmentally diverse sources can enable us to generate nanomaterials of different sizes, shapes, and dimensions [54]. This ecologically simple approach leading to non-toxic silver nanoparticles has advantages in the eco-biological, biomedical, and clinical fields [53]. The fabrication of silver nanoparticles can be determined by detecting the color change exhibited by the reduction of silver salt; the yellowish-brown color exhibited indicates the formation of silver nanoparticles [49].

2.2. Characterization Techniques

Biochemically reduced nanoparticles in the presence of plant extracts and their metabolites resulted in spherical, polygonal, cubical, and irregular shapes, sometimes with facets in structure [46]. UV-visible spectroscopy is the most frequently used technique to monitor the formation and evolution of biogenerated silver nanoparticles [55]. The sizing of silver nanoparticles is performed by transmission electron microscopy, while XRD analyzes the crystalline nature and lattice spacing of nanoparticles [56]. The intensity of diffraction peaks around 2θ for the silver peak obtained in the XRD reflects the high crystallinity of the synthesized nanoparticles [57]. Biological polymers present in plant extracts, such as flavonoids, polyphenols, proteins, carbohydrates, polysaccharides, alkaloids, and terpenoids, could bind and reduce silver ion molecules into silver nanoparticles [58]. Bioactive molecules present in the plant extracts might have various binding sites [59]. These groups would act as capping agents, stabilizing the charge on silver nanoparticles and providing a driving force to prevent aggregation between nanoparticles [42].

The hydrodynamic size and zeta potential of silver nanoparticles are measured by dynamic light scattering (DLS). The DLS provides information on stabilizing efficiency as well as the zeta potential and indicates the stability of nanoparticles [60]. The propagation of electromagnetic radiation and the interaction of light with the nanoparticles as a function of size were identified by NIR spectroscopy [61]. The morphology and confirmation of nanoparticles having functional groups were determined by scanning electron microscopy with energy-dispersive X-ray spectroscopy and Fourier Transform Infrared Spectroscopy [60]. The spectroscopic techniques have been used to evaluate functional groups present in the metabolites [62]. The chemical composition of synthesized silver nanoparticles is characterized by X-ray photoelectron spectroscopy [61].

3. Post-Harvest Quality of Orange Fruits

The post-harvest quality of orange fruits is critical for maintaining their market value and consumer appeal [63]. Various physiological and chemical properties, including total soluble solids (TSS), titratable acidity (TA), and ascorbic acid levels, are essential indicators of fruit quality. These parameters can be significantly affected by post-harvest handling practices [64]. Applying appropriate coatings and treatments can enhance the retention of TSS and ascorbic acid while minimizing weight loss during storage [65]. Research has shown that silver nanoparticles synthesized from different plant extracts can effectively reduce weight loss and preserve the nutritional quality of oranges by maintaining higher levels of ascorbic acid compared to untreated fruits [66, 67]. Furthermore, the integration of these nanoparticles not only improves the fruit's resistance to pathogens, such as *Penicillium digitatum*, which causes green mold disease, and enhances overall post-harvest longevity[16]. This dual benefit underscores the importance of innovative approaches in post-harvest technology to ensure that oranges retain their desirable qualities throughout their shelf life. In addition to chemical properties, diseases like green mold pose significant challenges to the post-harvest quality of oranges [11]. The rising prevalence of these diseases necessitates effective management strategies to mitigate their impact on fruit quality. The use of bio-silver nanoparticles has emerged as a promising alternative to traditional fungicides, demonstrating superior efficacy in controlling green mold while being less harmful to consumers and the environment [68]. Studies indicate that these nanoparticles not only outperform conventional treatments like imazalil fungicide but also contribute to lower decay rates and improved sensory attributes in oranges [69]. The application of silver nanoparticles can thus play a pivotal role in enhancing post-harvest quality by reducing spoilage and extending shelf life, ultimately leading to better marketability and consumer satisfaction [53].

3.1. Factors Affecting Post-Harvest Quality

Orange is one of the fruit crops that have been widely grown and eaten across the world [70]. The post-harvest period dramatically influences the freshness, quality, market value, and shelf life of this economically important fruit [71]. Excessive water loss, juice content, ascorbic acid content, total soluble solids content, flavor, aroma, and weight loss are vital factors that affect the post-harvest quality and overall sensory quality of orange fruits; therefore, protecting oranges from spoilage and managing green mold disease during post-harvest storage is urgent in the industry [72]. Although damage is unavoidable, in some cases, UV or UV plus heat treatment has been determined to be useful in supplying resistance to green mold decay and weight loss in orange fruits during long-term post-harvest storage [34]. Nevertheless, these treatments have been seen to reduce the juice content and flavor quality of the fruits [73]. Besides, other chemical compounds have also been used to manage the post-harvest decay of orange fruits [71]. Furthermore, nanotechnology has been proposed to play an important role in extending the life of agricultural products[74]. Nanoparticle synthesis by green methods using plant extracts has increasingly provided additional interest in the field of nanotechnology because of their unique properties, cost-effectiveness, and non-toxic nature [60].

3.2. Current Challenges and Strategies

In global agriculture of fruit crops, the situation is starting to represent a challenge [75]. This transformation is due to a rising perception of changing weather patterns, together with an increase in the incidence of imbalances that negatively impact fruit crops, including the fruit industry [76]. This economic relation is meaningful in countries with tropical or temperate climates. Hence, new contributions are required to maintain markets, avoid food waste, moderate fruit storage, and decrease deterioration [77]. Total world household and similar expenditures on total fruits in the whole supply networks are forecasted to grow significantly, of which a substantial amount is for fresh grapes, fresh citrus, and fresh apples [78].

The fruit industry has established innovative pre- and post-harvest methods to improve quality, nutritional values, shelf life, utilization of waste material, lower costs, and reduce chemical pesticides [79]. Due to the natural characteristics of fruit and its natural antimicrobial compounds, the fruit market has favorable commercial conditions for responding to recurrent risks and uncertainty [80]. However, when considering a point source for citrus stored at an unsuitable temperature, human activities still have an important role in facilitating the growth of pathogens [81]. Scientists now suggest beneficial materials that are environmentally friendly, edible, and safe to use for controlling citrus decay as beneficial agents with the least harmful side effects [82]. For global citrus commerce, the introduction of these alternatives will provide significant added commercial value [83]. Products that are more biodegradable, such as chitosan and grapefruit seed extracts, have been studied with favorable results [83, 84]. The same results with great potential are proving to be beneficial for essential oils, nanomaterials, and bioproducts [37, 68, 85]. In summary, incorporating alternative integrated pre-harvest/post-harvest strategies can reduce current environmental limitations and deliver improvements in response to potential crises.

4. Green Mold Disease in Orange Fruits

Citrus is a major economic crop, and its production is affected by different pathogens, pests, as well as abiotic stresses, causing fruit rot, loss of color, off-flavor production, and internal breakdown [86]. Green mold is a severe post-harvest disease of citrus fruits that has been recognized as a major constraint for long-term storage, commercialization, and expansion of domestic and export markets [34]. The green mold pathogen known as Penicillium digitatum is the primary natural source of green mold in citrus fruits [87]. A spore represents its free-living form and is regarded as the primary vector for the dissemination of green mold disease, as it initiates infection on physically damaged fruit wounds [88]. Green mold disease symptoms are usually seen as an infection on the fruit surface characterized by water-soaked tissues, a moldy layer covering the citrus fruit, and an unpleasant odor [86]. Infection is initially limited to the flavedo and albedo of the rind but may progress into the underlying juice sacs with a gradual increase in decay [89]. In addition to these symptoms, aerial mycelium and conidiophore structures are observed, which can better describe the symptoms of the green mold on the surface of the citrus fruit [90]. Currently, chemical agents are applied to control these post-harvest losses [91]. However, due to concerns about the safety of food consumers and the environment, the development of alternative post-harvest fungicides to respond to the commercial demand in the market is currently urgent [11]. The threat to human health and the environment posed by synthetic fungicides has prompted researchers to explore more natural, biological, and environmentally friendly substances for these uses [92].

4.1. Causal Agent and Symptoms

The causal agent of green mold is *Penicillium digitatum*, the most devastating postharvest pathogen in oranges worldwide [11]. This pathogen usually infects the orange rind through diverse types of wounds, such as those caused by other mold pathogens and abiotic injuries, with the primary infection beginning at the stem-calyx region [93]. Fruit treated with the pathogen usually shows white to gray circular lesions that grow in size and yield an intense green gelatinous mass due to the conidia release characteristic of this pathogen [87]. Attacked areas emit a distinctive strong, unpleasant musty smell and generate water condensation that spoils the fruit's storage properties [94]. The disease progression usually leads to the decay of the whole fruit [11]. A staining solution, one of the distinctive characteristics of this pathogen, labels fungal colonies greenish when observed under UV light, and it is used to visualize infected areas on oranges, increasing the experimental sensitivity to identify pathogenicity in naturally infected citrus fruit or fruit artificially inoculated with this pathogen [95]. This characteristic also controls the efficiency of our treatment to block infection by labeling the fungus in blue [95]. The conidia drag small drops of inoculum fluid over the orange surface, producing circular green-to-greenish conidial chains [86]. These characteristics distinguish this pathogen from other pathogens that severely affect citrus fruit.

4.2. Economic Impact and Management Practices

Several organic and synthetic compounds with fungicide effects have been standardized using different approaches [91]. They have been used in managing postharvest diseases of fruits and vegetables by curtailing sprays or incorporating them into packaging materials [84, 96]. Management practices for green mold rely on hygiene, temperature management, and sanitation processes, with some hydrothermal treatment conditions being recorded as the most efficient practices [79]. Indeed, temperature management below 10–15 °C is the best and easiest commercial management practice since it significantly delays the appearance of green mold[11]. This provides a useful way to extend the time of orange storage, with subsequent marketing and distribution proceeding more smoothly [11]. However, these extremes, either overly warm or overly cool temperature conditions, can inhibit the growth of *P. digitatum* and, therefore, reduce the internal disorders in the albedo tissue only, whereas the risk of the disease is not reduced [97].

Complementary to the management of green mold by thermal control and sanitary practices are the applications of fungicides and antimicrobial compounds with protective or curative actions [98]. These compounds are usually effective in intense management regimes of active ingredients to slow the incidence of the disease successfully [8]. Biological alternatives have been developed from research in searching for new options since there is increasing worldwide resistance to fungicides, and some fungicides have been paused concerning their legal use over the years [91]. In addition, consumer awareness of environmentally friendly food and fruits is growing, and consumer requirements are high concerning the absence of fungicide residues on fruits [99]. The development of alternative control strategies to manage the major postharvest pathogens, such as green mold, is considered a relevant issue in postharvest research in fruit [87]. All those mentioned earlier agronomical and commercial problems require valuable and effective solutions to enhance consumer confidence in treated fruits.

5. Role of Silver Nanoparticles in Disease Management

Silver nanoparticles have been well studied and have shown their potential not only in agriculture but also in health-related fields [100]. In agriculture, they have been widely used for disease management and show promise as an effective and eco-friendly alternative to synthetic fungicides for controlling post-harvest diseases in fruits [101]. Nanoparticles have strong antifungal characteristics that can significantly reduce fungal infections, which pose a considerable risk to the quality and shelf life of citrus fruits [19]. Recent studies indicate that AgNPs synthesized by green methods not only suppress fungal growth but also improve the quality indices of citrus fruits, including total soluble solids and ascorbic acid concentration [102]. When applied as a coating on orange peel, green-synthesized AgNPs have been shown to inhibit the growth of *Penicillium digitatum*, the fungus that causes green mold [103]. Due to their high surface area to volume ratio, AgNPs can come in close contact with fungal cells and release silver ions that disrupt the cell membrane and intracellular components, killing the fungus [104]. In contrast to chemical fungicides, AgNP treatments do not leave residues on treated fruit and decrease the possibility of acquiring fungal resistance [105]. AgNPs demonstrate more effectiveness than traditional fungicides such as Imazalil, resulting in reduced decay rates and enhanced fruit firmness during storage [101]. This is especially significant given the rising consumer desire for safer and more sustainable agriculture approaches. Furthermore, the application of AgNPs can activate the fruit's natural defense mechanisms, increasing disease resistance [106]. Integrating green synthesized AgNPs into post-harvest management techniques is a sustainable way to extend the shelf life and preserve the quality of citrus fruits while avoiding the risks associated with chemical fungicides.

Table 1. Examples of Ag Nanoparticles synthesized using plant extracts

Plant utilized	Size	Control against	Reference
Aegle marmelos	10-15	*Colletotrichum capsici* in chilli	[14]
Piper nigrum	9-30	*Erwinia cacticida* in watermelon	[107]
Citrus maxima	11-13	*Acidovorax oryzae* in rice	[108]
Artemisia absinthium	5-100	*Phytophthora parasitica* in citrus	[109]
Oryza sativa	16.5	*Rhizoctonia solani* (sheath blight) in rice	[110]
Phyllanthus emblica	20-93	*Acidovorax oryzae* in rice	
Cuminum cyminum	20-50	Various fungal pathogens	[111]
Punica granatum	15-30	Different bacteria and fungi	[112]
Azadirachta indica	8.78	Various fungi	[113]
Phyllanthus emblica	20-93	*Acidovorax oryzae* in rice	[114]
Fatsia japonica	-	*Penicillium italicum*-induced rot of Citrus, antibacterial activities against *Escherichia coli* and *Staphylococcus aureus*	[115]

5.1. Antimicrobial Mechanisms

The use of NPs in plant protection can be very important in reducing global agrochemical use and associated problems [116]. Essential oils have been previously demonstrated as alternative antifungal agents [117]. Although many studies have shown the antimicrobial activity of AgNPs against a range of plant pathogenic fungi, their mechanisms of action have not been fully elucidated [19, 84, 96]. Considering the safety of AgNPs and essential oils, their combination could be efficient for fungal management [118]. The most active tested NPs are of nanometric size [119]. Due to the PEGylation and the fact that AgNPs are embedded in the hydrophobic core of the micelles, they are stabilized in aqueous solutions [120]. The essential oil, regardless of the method, had higher antifungal activity compared to raw materials [121]. The increased activity of the encapsulated *Cymbopogon nardus* essential oil could be due to its controlled release from the AgNPs surface or better solubilization in the water phase, increasing the bioavailability of their antifungal components [122]. The presence of linalool, β-citronellol, and apiol in the *C. nardus* essential oil confirms the successful encapsulation of the essential oil and is quite interesting as beta-citronellol has similar biological activities, including signaling and antimicrobial effects, as silver nanoparticles [123]. It is known that lemongrass essential oils cause damage to the plasma membrane and cell structure, impair ergosterol biosynthesis, and reduce microbial metabolic activity by targeting the mitochondria, leading to the death of the cells [124]. The treatment of the cleaned nanoparticles against *Penicillium digitatum*, the main cause of green mold in oranges, in concentrations ranging from 10 to 1000 ppm caused changes in mycelial growth, internal and external mycelial morphology, and the spores germination process [11, 53].

5.2. Benefits and Limitations

Using AgNPs as antifungal agents in postharvest treatments, especially for citrus fruits, has numerous significant benefits. AgNPs are a nature-friendly alternative to standard fungicides for controlling green mold disease caused by *Penicillium digitatum* [125]. Notably, research has shown that AgNPs have no negative impact on the qualitative aspects that customers value most, such as taste, texture, and nutritional content [126-128]. This is critical for assuring initial sales and recurring purchases in the highly competitive fresh produce industry. Furthermore, AgNPs have competing effects against numerous postharvest decay organisms, which improves their protective capacities when combined with local necrotrophic pathogens [129]. This biocontrol method is especially effective for citrus products marketed at organic markets, where chemical fungicides are prohibited. The green synthesis of AgNPs not only supports sustainable agricultural methods but also benefits local economies by facilitating localized crop processing and protection [38]. Overall, adding AgNPs into postharvest management systems is a potential step toward preserving fruit quality while addressing the concerns of fungal pathogens.

Along with the various advantages of using AgNPs to control fungus in postharvest citrus fruits, there are several constraints to consider. A potential concern is how much control over green mold disease in oranges these green synthesized silver nanoparticles give at the consumer level [130]. Although several studies suggest that they suppress the disease, the control is usually very limited compared to the already prevalent chemical fungicides; which can be an area of improvement [38, 116, 128, 130]. According to the literature, developing AgNPs using green techniques requires little energy, but their control is insufficient to be used on a commercial scale [113]. Furthermore, as their application grows, the issue of AgNPs safety and sustainability becomes increasingly important, and steps must be taken to guarantee that they do not endanger human health or accumulate in the environment [131]Bridging the gap between environmentally sound procedures and biologically appropriate amounts is crucial for increasing AgNPs' effectiveness in treating postharvest diseases. Future research should focus on enhancing AgNPs' development and application methods, as well as developing innovative formulations and combinations with other biocontrol agents to enhance antifungal properties while remaining safe for consumers and the environment.

6. Applications in the Agricultural Industry

Plant materials are regarded as the most effective, economical, least harmful and renewable natural antioxidants that attain high suitability to get high added value and substantial advantages [132]. Both the use of green synthesized metallic nanoparticles to improve methodologies employed commercially and to preserve human food requirements, as well as the utilization of their renewable biological sources that have these advanced properties, are effectively supplemented and supported mutually [133, 134]. The quality of the nutritious content and bioactive compounds in the human diet play a notable role in the management of chronic diseases [135]. They differ from one another due to environmental conditions, loss of quality, and damage post-harvest brought about by the build-up of scent, flavor, texture, color, firmness, pH, moisture, transpiration and breathing rates, loss of mass, and rapid remote growth [136]. The synthesis of AgNPs using an eco-friendly methodology to control food and post-harvest quality issues and to package various foodstuffs promotes effectiveness and extension, guaranteeing further developed protective effects [137].

It enables consumer protection to be generally modified, improved, and extended from generation to generation without limiting it to specific people in different places and at different times to ensure consistent success and high-integrity sustainability [138]. The eco-safe preservation of fruits in the value-added commercial markets is a precondition that continues to guide and be supported by customer demand for organic, natural products free of synthetic pesticides and responsible flavors [139]. The appealing color, shape, natural scent, taste, nutrition, and bioactivity of citrus are essential fruit aspects that attract and captivate buyers [91]. Green-synthesized AgNPs on various citrus fruits are a good post-harvest management alternative to guarantee that terms are met [26, 91]. Their treatment mechanism offers promising insights for the food and agricultural sector by ensuring complete sterility from microorganisms [140], facilitating prevention, quality control, weight reduction, procurement, and preservation of vital antioxidant compounds, thereby alleviating itching sensations and physical defects on the skin, including roughness, navel and crown rings, and cracks [102]. After-treatment methods address unmet market needs. These applications are versatile.

6.1. Potential Benefits

A range of extracts derived from different plants, including parts like leaves, seeds, fruits, flowers, stems and/or bark, roots, and rhizomes, alone or in combination, have been used as reducing agents for the synthesis of AgNPs and have consequently been studied for their activity [37, 141, 142]. Many of these green methods are still incipient; in contrast, the antimicrobial activity of metallic NPs has a very long history [143]. In this way, there is still great potential in the development of the green synthesis of AgNPs and the conversion of AgNPs to more specific applications, especially in agriculture. There has been a visible increase in agricultural applications over the last decade. Still, an exponential growth derived from research associated with nanoparticles in plasma and magnetism technology and its convergence with nanotechnology is not closely associated with plant systems [144].

Considering current global needs, there is great potential in developing applications for green synthesized AgNPs in agriculture. For post-harvesting, post-disinfection procedures and packaging in fresh fruits, silver-based products could optimize the necessary energy consumption, diminish the presence of undesirable chemical residues, and consequently significantly impact environmental health [145]. Promisingly, silver has been used in common consumer products as an additive unlikely to have any major effect on resistance selection [146]. AgNPs can still be considered effective in the control of plant-based individuals, but they have yet to realize their full potential [145]. Silver has been present since ancient times and has been known to possess antimicrobial properties. However, AgNPs are considered to be more toxic and reactive [146]. Optimal, biologically produced AgNPs are safer and have been shown to be biodegradable, biocompatible, and more effective [147].

6.2. Regulatory Considerations

The regulatory framework for nanotechnology in the United States is not well defined. Different regulatory authorities possess various responsibilities and authorities for ensuring the safety of products involving nanomaterials, as well as the health and safety of workers handling these materials [148]. The US regulatory system has gaps and uncertainties as it is applied to nanotechnologies [149]. Regulatory actions are usually responsive to public concerns and incidents. Nonetheless, numerous ongoing agency collaborations, the launch of databases and strategic plans, and new definitions for nanomaterials are underway [150]. These federal efforts are aimed at ensuring the benefits of nanotechnology are pursued while paying close attention to potential risks [151]. It is also expected that the development of new assessment methods and analytical tools will result from these efforts, which could lead to the further refinement of nanotechnology risk governance mechanisms and risk management and communication procedures [152].

One of the challenges in defining the scope of the term 'nanomaterials' in the context of regulatory process discussions is that nomenclature varies widely across the globe, and specific terms are only slowly becoming aligned [150]. When it comes to nanotechnology-based products, the US does not have a publicly accessible national database [153]. In recent years, several focused national databases covering diverse nano-related topics have been announced rather than a shared centralized national database for nanotechnology-based products. However, considering the aforementioned programs and the burgeoning number of nanomaterial-based products in the US marketplace, the concern over the implications of the increased use of these products on human and environmental health cannot be underestimated [150, 153]. In the discussion of the international policies and responses that have emerged related to nanotechnologies, recognition has been given to the need for states to be better informed on these nanotechnologies to formulate public policies and/or to reform their current ones [154].

7. Future Directions and Research Opportunities

The use of AgNPs for postharvest treatment of fruits, especially citrus, provides several research opportunities. The latest research has shown that green synthesized AgNPs can inhibit diseases and extend the shelf life of citrus fruits, but the mechanism of action has yet to be completely investigated [155]. Understanding the molecular interaction between pathogens and AgNPs is critical for evaluating their agricultural application [127]. Furthermore, regulatory issues for the usage of nanotechnology must be addressed to ensure its environmental safety and efficacy. Recent research has shown that coating fruits with biogenic AgNPs is a cost-effective strategy that complies with organic farming standards. However, their organic nature and safety should be thoroughly investigated before commercial use [155].

Furthermore, the interactions of AgNPs with several disease-causing agents and their possible uses in other crops demand more research. Future studies should also look at field-level AgNPs use, including its inclusion in plant genetic improvement plan [155]. Since plant absorption of these nanoparticles might result in further environmental advantages, root-level interactions should be understood [156]. Studies supporting sustainable postharvest preservation methods will be crucial in lowering carbon emissions linked to worldwide food loss and waste as ecological safety becomes increasingly crucial in commercial applications.

7.1. Emerging Trends

Emerging trends in the green synthesis of nanoparticles have attracted researchers with the use of traditional and modern plants, as well as microorganisms such as bacteria, actinomycetes, fungi, and algae [157]. In particular, plants have gained wide application because of their ease of handling, large availability, eco-friendliness, and less toxic nature of the plant extract [8]. Furthermore, the plant extracts are comprised of different types of biomolecules such as phenolic compounds, flavonoids, proteins, alkaloids, vitamins, and saponins that can act as capping, reducing, and stabilizing agents for nanoparticle synthesis and delivery carriers for various drugs and bioactive compounds [158]. Silver nanoparticles are the most prominent among the different metallic nanoparticles. Silver nanoparticles are extensively used in biological, food, pharmaceutical, textile, paper, health, cosmetic, veterinary, drug, and medical sectors [159].

Silver nanoparticles synthesized from the green route are more popular than chemical and physical ones. The green synthesis of silver nanoparticles can be achieved through various approaches, particularly aqueous and non-aqueous methods, biological processes, chemical methods, phytofabrication, ultrasonication, and microwave techniques [160]. In this context, recent researchers have been focusing more on the study of green synthesized silver nanoparticles by applying plant extracts. This approach holds significant importance in the development of metallic and metal oxide nanoparticles due to their ability to reduce, cap, stabilize, and increase the stability and biocompatibility of the green synthesized nanoparticles [49].

7.2. Key Areas for Further Investigation

The study of AgNPs in postharvest fruit treatments, especially citrus, identifies numerous key topics for further research. While green synthesized AgNPs can increase the nutritional value and shelf life of citrus fruits, the specific underlying mechanism is unknown [40]. To improve the applications of AgNPs, it is necessary to understand how the reactive oxygen species (ROS) are scavenged and other biochemical interactions at the molecular level. Furthermore, the colloidal stability of AgNPs and their non-enzymatic antioxidant activities must be thoroughly investigated to assure their effectiveness and safety in commercial applications [41]. Furthermore, research should focus on the identification and quantification of organic compounds in citrus fruits that may interact with the AgNPs. The in-vivo and in-vitro antifungal activity of the nanoparticles should also be evaluated during the postharvest storage. Studying the potential of AgNPs to control a broader range of diseases and their compatibility with existing organic farming practices could further enhance their applicability. It is vital to develop cost-effective and environmentally friendly synthesis methods and thorough safety assessments to integrate AgNPs into sustainable agricultural practices [161]. Ultimately, increasing our knowledge of these nanoparticles will help to reduce food waste and improve postharvest preservation technology.

8. Conclusion

Green synthesized AgNPs present a valuable development in the postharvest management of fruits, especially oranges. This review highlights the importance of AgNPs in controlling green mold and enhancing the fruit quality and shelf life of citrus fruits. The synthesis of AgNPs using green principles not only reduces the hazardous environmental impacts but also fulfills the consumers' demand for organic and safe food products. Regardless of these benefits, certain critical areas need further research to use these AgNPs properly. To optimize their use in the agriculture sector, it is necessary to understand their underlying mechanism of action and interaction with the pathogens at the molecular level. Furthermore, regulatory concerns on their safety and environmental implications should be addressed for their acceptance at commercial scale. Future research should investigate the scalability of the production of AgNPs and their incorporation into the pre-existing postharvest treatment practices. By concentrating on these key areas, we can reduce food waste and increase marketability, leading to strengthening the sustainability of agricultural practices. Ultimately, further research can lead to innovative solutions supporting food security and environmental responsibility in the ever-demanding global market.

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تسخير قوة النبات: مراجعة لجزيئات الفضة النانوية المصنَّعة بيولوجيًا لتحسين جودة ما بعد الحصاد في البرتقال ومقاومة العفن الأخضر

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مستخلص. دفع الطلب المتزايد على المنتجات العضوية الطازجة إلى استكشاف طرق مبتكرة لتحسين جودة ما بعد الحصاد ومكافحة الأمراض في الفاكهة، وخاصة الحمضيات. تركز هذه المراجعة على التركيب الأخضر لجزيئات الفضة النانوية باستخدام المستخلصات النباتية، والتي تعمل كعوامل اختزال وتثبيت، كبديل مستدام لمبيدات الفطريات الكيميائية التقليدية. تتميز الجسيمات النانوية من حيث حجمها وشكلها واستقرارها باستخدام تقنيات مثل مطيافية الأشعة فوق البنفسجية والمرئية، حيود الأشعة السينية (XRD)، مطيافية الأشعة تحت الحمراء بتحويل فورييه (FTIR)، المجهر الإلكتروني الماسح (SEM) والمجهر الإلكتروني النافذ (TEM). تتمتع جزيئات النانو الفضية المصنعة باللون الأخضر بفعالية مضادة للفطريات ضد مسببات العفن الأخضر *Penicillium digitatum*. إنها تطيل العمر الافتراضي للبرتقال دون المساس بجودته الجمالية والتغذوية. تظهر جزيئات النانو الفضية هذه استقرارًا وفعالية طويلة الأمد، مما يقلل من فقدان وزن الفاكهة ويعزز مقاييس الجودة الرئيسية، بما في ذلك تركيز حمض الأسكوربيك والحموضة القابلة للقياس. على الرغم من البحث الشامل، لا تزال آلية عمل جزيئات النانو الفضية وتفاعلاتها الجزيئية مع مسببات الأمراض غير واضحة بشكل كافٍ. تؤكد هذه الدراسة على ضرورة إجراء أبحاث إضافية لكشف هذه الآليات وتقييم السلامة البيئية لجزيئات النانو الفضية. يجب أيضًا التحقيق في التطبيق المستقبلي لهذه جزيئات النانو الفضية في المحاصيل المختلفة. في نهاية المطاف، تهدف هذه الدراسة إلى المساهمة في الممارسات الزراعية المستدامة من خلال دمج الحلول الصديقة للبيئة في استراتيجيات إدارة ما بعد الحصاد.

الكلمات المفتاحية: التركيب الأخضر، الجسيمات النانوية الفضية، الحمضيات، ما بعد الحصاد، العفن الأخضر