Review

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

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A B S T R A C T

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.

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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 world 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, FeNPs, FeS2NPs, TiO2NPs, 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 ascendancy behavior over existing nanoparticles (Mohamed et al., 2017) because of their unique physicochemical properties imparting antimicrobial and antioxidant activities (Panyuta et al., 2016). These physicochemical 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 pH 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 filtrate is collected, and a 1 mM final concentration of AgNO3 solution must be added to it. The mixture is agi-
tated briefly in a shaking incubator. The color of the mixture changes due to the decrease of pure Ag\(^+\) ions to Ag\(^0\), 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 AgNO₃ 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 AgNO₃ 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 a 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. Aldebasli 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 rictulata 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 AgNO₃ 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. Arakiyaj 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 AgNO₃ 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 reiodex 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.
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 the negative impact on the production and development of crops. The situation is quite concerning in 1,125 million hectares, 76 million of which are only affected 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).

### 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)            |
| Arctocarpus heterophyllus    | Seeds                  | 10.78     | irregular                    | Jagtap and Bapat (2013)           |
| Aristolochia indica          | Leaf                   | 32–55     | spherical                    | Shammugam et al. (2016)           |
| Boerhaavia diffusa           | Whole plants           | 25        | spherical                    | Kumar et al., 2014a, 2014b, 2014c |
| Brassica rapa                | Leaves                 | 16.4      | –                            | Narayanan and Park (2014)         |
| Caulotropis giganteana       | Flower                 | 10–50     | spherical                    | Pavanai and Gayathrnamma (2015)  |
| Citrus limon                 | Limon                  | >30       | Spherical and spherical      | Pratnha et al. (2011)             |
| Chenopodium albumin          | 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 prostrata            | Leaves                 | 35–60     | Hexagons, triangles and pentagons | Rajakumar and Rahuman (2011)      |
| Eucalyptus globulus          | Leaf                   | 1.3–4.3 and 3–25 | – | Ali et al. (2015)            |
| Euphorbia myrsidoloides      | Plant                  | 7–20      | Spherical                    | Ciek et al. (2015)               |
| Engronem boninumus           | Leaf                   | 13        | Spherical                    | Kumar et al. (2015)              |
| Ficus carica                 | Leaves                 | 13        | –                            | Geetha et al. (2014)              |
| Hibiscus rosa sinensis       | Flower                 | 14        | Prism or spherical           | Philip (2010)                    |
| Hydrocotyle asiatica         | Leaf                   | 21        | spherical                    | Devi et al. (2016)               |
| Lantana camara              | Leaf                   | 33.8      | spherical                    | Manjmatha 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 Prabba (2015)         |
| Momordica charantia          | Leaf                   | 11        | Spherical                    | Ajitha et al. (2015)              |
| Nigella sativa               | Leaf                   | 15        | spherical                    | Anoopaiah et al. (2015)           |
| Olea europaea                | Seed                   | 34        | Crystalline                  | Sadeghi (2014)                   |
| Parkia roxburghii            | Leaf                   | 5–25      | poly dispersed, quasi-spherical | Paul et al. (2016)               |
| Peach gum                    | gum powder             | 23.56 ± 7.87 | spherical                 | Yang et al. (2015)               |
| Pedalium murex               | Leaf                   | 50        | spherical                    | Anandakishini 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                    | Ramachandran et al. (2015)        |
| Pterocarpus quassiodes       | Bark                   | 15.7–66.5 | 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                  | 28        | spherical                    | Moldovan et al. (2016)            |
| Solanum tuberosum            | Tubers                 | 10–12     | Crystalline and spherical    | Roy et al. (2015)                 |
| Sterculia africana           | Fruit                  | 10–20     | Spherical                    | Bogirreddy et al. (2016)          |
| Saraca indica                | Leaf                   | 23 ± 2    | spherical                    | Perugu et al. (2016)              |
| Salvadora persica            | Stem                   | 1–6       | spherical                    | Tahiri et al. (2015)              |
| Syzygium aumifolium          | 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 amni           | 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 foemina-gracem    | Seeds                  | 20–50     | spherical                    | Meena and Chouhan (2015)          |
| Ziziphora tenius             | Leaves                 | 8–40      | Spherical                    | Sadeghi and Gholamhosseinpoor (2015) |
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), monodehydroascor-
bute reductase (MDHAR), glutathione reductase (GR), proline, gly-
cine betaine and anthocyanin (Hasan et al., 2021b). Previous stud-
ies have shown that AgNPs can be used to reduce salinity and other stresses (Hasan et al., 2021a). For good crop production, sufficient soil water is essential for growth (Hasan et al., 2020a). Previous research has indicated that AgNPs can help to minimize oxidative stress and improve antioxidant defense systems in plants under heat stress conditions. Because AgNPs are able to minimize oxidative stress, they can be used to improve the performance of plants under heat stress. However, the exact molecular mechanisms underlying AgNPs stress-resilient properties are 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 to have knowledge of the toxic impacts of AgNPs 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 in 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 have to address critical aspects such as endogenous hormone traf- ficking between compartments and cells, as well as signal trans-
duction 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 sustain-
able agriculture against abiotic stresses.

Declaration of Competing Interest

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

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