Saudi Journal of Biological Sciences 28 (2021) 5631–5639

Contents lists available at ScienceDirect

Saudi Journal of Biological Sciences

journal homepage: www.sciencedirect.com

Review

Plant-based green synthesis of silver nanoparticles and its effective role in abiotic stress tolerance in crop plants

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ARTICLE INFO

Article history:
Received 9 May 2021
Revised 31 May 2021
Accepted 31 May 2021
Available online 4 June 2021

Keywords:
Nanotechnology
Drought stress
Salt stress
Heat stress
Crop
Plant extracts

ABSTRACT

The development of effective and environmentally friendly methods for the green synthesis of nanoparticles (NPs) is a critical stage in the field of nanotechnology. Silver nanoparticles (AgNPs) are significant due to their unique physical, chemical, and biological properties, as well as their numerous applications. Physical, chemical, and green synthesis approaches can all be used to produce AgNPs; however, synthesis using biological precursors, particularly plant-based green synthesis, has shown outstanding results. In recent years, owing to a combination of frequent droughts, unusual rainfall, salt-affected areas, and high temperatures, climate change has changed several ecosystems. Crop yields have decreased globally as a result of these changes in the environment. Green synthesized AgNPs role in boosting antioxidant defense mechanisms, methylglyoxal (MG) detoxification, and developing tolerance for abiotic stress-induced oxidative damage has been thoroughly described in plant species over the last decade. Although various studies on abiotic stress tolerance and metallic nanoparticles (NPs) in plants have been conducted, but the details of AgNPs mediated abiotic stress tolerance have not been well summarized. Therefore, the plant responses to abiotic stress need to be well understood and to apply the gained knowledge to increase stress tolerance by using AgNPs for crop plants. In this review, we outlined the green synthesis of AgNPs extracted from plant extract. We also have updates on the most important accomplishments through exogenous application of AgNPs to improve plant tolerance to drought, salinity, low and high-temperature stresses.

Contents

Peer review under responsibility of King Saud University.

Production and hosting by Elsevier

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https://doi.org/10.1016/j.sjbs.2021.05.081
1319-562X/

1. Introduction

Nanotechnology is the most dynamic subject of material science study, and the production of nanoparticles (NPs) is rapidly increasing around the world. NPs display completely new or improved properties as a result of specific qualities, such as size (1–100 nm), shape, and structure (Nejatzadeh, 2021; Taran et al.,2017). Inorganic and organic NPs are the two types of NPs that can be synthesized. Inorganic nanoparticles include metallic nanoparticles (like Au, Ag, Cu, Al), magnetic nanoparticles (like Co, Fe, Ni), and semi-conductor nanoparticles (like ZnO, ZnS, CdS), while organic nanoparticles include carbon nanoparticles (like quantum dots, carbon nanotubes) (Taran et al., 2017; Chouhan, 2018). Since nanoparticles have distinct properties, inorganic NPs can be used for sustainable crop productions (Nejatzadeh, 2021; Parisi et al., 2015). Several innovations and products integrating engineered nanoparticles (NPs) into agricultural practices, such as nanopesticides, nanofertilizers, and nanosensors, have been established over the last decade with the aim of improving the quality and sustainability of agronomic systems that need less production and generate less waste than traditional products and approaches (Servin et al., 2015; Liu and Lal, 2015).

Silver nano-particles (AgNPs) considered as a commercialized nanomaterial, which is extensively used for medical antimicrobial and personal care products, construction materials, water filtration, medical instruments (Borase et al., 2014). In recent years, several metallic nanoparticles (NPs) including AgNPs have earned a significant attention due to their environmentally friendly implementations in agricultural sector (Mahakham et al., 2017; Chouhan, 2018). There are several approaches for the synthesis of AgNPs including green methods, chemical and physical methods. But, AgNPs green synthesis by using plant and plant extracts have been used widely in agricultural sector (Yousaf et al., 2020; Castro-González et al., 2019).

The global agricultural food security is seriously affected by climate change and fast population growth (Hasan et al., 2021b; Hasan et al.,2019, Hasan et al.,2018). Abiotic stress around the environment has been a major concern. Drought, salinity and excessive high and low temperatures are the main abiotic stresses that are negatively affecting plant development and productivity (Jahan et al.,2021; Alharbi et al.,2021; Hasan et al.,2020a; Hasan et al.,2020b). Several of metallic NPs (AgNPs, AuNPs, CuNPs,18, FeNPs, FeS_2NPs, TiO_2NPs, ZnNPs, ZnONPs) have recently been used for seed germination, plant growth and stress tolerance of a number of crop plants (Taran et al.,2017; Latef et al.,2017). The effects of AgNPs have been identified in the agricultural sector, with an emphasis on seed germination (Ibrahim, 2016, Singh et al., 2016a), plant growth and development (Kim et al.,2018), and gas exchange rate (Wang et al.,2020) under various abiotic stresses. Silver nanoparticles (AgNPs) have remarkably ascendant behavior over existing nanoparticles (Mohamed et al., 2017) because of their unique physicochemical properties imparting antimicrobial and antioxidant activities (Panyuta et al., 2016). These physiochemical properties along with synthesis and characterization of AgNPs are influenced by several factors like pH, temperature, and incubation time etc. (Baker et al.,2013).

Although various studies on the synthesis and characterization methods of silver nanoparticles have been reported (Ahmed et al., 2016; Roy et al., 2015; Saravanakumar et al., 2016), relatively few reports on their green plant extract synthesis and their abiotic stress tolerance in plants. Therefore, in this review, we have attempted to include a detailed biosynthesis detail of AgNPs from herbal extracts. The goal of this review was to better understand and summarize the mechanisms underlying stress resistance and AgNP-mediated plant tolerance increase via antioxidant activity.

2. Green synthesis

The traditional methods for producing NPs are costly, poisonous, and unfriendly to the environment. To solve these issues, scientists have discovered the exact green paths, or naturally occurring sources and their materials, that can be used to synthesize NPs. The source of green synthesis can be categorized into three categories: (a) using microorganisms such as fungi, yeasts (eukaryotes), bacteria, and actinomycetes (prokaryotes), (b) using plants and plant extracts, and (c) the use of membranes, virus's DNA, and diatoms. In this review, we focused the green synthesis of AgNPs using plant extract.

2.1. Synthesis of AgNPs with plant extracts

The use of plants and plant extracts in green synthesis has gained popularity due to its quick development, single-step method, cost-effective protocol, non-pathogenicity, and environmentally friendly nature. Plant based green synthesis tends to be quicker than other microorganisms like bacteria and fungi. Therefore, in green synthesis, the use of plant extract has prompted many studies and researched them so far. Depending on the nature of the plant extract, it was observed that the production of metal NPs using plant extract could be achieved in the metal salt solution in a short period of time at room temperature. The concentration of the extract, temperature, metal salt, and p^H are the key influencing parameters after the plant extract has been chosen (Mittal et al.,2013). Aside from the formation conditions, the most important consideration is the plant from which the extract will be extracted. Plants for the synthesis of NPs have the benefits of being readily available and safe to treat, as well as having a wide variety of active agents that can aid in the reduction of Ag ions. Leaves, stems, shoots, barks, flowers, seeds, and their derivatives have all been successfully used for the biosynthesis of nanoparticles (Kharissova et al., 2013) (Fig. 1). The important point is the active agent found in this component, which allow stabilization and reduction, and the biomolecules that create stable NPs. Biomolecules, e.g. amino acids, polysaccharides, alkaloids, and proteins are the key compounds that affect reducing and capping NPs (Fig. 2). Likewise, methyl chavicol, chlorophyll pigments, ascorbic acid, caffeine, and other vitamins have also been investigated (Bindhu and Umadevi, 2013).

Gardea-Torresdey et al. (2003) showed that *Alfalfa* sprouts were a first approach to plant synthesis for metallic NPs, and provided the first explanation of AgNPs synthesis using a living plant system. The standard technique for synthesizing nanoparticles includes the collecting of the desired plant part/material from available places, followed by thorough washing rinsed with distilled water (Roy and Das, 2015). Afterwards, plant sources are dried for 10–15 days in the dark before being powdered with a household blender. Then, 10 g of the dry powder is boiled with 100 mL distilled water to make the plant broth. The resultant solution is then extensively filtered to remove any insoluble particles from the broth. The filtrate is collected, and a 1 mM final concentration of $AgNO_3$ solution must be added to it. The mixture is agi-

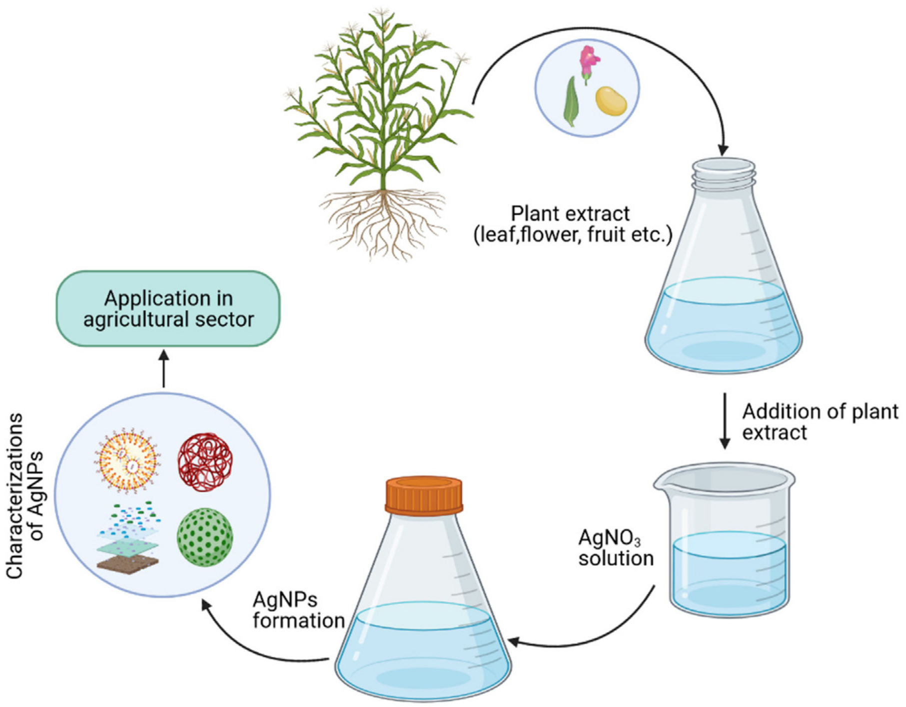

Fig. 1. Schematic diagram for synthesis of AgNPs by using plant extracts. Created with Biorender.

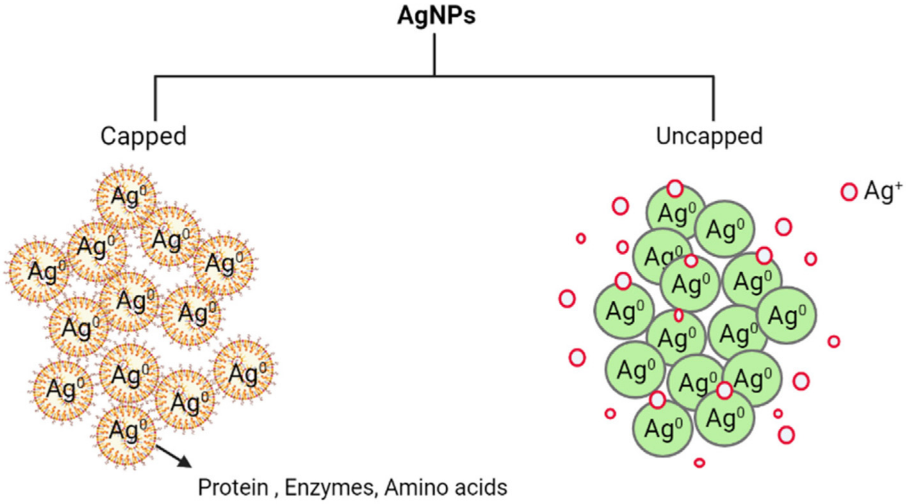

Fig. 2. Capped and uncapped silver nanoparticles (AgNPs) adapted from Guilger-Casagrande and de Lima (2019). Capped AgNPs are more stable and have better size control than uncapped AgNPs. Created with Biorender.

tated briefly in a shaking incubator. The color of the mixture changes due to the decrease of pure Ag^+ ions to Ag^o, and the resulting sample must be monitored at periodic times in the ultra violet spectrum of the solutions to detect the unique absorption features of nanoparticles. Various techniques must be used to characterize the synthesized nanoparticles (Roy and Das, 2015).

For an example, High Resolution Transmission Electron Microscopy (HRTEM), UV–Vis spectrometer, Energy Dispersive X-ray Spectroscopy (EDX), and Selected Area Diffraction were used to characterize synthesized AgNPs by using *Ananas comosus* (Ahmad and Sharma, 2012). The spherical NPs with an average diameter of 12 nm were depicted in transmission electron microscopy (TEM) micrographs. *Argemone mexicana* leaf extract is used as a capping and reducing agent in the production of AgNPs by adding it to an aqueous solution of $AgNO_3$. Using a UV–Vis spectrometer, X-Ray diffractometer (XRD), Scan Electron Microscopy (SEM) and Fourier Transmission Infrared (FTIR) Spectrophotometer, the properties of NPs are analyzed. According to Singh et al. (2010), XRD and SEM showed that the average size of NPs is 30 nm. Gavhane et al. (2012) reported that AgNPs were produced from the extract of Neem and Triphala by decreasing the aqueous $AgNO_3$ solution. EDX, nanoparticles tracking analysis (NTA), and TEM were used to examine the properties of NPs. The size range of spherical particles identified by nanoparticles tracking analysis (NTA) and transmission electron microscopy (TEM) was 43 nm to 59 nm. Velmurugan et al. (2015) demonstrated that Ag-NPs can be made from peanut shell extract and compared to commercial AgNPs in terms of characteristics and their antifungal activity.

The similarity of synthesized and commercial NPs was confirmed by the analysis of UV–Vis spectra, XRD peaks, and FTIR. These findings show that NPs are mainly oval and spherical in shape, measuring 10–50 nm of diameter (Velmurugan et al., 2015). In another method, Roy et al. (2014) used the fruit extract of *Malus domestica* as a capping agent to synthesize spherical Ag-NPs with an average diameter of 20 nm. UV–Vis spectroscopy is used to examine NP formation and XRD and TEM are used to validate distinct phases and morphology, as well as FTIR is used to classify the biological molecules involved in NP reduction and stabilization. According to Rout et al. (2012), spherical-shaped AgNPs were synthesized from the leaf extract of *Ocimum sanctum* and particle properties were analyzed using a UV–Vis spectrometer, SEM, XRD, and SEM. Bar et al. (2009) showed that Ag-NPs is synthesized by reducing aqueous $AgNO_3$ solution with latex from *Jatropha curcas*. Udayasoorian et al. (2011) demonstrated that Ag-NPs were also produced using *Cassia auriculata* leaf extract as a capping agent.

Shankar et al. (2003) demonstrated the AgNPs extracellular synthesis using *Geranium* leaf extract to incorporate $AgNO_3$ and rapid degradation of Ag ions has led to the generation of stable AgNPs of 40 nm of dimensions. *Ficus benghalensis* leaf extract is used to make stable and spherical Ag-NPs with an average particle size of 10–50 nm. FTIR, SEM, thermal gravimetric analysis (TGA), and XRD were used to investigate the properties of synthesized NPs (Saware et al., 2014). As capping agent for Ag-NPs synthesis, the *Acorus calamus* extract can be used to assess their oxidation, anticancer and antibacterial effects (Nakkala et al., 2014). Kumar et al. (2014a, 2014b, 2014c) studied synthesizing AgNPs through extract from the *Boerhaavia diffusa*.

The findings of XRD and TEM displayed a usual size of about 25 nm having spherical shape. These NPs have been used against bacteria namely, *Aeromonas hydrophila, Flavobacterium, and Pseudomonas fluorescens*. Krishnaraj et al. (2010) used the extract of a leaf of *Acalypha indica* to synthesize Ag-NPs. According to Dwivedi and Gopal (2010), spherical AgNPs are synthesized from the noxious weed *Chenopodium album*, which has a size range of 10–30 nm. Aldebasi et al. (2015) used an aqueous mixture of *Ficus carica* leaf extract to synthesize AgNPs. In another method, Awwad et al. (2012) synthesized AgNPs from *Olea europaea* extract and characterized them using SEM, XRD, and FTIR. The spherical AgNPs were synthesized using *Abutilon indicum* extract, and their strong antibacterial action against *S. typhi, E. coli, S. aureus*, and *B. subtilis* microorganisms was investigated (Ashokkumar et al. 2015).

Logaranjan et al. (2016) described size and shape based controlled AgNPs synthesis from *Aloe vera* plant extract (Table 1). Aqueous fruit extract of *Syzygium alternifolium* was used to make reliable and capped Ag NPs with a diameter of 5–68 nm. Moldovan et al. (2016) stated green synthesis of spherical AgNPs from the fruit extract of *Sambucus nigra*. They were found to be crystalline after an XRD study. Artocarpus heterophyllus seed powder extract was used to produce AgNPs (Jagtap and Bapat, 2013). SEM, TEM, SAED, EDAX, and IR spectroscopy were used to assess the nanoparticles' structure and crystal structures. They were observed to have an unusual shape. Kumar et al. (2014a, 2014b, 2014c) reported green synthesis of AgNPs from *Boerhaavia diffusa* plant extract, in which the plant extract represented as both a capping and reducing agent. In the UV–vis spectrum, the colloidal solution of AgNPs had an absorption limit at 418 nm. A face-centered cubic structure with an average particle size of 25 nm was reported by XRD and TEM studies. Ag NPs is synthesized from methanolic leaf extract of *Leptadenia reticulate* and they were crystalline, face-centered, spherical particles measuring 50–70 nm (Swamy et al. 2015) (Table 1).

According to Awwad and Salem (2012), mulberry leaves extract was used to synthesize mono-dispersed and spherical Ag-NPs with a particle size of 20 nm. UV–Vis spectroscopy, XRD, and SEM were used to examine the properties of synthesized Ag-NPs, which showed their powerful antibacterial action against *Staphylococcus aureus* and *Shigella spp* (Awwad and Salem, 2012). Khalil et al. (2014) studied that AgNPs are obtained by reducing $AgNO_3$ solution with olive leaf extract, and they have shown to be effective antibacterial agents against drug-resistant bacteria. UV–Vis spectroscopy, XRD, TGA, and SEM were used to investigate the properties of NPs, and the findings revealed that NPs with an average of 20–25 nm are mostly spherical. Kumar et al. (2014a, 2014b, 2014c) used *Alternanthera dentate* plant extract as a capping agent in the green synthesis of AgNPs. Murugan et al. (2014) stated that *Acacia leucophloea* extract is used to synthesize Ag-NPs with a size range of 38–72 nm. Arokiyaraj et al. (2014) suggested that *Chrysanthemum indicum* L. was used to generate Ag-NPs with a size range of 17–29 nm. Kumar et al. 2013 showed that the *Parthenium hysterophorus* leaf extract and *Premna herbacea* were used to make AgNPs, which were then mixed with $AgNO_3$ solution.

2.2. Factors affecting AgNPs green synthesis

Several important factors influence the synthesis, characterization, and application of nanoparticles. The factors include the pH of the solution, temperature, extract concentrations, concentration of the raw materials used, size, and, most importantly, synthesis methods are all factors to consider (Baker et al., 2013). The control of the NPs polydispersity is a major challenge, despite the benefits for organic green synthesis. To resolve this issue, the conditions of the reaction can be optimized by adjusting the pH, temperature, incubation time, irradiation, salt concentration, and redox state. For an example, pH is a critical factor that affects the green synthesis of nanoparticles. In the case of plants, pH variations lead to changes in the charge of the phytochemicals, which affects the reduction and biding of the Ag during the synthesis process (Singh et al., 2016b). In most situations, green technology is used to synthesize nanoparticles at temperatures below 100 °C (Baker et al., 2013). Furthermore, the properties of green synthesis of silver nanoparticles are influenced by particle size and porosity.

3. AgNPs role in abiotic stress tolerance

Plants are exposed to a variety of abiotic stresses in nature, including heat, drought, salinity, low temperature and the occurrence of these stresses has risen in the global environment (Khan et al., 2017). In the last few years, nanotechnology has gained the interest of researchers in a variety of fields. Because of their incredibly small size, nanoparticles have developed certain unique characteristics that distinguish them from their bulk equivalents. As compared to bulk material, nanoparticles have more solubility, surface area, and reactivity. Therefore, they have been able to achieve the aim of sustainable agriculture globally with a promising role to improve the harmful effects of abiotic stress. The use of silver nanoparticles (AgNPs) in agriculture is gaining popularity due to their effect on stress tolerance. Different forms of AgNPs nanoparticles have been investigated for their possible function in abiotic stress defense. These silver nanoparticles have been shown to enhance crop stress tolerance by overcoming nutrient shortages, increasing enzymatic processes, and assisting in the adhesion of plant growth-promoting bacteria to plant roots under abiotic stresses (Fig. 3). These preliminary findings were encouraging, and they also ushered in a new era of using nanoparticles to boost crop production under adverse environmental conditions.

Table 1
Green synthesis of silver nanoparticles (AgNPs) using plant and plant extracts adapted and rearranged from Siddiqi et al. (2018) and Rafique et al. (2016).

Species	Source/used of extract	Size (nm)	Shape	References
Acmella oleracea	Flower	2–20	spherical	Raj et al. (2016)
Aegle marmelos	Fruit	22.5 nm	spherical, hexagonal, roughly circular	Velmurugan et al. (2015)
Allium cepa	Leaves	33.6	Spherical	Saxena et al. (2010)
Aloe vera	Leaf gel	5–50	octahedron	Logaranjan et al. (2016)
Albizia lebbeck	Leaves	–	Spherical	Parvathy et al. (2014)
Artocarpus heterophyllus	Seeds	10.78	irregular	Jagtap and Bapat (2013)
Aristolochia indica	Leaf	32–55	spherical	Shanmugam et al. (2016)
Boerhaavia diffusa	Whole plants	25	spherical	Kumar et al., 2014a, 2014b, 2014c)
Brassica rapa	Leaves	16.4	–	Narayanan and Park (2014)
Calotropis gigantean	Flower	10–50	spherical	Pavani and Gayathramma (2015)
Citrus limon	Limon	>50	Spheroidal and spherical	Prathna et al. (2011)
Chenopodium album	Leaves	10–30	Spherical	Dwivedi and Gopal (2010)
Cuminum cyminum	Seeds	12	Smooth surface and spherical	Kudle et al. (2012)
Cydonia oblonga	Seeds	38	face-centered cubic	Zia et al. (2016)
Carica papaya	Fruit	15	Hexagonal and cubic	Jain et al. (2009)
Catharanthus roseus	Leaves	20	Spherical	Al-Shmgani et al. (2016)
Chelidonium majus	Root	15.42	spherical	Alishah et al. (2016)
Eclipta prostrate	Leaves	35–60	Hexagons, triangles and pentagons	Rajakumar and Rahuman (2011)
Eucalyptus globulus	Leaf	1.9–4.3 and 5–25	–	Ali et al. (2015)
Euphorbia amygdaloides	Plant	7–20	Spherical	Cicek et al. (2015)
Erigeron bonariensis	Leaf	13	spherical	Kumar et al. (2015)
Ficus carica	Leaves	13	–	Geetha et al. (2014)
Hibiscusrosa sinensis	Flower	14	Prism or spherical	Philip (2010)
Hydrocotyle asiatica	Leaf	21	spherical	Devi et al. (2016)
Lantana camara	Leaf	33.8	spherical	Manjamadha and Muthukumar (2016)
Leptadenia reticulate	Leaf	50–70	crystalline, face centered	Swamy et al. (2015)
Mangifera indica	Seed	14	spherical and hexagonal	Sreekanth et al. (2015a)
Melia dubia	Leaves	35	Spherical	Kathiravan et al. (2014)
Morinda tinctoria	Leaf	80–100	spherical	Vennila and Prabha (2015)
Momordica charantia	Leaf	11	Spherical	Ajitha et al. (2015)
Nigella sativa	Leaf	15	spherical	Amooaghaie et al. (2015)
Olea europaea	Seed	34	Crystalline	Sadeghi (2014)
Parkia roxburghii	Leaf	5–25	poly dispersped, quasi-spherical	Paul et al.(2016)
Peach gum	gum powder	23.56 ± 7.87		Yang et al. (2015)
Pedalium murex	Leaf	50	spherical	Anandalakshmi et al. (2016)
Prunus serotina	Fruit	20–80	spherical	Kumar et al. (2016)
Piper nigrum	Seeds	10–60	rod shaped	Mohapatra et al. (2015)
Psidium guajava	Leaves	26 ± 5	Crystalline and spherical	Raghunandan et al. (2011)
Piper betle	Leaf	48–83	spherical	Kamachandran et al. (2015)
Picrasma quassioides	Bark	17.5–66.5	spherical	Sreekanth et al. (2015b)
Prunus japonica	Leaves	26	Hexagonal and spherical	Saravanakumar et al., 2016
Rubus glaucus	Fruit	12–50	Spherical	Kumar et al. (2017)
Solanum lycopersicum	Fruit	10	Spherical	Umadevi et al. (2013)
Sambucus nigra	Fruit	26	spherical	Moldovan et al. (2016)
Solanum tuberosum	Tuber	10–12	Crystalline andspherical	Roy et al. (2015)
Sterculia acuminata	Fruit	~ 10	Spherical	Bogireddy et al. (2016)
Saraca indica	Leaf	23 ± 2	spherical	Perugu et al. (2016)
Salvadora persica	Stem	1–6	spherical	Tahir et al. (2015)
Syzygium alternifolium	Fruit	4–48	spherical	Yugandhar et al. (2015)
Salacia chinensis	Powdered plant	20–80	spherical, rods, triangular, hexagonal	Jadhav et al. (2015)
Terminalia arjuna	Bark	2–100	Spherical	Ahmed et al. (2016)
Tribulus terrestris	Fruit	16–28	Spherical	Gopinath et al. (2012)
Terminalia cuneata	Bark	25–50	Spherical	Edison et al. (2016a), Edison et al. (2016b)
Trachyspermum ammi	Seeds	36 nm	cubic	Chouhan and Meena (2015)
Terminalia chebula	Fruit	30	distorted spherical	Edison et al. (2016a), Edison et al. (2016b)
Tamarindus indica	Seed coat	~ 12.73	–	Ramamurthi et al. (2015)
Trigonella foenum-graecum	Seeds	20–50	spherical	Meena and Chouhan (2015)
Ziziphora tenuior	Leaves	8–40	Spherical	Sadeghi and Gholamhoseinpoor (2015)

3.1. AgNPs and salt stress

Soil salinity is the most common source of abiotic stress in plants, and it has a significant impact on plant productivity (Alharbi et al., 2021). This stress caused massive economic damage because of their negative impact on the production and development of crops. The situation is quite concerning in 1,125 million hectares, 76 million of which are affected only by anthropogenic activities, resulting 1.5 million hectares of arable land lost each year owing to salinization and sodification (Abou-Zeid and Ismail, 2018). As a result, new approaches to reducing the detrimental effects of these stresses on plants are constantly required. Salt content in plants exposed to AgNPs substantially enhanced osmolality, chloride, sodium and potassium. The stability of AgNP can be controlled by changing the salinity in aquatic environments and it was observed that AgNPs are more stable in low salinity waters (Banan et al., 2020). High salinity may be detrimental to a plant's growth or production (Sagghatol-Islami, 2010). Scientists have tried to promote the germination of plants in field conditions since the development, management and production of new transgenic plant varieties have become more prominent. The priming of a seed before plantation is one approach to promote plant germination in field conditions (Salami et al., 2007). Abou-Zeid and Ismail (2018) reported that AgNPs priming stimulates wheat grain germination and development (Table 2).

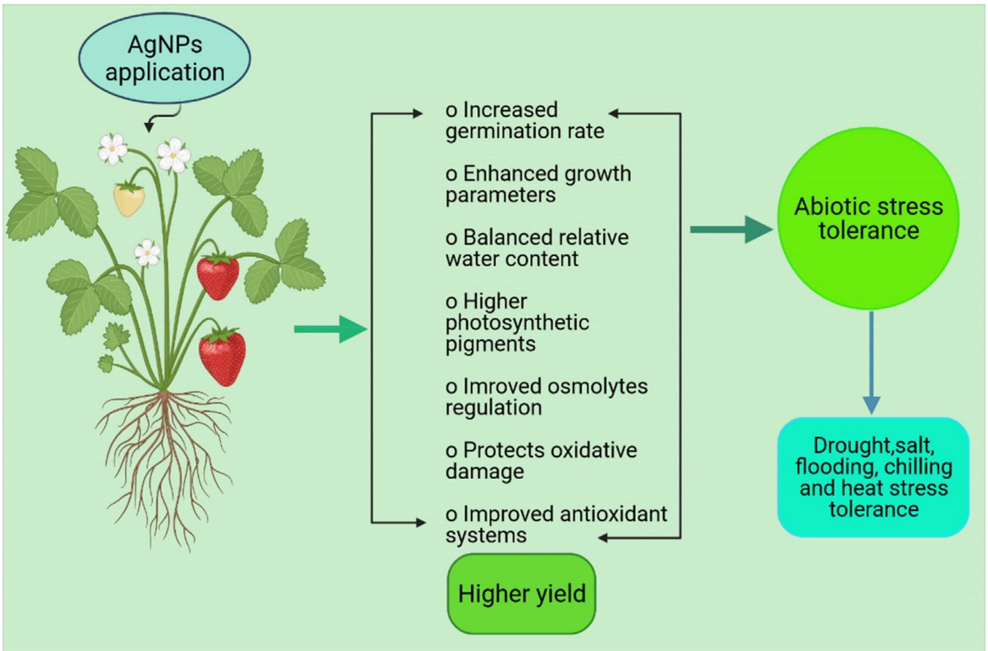

Fig. 3. A schematic model figure is showing how exogenous AgNPs application improves the abiotic stress (drought, salt, flooding chilling and heat stress) tolerance in plants. Created with Biorender.

Table 2
Exogenous application of AgNPs induces abiotic stress tolerance in different plant species.

Species	Abiotic Stresses	AgNP$_S$ Treatment	Effect	Outcome	References
Cuminum cyminum L	Salt stress (30, 60, 90, 120, 150, 180 mmolL^{-1})	0, 20, 40, 60, 80 and 100 mg kg^{-1}	Enhanced germination percentage, germination speed and vigor	Increased Salt tolerance	Ekhtiyari and Moraghebi, (2011)
Lentil (*Lens culinaris* Medic)	Drought stress (polyethyleneGlycol, PEG, −0.4, −0.6, −0.9 and −1.1 Mpa)	0, 10, 20, 30, and 40 μg mL^{-1}	Improved germination percentage, germination rate, shoot length, fresh and dry weight	Increased drought stress tolerance	Hojjat (2016)
Phaseolus vulgaris L.)	Chilling temperatures	0.25, 1.25, and 2.5 mg dm^{-3}	Increased seedling height, fresh and dry weight and net photosynthesis	Improved chilling stress tolerance	Prazak et al.2020
Saffron (*Crocus sativus)*	Flooding stress	0, 40, 80, and 120 ppm	Enhanced root and leaves fresh and dry weight	Improved flooding tolerance	Rezvani et al.2012
Satureja hortensis L.	Salt stress (0, 30, 60, 90, and 120 mM L^{-1})	0, 40, 60, and 80 ppm	Enhanced germination percentage growth parameters such as shoot length	Improved salt stress tolerance	Nejatzadeh (2021)
Solanum lycopersicum L.	Salt stress (0.05, 0.5, 1.5, 2 and 2.5 mg L^{-1}	150 and 200 mM	Increased germination rate, fresh and dry weight.	Significantly mitigated salt stress	Almutairi (2016)
Triticum aestivum L. *cv.* Pusa Kiran	Salt stress (100 mM NaCl)	300 ppm	Protected oxidative damage and upregulated antioxidative enzymes during salt stress	Regulated Salt tolerance	Wahid et al., 2021
Triticum aestivum L	Heat stress (35–40 °C)	25, 50, 75, and 100 mg/l	Balanced relative water content (RWC) and improved chlorophyll content	Increased heat tolerance	Iqbal et al.2018
Triticum aestivum L.	Salt stress (150 mM)	0, 2, 5 and 10 mM	Improved growth parameters and decreased malondialdehyde (MDA), hydrogen peroxide (H_2O_2) content	Significantly alleviated salt stress	Mohamed et al.2017
Triticum aestivum L.	Salt stress (25 and 100 mM NaCl)	1 mg L^{-1}	Improved germination and growth of wheat seedlings	Improvement of plant tolerance against salt stress	Abou-Zeid and Ismail (2018)

Furthermore, in tomato plants, the application of AgNPs increased seed germination rates (Almutairi, 2016). Under natural and stress conditions, reactive oxygen species (ROS) are generated in various plant cell compartments such as plasma membranes, peroxisomes, chloroplasts, and mitochondria. Overproduction of reactive oxygen species (ROS) in plants is linked to oxidative damage and is influenced by genotype, developmental level, and the involvement of stresses such as salt. Compared to NaCl-treated plants, Wahid et al. (2020) found that combining AgNP and NaCl reduced hydrogen peroxide (H_2O_2), thiobarbituric acid reactive substances (TBARS), and the percentage of electrolyte leakages (EL). Plants increase their antioxidant defenses in response to the negative effects of salt (Alharbi et al., 2021). In these antioxidant systems, a number of antioxidant enzymes are involved such as superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APX), dehydroascorbate reductase (DHAR), monodehydroascorbate reductase (MDHAR), glutathione reductase (GR), proline, glycine betaine and anthocyanin (Hasan et al., 2021b). Previous studies confirmed that salt stress is reduced by AgNPs through triggering the antioxidant systems (Wahid et al., 2020) (Fig. 3). Overall, the study revealed and demonstrated a promising method in AgNPs mediated salt tolerance, indicating that processes of inducing salt tolerance are dependent on proline metabolism, ion accumulation, and antioxidant defense systems.

3.2. AgNPs and drought stress

Low water availability is a major abiotic stress that has a significant negative impact on plant growth and yield (Hasan et al., 2020a). For good crop production, sufficient soil water is essential for short- to long-distance transport, osmoregulation, and single-cell expansion via cellular membranes (Iwuala et al., 2020). Drought has a detrimental effect on the flow of water in plants, but can be partly regulated by the opening of membrane channels called water-permeability aquaporins (AQPs) (Hasan et al., 2021a).

To ensure food security, it is critical to reduce drought stress and develop drought-tolerant cultivars (Hasan et al., 2020a). Although multiple research found that AgNPs effectively reduced salt stress (Abou-Zeid and Ismail, 2018; Almutairi, 2016), there was only a little research in the past literature that focused on the combination between drought and AgNPs. A single study reported that AgNPs helped to maintain water balance in lentil under drought stress by improving growth traits such as such shoot length, fresh and dry weight (Hojjat, 2016) (Table 2). Also, the results of these experiments concluded that the use of AgNPs increased the germination in lentil under drought Levels.

3.3. AgNPs and other important abiotic stresses

Exogenous AgNPs treatments have been shown in several studies to increase plant tolerance to chill temperatures (Prazak et al., 2020). For example, low concentrations of AgNPs (0.25, 1.25 mg dm^{-3}) had an obvious positive impact on green beans, resulting in quick and uniform germination in laboratory and field environments, observed as an improvement in plant height, fresh and dry weight, and photosynthesis (Prazak et al., 2020). Iqbal et al. (2018) found that green synthesized AgNPs played a key role in reducing the harmful effects of heat stress in wheat plants. AgNPs reduced the malondialdehyde (MDA) concentration, hydrogen peroxide (H_2O_2) contents and improved antioxidant defense systems in the wheat plants during heat stress conditions. Because of their unusual plasmon-resonance optical scattering features against heat stress, AgNPs are able to minimize oxidative stress in plants. Overall, it was concluded that treatment with green synthesized AgNPs could represent an amazing strategy for cultivation in high temperature areas of the world (Fig. 3).

4. Conclusion and future perspective

In summary, it is confirmed that many efforts have been undertaken in the last few years to produce green synthesis of nanoparticles (NPs). The motivation to develop eco-friendly approaches arose from a growing knowledge of green technology and the use of green routes for the synthesis of AgNPs. Exogenous green synthesized AgNPs applications have been shown to increase stress tolerance in a variety of experiments. AgNPs may have radical-scavenging capacity, indicating that AgNPs may have an antioxidative function by inhibiting lipid peroxidation and ROS productions. However, the exact molecular mechanism underlying AgNPs stress-resilient properties is still unknown. To establish the action of nanomaterials in inhibiting plant stress, further research was needed at various levels, including molecular and subcellular levels. Furthermore, AgNPs are crucial to investigate relative genome-induced responses to abiotic stressors in real-time. The most important thing is for the mitigation of the toxic impacts of AgNPs compounds on plants by identifying new diagnostic and prognostic biomarkers. The spatial mapping of transcripts induced under several abiotic stresses in reaction with green-synthesized AgNPs will undoubtedly be a focus of research over the next years. Additional research is required to develop a full understanding of the features that influence the gene interactions of plants in response to green-synthesized nanoparticles. In addition, we must conduct extensive research on hormone signaling in response to abiotic stressors and early actions generated by AgNPs. We still have to address critical aspects such as endogenous hormone trafficking between compartments and cells, as well as signal transduction pathways in the presence of AgNPs. We anticipate that a thorough molecular and signalling analysis addressing these and other fundamental concerns will yield novel insights into sustainable agriculture against abiotic stresses.

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.

Acknowledgments

The authors would like to extend their sincere appreciation to the Department of Biology, College of Science, Imam Abdulrahman Bin Faisal University, Saudi Arabia and School of Life Sciences, Lanzhou University, China.

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