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Green Synthesis and Application of Biogenic Nanomaterials as a Blueprint in Mitigation of Abiotic Stress in Crop Plants: A Conceptual Review

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Abstract

Plants being sessile, constantly encounter environmental perturbations that restrict their growth, development, and crop yield. Abiotic stressors like salt, heavy metals, drought, flooding, cold, and elevated temperatures impose heavy yield penalties yearly. The environmental fluctuations resulted in stress conditions impelled the scientific community to focus on developing stratagems to sustain the development and growth of a plant under adverse environmental conditions. Due to the constantly changing global climatic conditions, developing dependable and eco-friendly approaches to overcome the production barrier are of paramount importance. Phyto-nanotechnology is therefore considered as a viable alternative in mitigating environmental stresses with minimum negative repercussions. Conventional synthesis of nanomaterials (NMs) based on physical and chemical means became matters of concern due to their possible environmental emissions, which could have come up with detrimental effects on the ecosystem. Therefore, the synthesis of NPs from green sources has been projected as a safe and environment-friendly method of nanoparticle (NP) synthesis. The biogenic NPs derived from various organisms like bacteria, algae, fungi, and higher plants evade the use of chemical stabilizers owing to their intrinsic stability, thereby reducing toxic emissions to the environment. Here, we have elaborated the latest developments of NP biogenesis of various sizes and shapes synthesized using the reducing power of secondary metabolites in natural extracts. This chapter also discussed the recent advances in biogenic NPs in ameliorating abiotic stress response, improving plant defense mechanisms, restoring crop yield, and improving growth and development. Therefore, biogenic NPs might come up with a future roadmap for the agricultural community to improve stress-resilience and sustainable development of crop plants.

Keywords

Abiotic stress · Crop plant · Green synthesis · Nanotechnology · Nanoparticle · Tolerance

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11.1 Introduction

The term abiotic stress is used to describe the environmental factors that limit plant growth, vigor, and fertility. Stochastic climate change in every corner of the earth is paying a heavy toll on total crop production worldwide. Abiotic stressors brought on by these climatic changes include soil with increased salt and heavy metal content, changing precipitation patterns, water stress in the form of catastrophic floods or droughts, etc. (Saha et al. 2015; Khan et al. 2021a; Kumari et al. 2022). Additionally, global warming has greatly facilitated the salinization of arable land as it has accelerated evaporation, causing unpredictable soil water content due to deluge or drought and changing precipitation patterns. All of these catastrophes mentioned above have a significant adverse effect on global food security (Mafakheri et al. 2021). It is reported that, from 1990 to 2013, in two decades, there has been a 37% increase in the salinity of irrigated farmland (Qadir et al. 2014). The incessant shortfall in precipitation (meteorological drought) associated with elevated evapotranspiration demand results in an agricultural drought that occurs owing to a lack of abundant moisture needed for the natural growth of plants and the completion of their life cycle (Wahab et al. 2022). Moreover, heavy metals are continuously dribbled into the soil due to poor agricultural practices, rapid urbanization, and industrial development. Increased heavy metal contamination in agricultural lands poses major health dangers to humans and restricts crop output (Rehman et al. 2018). Several strategies and approaches have been evolved by researchers from various fields in order to offset the adverse impact of abiotic stress and aid the plant with efficient adaptations.

The eminent physicist Richard Phillips Feynman proposed the idea of nanotechnology in 1959. Prof Norio Taniguchi is credited with coining 'nanotechnology' a decade later (Ansari et al. 2020). In the epoch of agriculture, nanotechnology has emerged as a promising tool to combat abiotic stress without fettering the growth of a plant and crop productivity (Zahedi et al. 2020). Numerous physiological pathways in plants can be modified by NPs, which are also capable of altering gene expression that impedes the development of plants (Chandrika et al. 2018). Nanoparticles (NPs) have extremely small particle sizes between 0.1 and 100 nm. They are significant because of their microscopic size and unique properties compared to the bulk material. The tiny particle size attributes them to the considerably higher surface area-to-volume ratio, magnetism, electrical conductivity, chemical reactivity, physical strength, optical effects, etc., and NPs differ from those of the bulk (Boisseau and Lobaton 2011; Ansari et al. 2020). Recently, plant scientists have proceeded with a sustainable, inexpensive, eco-friendly, and non-toxic method for synthesizing NPs of biological origin compared to chemical or physical methods of NPs' synthesis (Kumari et al. 2022). Plant system responds to NPs based on a dose-dependent manner, as high NP doses confer oxidative injuries to the biomolecules resulting in cellular damage and cell death, while lower concentrations of NPs (at optimal levels) function as the key administrator of plant growth (Chandel et al. 2022). The application of NPs boosts the plant's adaptability toward adverse environmental factors like temperature stress, heavy metal toxicity, salinity, and drought that is mediated by adjusting metabolic pathways and stimulating intrinsic antioxidative defense system to curtail the Reactive Oxygen Species (ROS) generated from stress injury (Khan and Upadhyaya 2019). Following their exogenous administration, an NP influx plays a crucial role in controlling the expression of stress-responsive genes, and the protein they produce channelizes the physiological and biochemical processes leading to plant stress tolerance responses. After sensing the changing environment, the biogenic NPs act as signaling molecules that harmonize the underlying signaling networks to help the plant to reprogram the events from germination to senescence and to acquire stratagem to combat stress factors (Chakraborty et al. 2022).

Various biological sources include bacteria, viruses, actinomycetes, fungi, algae, and other parts of phanerogams, such as roots, shoots, twigs, stems, leaves, fruits, flowers, and seeds, which are widely explored for the green synthesis of NPs. The chapter presents a comprehensive synopsis of recent advances in the biosynthesis of NPs of diverse sizes and shapes, employing the reducing power of different secondary metabolites found in natural extracts. Efforts have been made to enlighten the recent updates in green nanotechnology and the role of biogenic nanoparticles (BNPs) in ameliorating plant abiotic stress by enhancing plants' innate defense mechanisms that restore crop yields and ensure agricultural sustainability.

11.2 Materials and Methods

As this chapter is concerned, the basic sources of data used to formulate the prime objective of the work are to focus the fundamental concepts like 'green synthesis', 'biogenic nanomaterials', and 'abiotic stresses' from various secondary fields or data sources. In the true sense of the term, this chapter has used secondary and tertiary data to incorporate the prime objective of this review kind of research. Firstly, the relevant keywords have been chosen, and thereafter, the significant literature survey has been made on the basis of prime objective of the study. The basic method of the literature survey was online survey from genuine sources dominated in the scientific knowledge world. The thematic sub-paragraph presentations of the concepts are as follows.

11.3 Plant Responses to Abiotic Stresses

According to an approximate estimate by Cramer et al., based on the Food and Agriculture Organization, the USA (FAO) reports, abiotic stressors affect about 96.5% of all rural lands worldwide (Cramer et al. 2011). The majority of the crops shows sensitivity toward abiotic stress. Of the sessile nature of plants and the ubiquity of abiotic stress, plants have developed plenty of tolerance mechanisms at morphological, molecular, and biochemical levels, but this endurance affects their productivity. Plants restrict their vegetative and reproductive development at the onset of stressful situations, using their energy reserves and metabolic precursors to withstand the stress's impacts (Iqbal et al. 2020).

Stress sensing, signaling, and exhaustion are three primary stages of the abiotic stress response of plants (Bhattacharya and Kundu 2020). After sensing stress, a plant can mitigate the stress-induced effects by escape or tolerance. Throughout stress acclimatization, numerous metabolites are produced, and several genes are turned on or off. Many changes have been found at the morpho-anatomical, biochemical, and molecular levels. For example, at the onset of arid conditions, the drought response mechanism is triggered whenever the plants detect a water crisis. Genes related to drought response are switched on, and their expressions result in synthesizing hormones, osmoticums, and other metabolites within the cell to alleviate the stress. Signal molecules like Ca^{2+}, inositol-1, 4, 5-triphosphate (IP3), abscisic acid (ABA), cyclic adenosine 5'-diphosphate ribose (cADPR), nitrogen oxides (NO), etc. are produced in response to drought and bring forth changes at morphological to the molecular level. Coordinated actions of these stress responders affect the host physiology and aid plants in adaptation during stress. The regulatory gene products such as calcium-dependent protein kinases (CDPKs), mitogen-activated protein kinases (MAPKs), HD-zip/bZIP, AP2/ERF, MYB, WRKY, and NAC can alter plant morphology or physiology and help plants to survive in arid conditions by altering signal transduction pathways or by acting as transcription factors to regulate the expression of downstream genes (Yang et al. 2021). An increase in (Na^+) contents in the soil limits the influx of Na^+ in the cell. Moreover, an increase in cytosolic free calcium (Ca^{2+}) concentration has also been observed (Yang et al. 2019). The sequestered action of several plant growth regulators (PGR) plays a pivotal role in combating salinity stress. Salinity also disrupts cellular ionic homeostasis. Unwanted salt accumulation in the cells results in higher production of ROS, which reduces physiological efficiencies (Hashem et al. 2016). Plants can resist heavy metal toxicity by limiting (heavy metal) absorption from the surrounding environment, extracellular and cytoplasmic complexation, and chelation (Yu et al. 2019). High-temperature stress may also add to the production of cellular ROS. The unfavorable temperature or light affects the chloroplast and decreases the functionality of the photosynthetic electron transport chain (PETC). The triplet state of chlorophyll in the photosystem II (PSII) can be induced by extra energy and transmit excitation energy to O_2, creating $_1O^2$ (Szymańska et al. 2017). Prevalence of abiotic stress causes the reduction of photosystem-I (PS-I), which may often result in the production of O_2 and then H_2O_2 (Foyer et al. 2006; Foyer and Noctor 2016). To counter oxidative stress, plants frequently garner a variety of antioxidants. There are many enzymatic antioxidants like catalases (CAT), peroxidase (POX), glutathione reductase (GR), superoxide dismutase (SOD), etc., and some nonenzymatic antioxidants present in a plant cell (Asada 1999; Saha et al. 2015). Redox shuttling across cellular compartments is an important strategy often used by plants to tolerate stress (Geigenberger and Fernie 2014). An organic acid, ascorbate, is crucial for buffering redox systems and transmitting redox equivalents across organelles (Igamberdiev and Bykova 2018). After exposure to stress, ROS is produced in mitochondria and is eventually scavenged by different antioxidant systems, either enzymatic or nonenzymatic. Alternate respiratory pathways significantly reduce ROS generation using the enzyme alternative oxidase (AOX) (Dikshit et al. 2021). The ubiquinone pool of AOXs, which present at the inner mitochondrial membrane, accompanied by ascorbate as a cofactor, reduces O_2 to H_2O and dissipates heat (Saha et al. 2016). The agro-production is inevitably compromised by the inherent in vivo stress response systems outlined above. To sustain crop yield at a higher level, the plant needs to be assisted by additional stress ameliorators that can strengthen the stress responder mechanisms to cope with changing environment with no or minimum compromisation of the crop production.

11.4 Advantages of Using Green NPs

Sustainable advancement is the development that satisfies the demands of the present and balances future generations' potential (Robert et al. 2005). Therefore, limiting the release and accumulation of detrimental chemicals in nature is crucial to create a greener and safer planet for future generations. The majority of chemical procedures used for nanoparticle production are excessively expensive and employ toxic substances that pose some environmental threats (Nath and Banerjee 2013). Techniques with green chemicals have arisen as a novel avenue in the industry of chemical substances in the past twenty years due to the limitations and drawbacks of traditional physical or chemical methods of NP production (Rónavári et al. 2018, 2021). Compared to conventional methodologies, it is more favorable to use microorganisms (bacteria/fungi) or natural materials (fruit juice, polysaccharides, and plant extracts) as they possess abundant hydrogen atoms for NPs manufacturing. Bio-NPs are more biocompatible and have less production cost (Li et al. 2011; El-Sherbiny and Salih 2018). The green synthesis processes also do not require chemical precursors, toxic solvents, or extra-reducing agents (Roy et al. 2019; Naikoo et al. 2021). Choices of an eco-friendly or green solvent, some natural extracts as a suitable reducing agent, and a non-toxic stabilizing substance are the three key prerequisites for the synthesis of nanoparticles (Jadoun et al. 2021).

NPs Characterization:

The synthesized NPs must undergo fine-tuned characterization for their mechanical, physical, and chemical properties before releasing in various fields. Physicochemical parameters of NPs, including their size, surface area, shape, structure, surface morphology, stability, mineral, and elemental decomposition, and purity of NPs can be determined using Ultraviolet–visible spectroscopy (UV–vis), X-Ray Diffraction (XRD), Electron Microscopy, Fourier Transform Infrared Spectroscopy (FTIR), Energy-Dispersive Spectroscopy (EDS), etc. (Dikshit et al. 2021).

11.5 Biogenesis of Green NPs

The biosynthetic pathway involves viruses, microbes (Table 11.1), and higher plants (Table 11.2) to create NPs that are safe, biocompatible, and eco-friendly for biomedical (Razavi et al. 2015) and agricultural applications. The biological organisms employed to produce the NPs are called the 'nano-factories' (Marchev et al. 2020). The mechanism of the production varies from one organism to another (Fariq et al. 2017). Bioproduction of NPs is classified into two categories.

11.5.1 Biosorption

The process involves the association of metal cations present in the surrounding fluid to the organism's cell wall. Stable NPs are formed due to interactions with the cell wall or peptides; the process is energy-independent (Pantidos 2014; Saravanan et al. 2021). The different polysaccharide compounds containing glycoprotein, lipopolysaccharide, etc., are naturally secreted by organisms. The molecules that typically have anionic functional groups can draw cations from polluted or aqueous solutions. In the case of bacteria, the cell wall having peptidoglycan, teichoic acids, liposaccharides, and phospholipids, specifically allow the binding of positive metal ions to negative charges. Chitin, the primary component of the fungal cell wall, also remains involved in the heavy metal complexation and subsequently synthesizes NPs (Wang et al. 2018).

11.5.2 Bioreduction

The process of bioreduction involves the synthesis of biologically stable ions by reducing metal ions chemically. This process utilizes the natural flora and its inert enzymes and can be separated from the polluted environment (Jamkhande et al. 2019). A variety of chemicals found in microbial cells and plant cells, including amides, amines, carbonyl groups, terpenoids, phenolics, flavonoids, alkaloids, proteins, pigments, and other reducing agents, may elicit NP production (Asmathunisha and Kathiresan 2013). Bacteria, fungi, and algae sometimes release compounds with a high propensity to oxidize or reduce metal ions to produce zero-valent/magnetic NPs (Saravanan et al. 2021).

11.6 Sources of Biogenic NPs

11.6.1 Virus: As a Source of NP Production

Viruses' ability to mono-disperse, their NP synthesis's stability and robustness, and chiefly genetic modification are easier on viral platforms. All these characteristics make viruses an attractive source for producing nano-conjugates containing noble metal NPs. A homogeneous shape, size, well-documented structures, and presence of diverse functional groups on their surface make the viral particle, and even often only the protein cage, suitable for regulated production of mono-dispersed NPs (Saratale et al. 2018). The Tobacco Mosaic Virus (TMV) employed for spontaneous synthesis of crystalline, uniform palladium NPs of 1–2 nm size does not require any additional reducing agent (Yang et al. 2013). TiO_2 nanowire production by infecting Escherichia coli with M13 phage has also been reported (Chen et al. 2015). The viral NPs are frequently utilized in imaging, targeted therapies, immune therapeutics, drug administration, and vaccination. However, the production of viral-mediated NPs still has significant drawbacks, including that the virus may not be expressed in a host microbe. Moreover, safety issues must be

Table 11.1 Green synthesis of NPs from microorganisms and cryptogams

Sl. no.	NP type	Name of the organism	Organism type	Shape and size	Production	References
1	Ag	*Bacillus cereus*	Bacteria	4–5 nm; spherical	Intracellular	Ganesh Babu and Gunasekaran, (2009)
2	Ag	*Corynebacterium glutamicum*		5–50 nm, irregular	Extracellular	Sneha et al. (2010)
3	Ag	*Corynebacterium glutamicum*		10–30 nm; spherical	Extracellular	Jo et al. (2016)
4	Ag	*Bacillus methylotrophicus*		10–30 nm; spherical	Extracellular	Wang et al. (2016)
5	Ag	*Phanerochaete Chrysosporium*		34–90 nm; spherical, oval	Extracellular	Saravanan et al. (2018)
6	Ag	*Weissella oryzae*		150 nm; spherical	Extra and intracellular	Singh et al. (2016a)
7	Hg	*Enterobacter sp.*		2–5 nm; spherical	Intracellular	Saratale et al. (2018)
8	CdS	*Escherichia coli*		2–5 nm; elliptical, spherical	intracellular	Saratale et al. (2018)
9	Ag/Au	*Bhargavaea indica*		Anisotropic (Ag) Floral (Au)	Extracellular	Singh et al. (2016b)
10	CdS	*Bacillus amyloliquefaciens*		3–4 nm; Hexagonal/cubic	Extracellular	Singh et al. (2011)
11	Ti	*Lactobacillus sp.*		40–60 nm; spherical	Extracellular	Prasad et al. (2007)
12	Ag	*Streptomyces sp. Strain:LK3*	Actinomycetes	5 nm; spherical	Extracellular	Karthik et al. (2014)
13	Au	*Rhodococcus sp.*		5–15 nm; Mostly spherical	Intracellular	Ahmad et al. (2003)
14	Ag/Au	*Neurospora crassa*	Fungi	Less than 100 nm quasispherical	Extra and intracellular	Castro-Longoria et al. (2011)
15	Ag	*Phomopsis liquidambaris*		18.7 nm spherical	Extracellular	Seetharaman et al. (2018)
16	Ti, Zr, ZrO2	*Fusarium oxysporum*		6–11 nm (Ti, spherical) 3–11 nm (Zr, quasispherical) 3–11 nm (ZrO_2, spherical)	Extra and intracellular	Bansal et al. (2004, 2005)
17	Ag	*Candida utilis NCIM 3469*		20–80 nm; spherical	Extracellular	Waghmare et al. (2015)
18	Ag	*Yarrowia lipolytica NCYC 789*		15 nm; spherical	Extracellular	Apte et al. (2013)
19	Ag	*Penicillium fellutanum*		5–25 nm; spherical	Extracellular	Kathiresan et al. (2009)

(continued)

Table 11.1 (continued)

Sl. no.	NP type	Name of the organism	Organism type	Shape and size	Production	References
20	Se	*Rhodotorula mucilaginosa*	Aquatic yeast	83 nm, 478 nm; spherical and rod shaped	Extra and intracellular	Ashengroph and Tozandehjani (2022)
21	Ag	*Saccharomyces cerevisiae Strain MKY3*	yeast	2–5 nm; hexagonal	Extracellular	Kowshik et al. (2002a)
22	CuO	*Macrocystis pyrifera*	Algae	5–50 nm; spherical	Extracellular	Araya-Castro et al. (2021)
23	Ag	*Macrocystis pyrifera*		50–100 nm; triangular, spherical	Extracellular	Kathiraven et al. (2015)
24	Pd	*Sargassum sp.*		5–10 nm; octahedral	Extracellular	Momeni and Nabipour (2015)
25	Au	*Chlorella vulgaris*		2–10 nm; self-assembled 3D structure	Extracellular	Annamalai and Nallamuthu (2015)
26	Ag	*Ulva compressa*		66.3 nm and 81.8 nm cuboidal	Extracellular	Minhas et al. (2018)
27	Ag	*Gracilaria corticata*		18–36 nm; spherical	Extracellular	Kumar et al. (2013)

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considered, as many viruses are pathogenic, and there is a necessity for further study before large-scale applications can be made (Chakraborty et al. 2022; Saratale et al. 2018).

11.6.2 Bacteria: As a Source of NPs

Microorganisms are frequently used in the synthesis of NPs because of their ease of cultivation, rapid reproduction rate, and ability to thrive under ambient pH, temperature, and pressure (Saravanan et al. 2021). There are numerous microorganisms that produce various inorganic components, either extracellularly or intracellularly. The bacteria and Actinomycetes can convert metal ions to metallic NPs most of the time extracellularly. Most importantly, their proficiency in generating NPs is owing to their higher rate of reproduction in a small scale of time and comparatively easier cultivation (Saratale et al. 2018; Saravanan et al. 2021). The reductase enzyme manufactured by bacteria aids in the bioreduction mechanism and serves as the basis for synthesizing all NPs by bacteria (Saravanan et al. 2021). Due to their resistance to the metal, many bacteria can thrive in environments with high metal ion concentrations. During this process, formation of extracellular complexes occurs due to metal precipitation, altered solubility, toxicity, biosorption, bioaccumulation, efflux systems, and the absence of dedicated metal transport methods (Husseiny et al. 2007; Razavi et al. 2015). The concept of green synthesis of AgNPs from bacteria is an age-old idea. Lactic acid producers like Enterococcus faecium, Lactococcus garvieae, and Pediococcus pentosaceus are used for the synthesis of AgNP in a two-stage procedure. Initially, Ag ions are accumulated inside the cell wall area through biosorption trailed by subsequent metallic reduction and, finally, the production of AgNPs (Sintubin et al. 2009). The evidence of bacterial AgNP production is also found in the Pseudomonas stutzeri

Table 11.2 Green synthesis of NPs from higher plant source

Sr. no.	NP type	Biological source	Parts used	Shape and size	References
1	Ag	Acalypha indica	*Leaf*	20–30 nm; spherical	Krishnaraj et al. (2010)
2	Ag	*Convolvulus arvensis*	Leaf	28 nm; spherical	Hamedi et al. (2017)
3	Se	*Sorghum bicolor*	Leaf	10–40 nm; mostly he–agonal	Djanaguiraman et al. (2018)
4	Cu	*Ginkgo biloba*	Leaf	15–20 nm; spherical	Nasrollahzadeh and Mohammad Sajadi (2015)
5	Fe	Gardenia jasminoides	Leaf	32 nm; rock-like	Naseem and Farrukh (2015)
6	Pb	Cocos nucifera	Leaf	47 nm; spherical	Elango and Roopan (2015)
7	Pd	Catharanthus roseus	Leaf	40 nm; spherical	Kalaiselvi et al. (2015)
8	Ag/TiO_2	Euphorbia prostrata	Leaf	10–15 nm(Ag); 81.7–84.7 nm (TiO_2); spherical	Zahir et al. (2015)
9	S	Rosmarinus officinalis	Leaf	5–80 nm; spherical	Al Banna et al. (2020)
10	Au	Euphorbia fischeriana	Root	20–60 nm; spherical	Zhang et al. (2020)
11	Ag	Chasmanthera dependens	Stem	24.53–98.38 nm; cuboidal	Aina et al. (2019)
12	Ag	Momordica charantia	Stem	27.81 nm; quasispherical	Akinsiku et al. (2018)
13	Au/Ag	*Cibotium barometz roots*	Root	6 nm and 23 nm; spherical	Wang et al. (2017)
14	Ag	Anogeissus latifolia		5.5–5.9 nm; spherical	Kora et al. (2012)
15	Ag	*Salvia leriifolia*	Root	27 nm; spherical	Baghayeri et al. (2018)
16	Ag	*Beta vulgaris*	Root	5–100 nm; spherical	Bin-Jumah et al. (2020)
17	Ag	*Berberis vulgaris*	Root	30–70 nm; spherical	Behravan et al. (2019)
18	Ag	*Zingiber officinale*	Root	10 nm; spherical	Judith Vijaya et al. (2017)
19	ZnO	*Sphagneticola trilobata*	Root	65–80 nm; irregular	Shaik et al. (2020)
20	Ag	*Jatropha curcas*	latex	20–40 nm; spherical to uneven	Bar et al. (2009)
21	Ag	*Nelumbo nucifera*	Seeds	12.9 nm; quasispherical	He et al. (2018)
22	Fe_2O_3	*Punica granatum*	Seed	25–55 nm; semispherical	Bibi et al. (2019)
23	Fe_3O_4	*Borassus flabellifer*	Seed coat	35 nm; hexagonal	Sandhya and Kalaiselvam (2020)

(continued)

Table 11.2 (continued)

Sr. no.	NP type	Biological source	Parts used	Shape and size	References
24	Zn	Artocarpus gomezianus	Fruit	Less than 20 nm; spherical	Suresh et al. (2015)
25	Au	Lycium chinense	Fruit	20–100 nm; polydispersed agglomerated particles	Chokkalingam et al. (2019)
26	ZnO	Musa acuminata	Fruit skin	30–80 nm; of various shapes	Abdullah et al. (2020)
27	Ag	Ferulago macrocarpa	Flower	14–25 nm; spherical	Azarbani and Shiravand (2020)
28	Ag	Nyctanthes arbortristis	Flower	5–20 nm; spherical to oval	Gogoi et al. (2015)
29	Ag	Spartium junceum	Flower	15–25 nm; spherical	Nasseri et al. (2019)

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AG259 strain derived from silver mines (Jorge de Souza et al. 2019). The silver NP production is effectively mediated by a Cupriavidus strain obtained from urban soil (Ameen et al. 2020). Samadi et al. isolated the same from Proteus mirabilis PTCC 1710, obtained from photographic waste. These NPs are spherical with a size range from 10 to 20 nm confirmed through TEM imaging (Samadi et al. 2009). When exposed to precursor ions, Lactobacillus bacteria, frequently found in buttermilk, aid in forming submicron-sized crystals of silver, gold, and gold–silver alloy NPs (Nair and Pradeep 2002). Escherichia fergusonii, Shigella sp., Enterobacter cloacae, Klebsiella sp., Bacillus, and Paenibacillus sp. are all common soil bacteria capable of synthesizing silver NPs with spherical to hexagonal forms with an average size range of 10–20 nm (Pourali and Yahyaei 2016). Johnston et al. showed the ability of the bacteria, Delftia acidovorans to produce pure gold NPs. He explained that delftibactin, a small non-ribosomal peptide, aids in fabricating Au-NPs (Johnston et al. 2013). Geobacillus stearothermophilus, Pseudomonas fluorescens, and Staphylococcus epidermidis are also widely used for the green production of Au-NPs, spherical within the size range between 5 and 90 nm (Shukla and Iravani 2018).

Cd Sulfide NPs can be synthesized from Rhodopseudomonas palustris when the culture is supplemented with 1 mM $CdSO_4$ solution for 72 h at 30 °C temperature (Sweeney et al. 2004; Bai et al. 2009). Further investigations have indicated that the cytoplasmic enzyme cysteine desulfhydrase is responsible for synthesizing CdS nanocrystals, and the protein thus secreted is stabilized and produces CdS NPs (Bai et al. 2009). Bacteria in heavy metal-contaminated alpine areas are used to synthesize zero-valent palladium (Pd0) NPs (Schlüter et al. 2014). The hydrogenase enzyme in Escherichia coli enables the bacteria to synthesize Pd0 NPs (Lloyd et al. 1998). The pH variations in Aeromonas hydrophila suspension culture augmented with zinc oxide triggers oxidoreductase enzymes of different pH sensitivities, leading to the form Zn-NPs (Jayaseelan et al. 2012). Due to the potential for tellurite resistance, bacteria like Escherichia sp. WYS and Raoultella sp. obtained from wastewater can produce tellurite NPs (Nguyen et al. 2019). The production of Cadmium Sulfide (CdS) nanocrystals from Rhodopseudomonas palustris, a photosynthetic bacterium, suggested the synthesis of the nanocrystals which is mediated by the intracellular enzyme, Ce S-lyase, present in the cytoplasm of the bacteria (Jayabalan et al. 2019).

11.6.3 Actinomycetes as a Source of NPs

The actinomycetes, a new source of biological NP, showed monodispersity stability and significant biocidal activity toward various pathogens (Golinska et al. 2014). The actinomycetes demand special attention over other microbial organisms because of their saprophytic behavior and the synthesis of several bioactive chemicals and extracellular enzymes (Chakraborty et al. 2022). The reductase enzyme produced by Streptomyces sp. plays a crucial role in reducing metal salts and thus plays a pivotal role in the green synthesis of Ag, Zn, and Cu NPs (Karthik et al. 2014). Genera like Thermomonospora, Nocardia, Streptomyces, and Rhodococcus have been investigated for their role in producing Au-NPs (El-Batal et al. 2015). The cytoplasmic membranes and mycelial surface are the sites of NP production in actinomycetes (Ahmad et al. 2003). The synthesis of NPs is caused by an electrostatic interaction between the negatively charged carboxylate groups found in the mycelial cell wall enzymes and positively charged silver ions (Abdeen et al. 2014).

11.6.4 Algae as a Source of NPs

The World Health Organization (WHO) affirmed that proteins found in algae could play a crucial role in medications and other nutraceutical industries. Marine ecology is mainly made up of an algal population. In algal cells, proteins, carbohydrates, minerals, and other bioactive (polyphenols, tocopherols, chlorophyll, and other pigments) function as reducing and stabilizing agents (Jacob et al. 2021). Algae may make NPs both extracellularly and intracellularly. The process of NP synthesis with algae includes the preparation of algal extract and the suspension of the metal precursor. The key factors that control nanomaterial production are ambient temperature, pH, extract concentration, precursor, time, etc. (Aboelfetoh et al. 2017). Encapsulation of Klebsormidium flaccidum with a silica gel suspension resulted in the color transformation of the chloroplast from green to purple, indicating a reduction of gold salt within the entrapped cells. Further, Transmission Electron Microscopic analysis affirmed the presence of NADPH and NADPH reductase enzyme that facilitates NP production (Sicard et al. 2010). There are reports of the synthesis of AgNPs by algae, such as Chaetomorpha linum, Padina gymnosperm, and Sargassum wightii (Kannan et al. 2013; Singh et al. 2012). After 120 h of incubation, Spirulina platensis biomass produced globular AgNPs (size range 7–16 nm) by extracellular reduction of $AgNO_3$ at 37 °C temperature and at a pH of 5.6 (Govindaraju et al. 2008). Investigations on Chlorella vulgaris extract have revealed the formation of triangular and hexagonal single-crystalline gold nanoplates (Xie et al. 2007). The reports indicate a single-step synthesis of ZnO-NPs by S. muticum (Namvar et al. 2015). The mean size of these ZnO particles is 42 nm, and the polysaccharide in the alga plays a vital role in NP synthesis (Namvar et al. 2015). Bifurcaria bifurcate a Phaeophyceae member is reported to produce CuO-NPs (Abboud et al. 2014). Arya et al. have prepared AgNPs of 40–90 nm size range from Botryococcus braunii green algae and characterized its catalytic property in synthesizing benzimidazoles (Arya et al. 2019). In a recent study with a Rhodophycean member, Portieria hornemannii has been shown to produce AgNPs (Fatima et al. 2020). Spherical nanostructures of Ag are obtained from an aqueous extract of the marine Phaeophyceae member, Macrocystis pyrifera (Araya-Castro et al. 2021).

11.6.5 Fungi as a Source of NPs

Instead of bacteria, mycosynthesis of NP can be a good alternative for stable NP synthesis. Most fungi have significant metabolites with increased biomagnification potential and straightforward downstream processing, making them simple to cultivate for effective, economic NP synthesis (Alghuthaymi et al. 2015; Singh et al. 2016c). Furthermore, fungi are more competent in uptaking and ingesting metals than bacteria and show a better tolerance, notably in terms of the property of the metal salts to bind with the cell wall of the fungal biomass and resulting in a higher yield of NPs (Castro-Longoria et al. 2011). Three plausible routes for metal NP mycosynthesis have been proposed: electron shuttle quinones, nitrate reductase activity, and sometimes the both (Alghuthaymi et al. 2015). Fungal enzymes like nitrate reductases and α-NADPH-dependent reductases from Fusarium oxysporum and Penicillium sp. play a crucial role in NP synthesis (Anil Kumar et al. 2007).

Several studies have demonstrated the application of yeasts for synthesizing metallic NPs because of their greater resistance to toxic metals (Saratale et al. 2018). MKY3, a yeast strain resistant to silver, can produce AgNPs extracellularly of 2–5 nm average size (Kowshik et al. 2002b). Bhainsa et al. have investigated the extracellular production of AgNPs from Aspergillus fumigatus, and the size ranges between 5 and 25 nm (Ahmad et al. 2002; Bhainsa and D'Souza 2006). AgNPs can also be synthesized using Pleurotus and Phoma sp., as well as an edible mushroom Volvariella volvacea (Zhou et al. 2009). Mono- and bimetallic Au or Ag NPs are effectively produced by the non-pathogenic filamentous fungus Neurospora crassa (Bansal et al. 2005). The production of ultra-small-sized copper and copper oxide (CuO) NPs is possible using the white-rot fungus Stereum hirsutum (Cuevas et al. 2015). Phomopsis liquidambar has produced AgNPs (Seetharaman et al. 2018). Ag nanocrystal synthesis has been conducted using the ligninolytic fungi Trametes trogii. In addition to the supplementation of the fungal filtrate with $AgNO_3$, the role of pH is also very crucial. The NP production is optimum at alkaline pH of 13 (Kobashigawa et al. 2019). Wanarska and Maliszewska (2019) have reported that Penicillium cyclopium may produce metallic silver NPs. The cell wall proteins and saccharides are responsible for synthesizing metallic AgNPs, even from the perished fungal biomass. FTIR mycelium analysis confirmed that the fungal mycelia's saccharides or proteins are responsible for the biomineralization of Ag. These biomolecules are present in the cell-free extract, and bioreduction occurs when silver ions are incubated with polypeptides that contain thiol groups (Wanarska and Maliszewska 2019). Besides AgNPs, there are ample fungi capable of synthesizing Au-NPs. Their higher tolerance to metals and bioaccumulation ability contribute unique advantages to the filamentous fungi over other microbes (Saravanan et al. 2021). The fungal phytopathogen, Fusarium oxysporum synthesizes spherical or hexagonal gold nanoparticles with an optimal size of 20 nm (Naimi-Shamel et al. 2019). Trichoderma viride has been employed to establish a rapid and environmentally friendly technique for synthesizing Au-NPs by synthesizing secondary metabolites and denatured proteins even at a high temperature of 100 °C. The NPs thus produced serve as biocatalysts and convert 4-nitrophenol to 4-aminophenol, a novel alternative in green bioremediation (Mishra et al. 2014). Extract of Flammulina velutipes produced by boiling tiny fragments of mushroom in distilled water and incubating for 30 min with chloroauric acid triggers the nucleation process and, ultimately, Au-NP formation indicated by the production of deep violet color (Rabeea et al. 2020). CuO-NP can be obtained from Trichoderma asperellum by supplementing the mycelia-free aqueous solution with copper nitrate. The hydryl ion of water reacts with copper to form Cu-hydroxide. The cellular enzymes and proteins convert this copper hydroxide into CuO-NPs (Saravanakumar et al., 2019). Saccharomyces cerevisiae has been employed in synthesizing MnO-NP production (Salunke et al. 2015). There are reports of the utilization of S. cerevisiae in the production of cadmium telluride quantum dots that are systemically biocompatible (Kowshik et al. 2002a).

11.6.6 Higher Plant as a Source of NPs

However, most microorganism-based NP syntheses are slower and have a moderate-to-poor yield. The NP recovery necessitates additional downstream processing. Furthermore, challenges associated with microorganism-based NP manufacturing involve complex processes such as collecting microbiological samples, isolation, proper culturing, and maintenance (Singh et al. 2016c). In the green synthesis of NPs, phytonanotechnology has opened a new arena of eco-friendly, convenient, efficient, stable, rapid, and cost-effective fabrication of NPs. Extraction of different plant parts, like roots, shoots, fruit, etc., is used for making NPs (Table 11.2). AgNP biosynthesis may be accomplished most simply by reducing Ag^+ and fusing it with biomolecules like vitamins, polysaccharides, saponins, amino acids, proteins, terpenes, phenols, alkaloids, etc. (Tolaymat et al. 2010). An intriguing work by Bar et al. demonstrated a concise green synthesis pathway for AgNPs from silver salts like $AgNO_3$ utilizing a Jatropha curcas leaf extract. Consequently, in 4 h, fairly homogeneous (10–20 nm) AgNPs have been produced (Bar et al. 2009). A study with Acalypha indica leaf extracts has shown achievable plant-based AgNP production (Krishnaraj et al. 2010). Crystalline Au-NPs of almost uniform size and shape are obtained from the dehydrated roots of Euphorbia fischeriana (Zhang et al. 2020). Both Au and Ag NPs can be derived efficiently from the pulverized dried roots of Cibotium barometz (Wang et al. 2017). Elephantopus scaber and Salvia leriifolia leaf extracts are reported to produce AgNPs (Baghayeri et al. 2018). Zn is an important micronutrient indispensable for plant growth, development, and maturation; its dearth can be detrimental (Ibrahim et al. 2016). The better agronomic output of Abelmoschus esculentus has been achieved using ZnO-NPs made from Citrus medica fruit peels (Keerthana et al. 2021). CuO-NPs can also often have plenty of effects on crop plants. Utilizing Cuscuta reflexa leaf extract, the Cu-NPs can be reduced from Cu^{+2} ions to Cu-NPs. The graphene oxide/MnO_2 nanocomposites are used to immobilize the Cu-NPs (Naghdi et al. 2018). Pt and Pd are both expensive and highly valued in the production of NP (Jadoun et al. 2021). An aqueous solution of $[Pd(OAc)_2]$ is stirred for one hour at 60 °C temperature along with a methanolic leaf extract of Catharanthus roseus. The decoction comprises a mixture of eight compounds containing -OH groups responsible for reducing the metal ion to metallic NPs. A change in the color of the solution indicated the formation of Pd-NPs (Kalaiselvi et al. 2015). Due to their unique morphologies and surface chemistry, titanium oxide NPs is of considerable interest (Jadoun et al. 2021). Annona squamosa leaf extract and an aqueous solution of TiO_2 salt when combined together at room temperature produce spherical TiO_2-NPs (Roopan et al. 2012). Cucurbita pepo seed extract is used for green synthesis of TiO_2-NPs of uniform spherical size (Abisharani et al. 2019). Resource distribution, availability and acquisition of nutrients, biogeochemical processes, interactions between microbes and roots, and spatiotemporal heterogeneity coupled with soil complexes are all aided by the structural dynamics and morphology of the roots (Erktan et al. 2018). Hence, roots are considered a very important site for the green synthesis of NPs. AgNP synthesis has been reported from root extracts from Beta vulgaris (Bin-Jumah et al. 2020), Borassus aethiopum (Danbature et al. 2020), Zingiber officinale (Judith Vijaya et al. 2017), etc. There are great uses of the plant stem and shoot extract as a source of different NP productions. There are reports of the extraction of AgNPs from the decoction of the stem of Coleus aromaticus (Vanaja et al. 2013), Salvadora persica (Tahir et al. 2015), and Momordica charantia (Akinsiku et al. 2018). The stem extracts of Leucas lavandulifolia are used to generate spherical selenium (Se) NPs. Se-NPs are synthesized when Se ions are reduced in the presence of diverse phytoconstituents, such as polyphenols and water-soluble heterocyclic compounds (Kirupagaran et al. 2016). The floral parts of a plant are always rich in pigments like chlorophyll, xanthophyll, carotenoids, anthocyanins, etc., along with other bioactive compounds like phenols and flavonoids add to the color and aroma of the flower. The floral extracts of Ferulago macrocarpa (Azarbani and Shiravand 2020) and Cuscuta reflexa (Shaik et al. 2020) are widely used in AgNP production.

11.7 Role of Green NPs in Abiotic Stress Response

11.7.1 Salt Stress

Salt stress is an ominous factor that jeopardizes growth and crop yield worldwide. Soil salinization has resulted from the gradual worsening of environmental conditions, climate change, and poor irrigation practices, affecting approximately 20% of the earth's irrigated agricultural lands. Salinity adversely affects the molecular, physiological, and biochemical processes, limiting quantitative and qualitative food production. The onset of salt stress leads to immediate osmotic and ionic imbalances that elevate the build-up of ROS and toxic ions with a concomitant oxidative burst instigating lipid peroxidation, distortion of biomolecules, and ultimately resulting in cell death.

Biogenic NPs are considered an eco-friendly and low-cost method that can be used as an antidote to increasing salt stress resilience in crop plants. Recent findings revealed that seed priming with ZnO-NPs (5 and 10 mg/L), synthesized from *Agathosma betulina,* significantly improved shoot lengths, fresh weights, anatomical structure, lowered Na^+/K^+ ratio (1.53 and 0.58) mending element distribution, reduced biomolecules damage by declining oxidative stress in Sorghum bicolor under the treatment of 400 mM NaCl salt (Rakgotho et al. 2022). Bio-synthesized gold NPs (Au-NPs) recuperated the wheat plant (*Triticum aestivum*) from salt stress by modifying the K^+/Na^+ ratio, nitrogen assimilation, chlorophyll content, stomatal dynamism, controlled reactive oxygen/nitrogen species accumulation (Wahid et al. 2022). Se-NPs can be synthesized from selenium dioxide as a precursor molecule using a reducing/capping agent derived from the aqueous flower extract of *Allamanda cathartica*. They exhibited restored germination percentage (31%), shoot length (92%), root length (78%), and total chlorophyll content (49%) in *Brassica campestris* (TS-36 variety) under 200 mM NaCl stress (Sarkar and Kalita 2022a). In another study, they have shown that biosynthesized Se-NPs (30 mg L^{-1}) from fresh grape aqueous extract enhanced SOD, CAT, Ascorbate peroxidase (APX), and POX activities by 41.20%, 64.10%, 63.06%, and 70.43%, respectively, phenolic and flavonoid content by 98.88% and 86.90%, respectively, and 61.89% free radical scavenging activity in mustard plants (TS-36 variety) grown hydroponically under 200 mMNaCl (Sarkar and Kalita 2022b). In addition to that, the significant increase in the seed germination percentage (39.66%), root and shoot length (75% and 60.64%, respectively), dry and fresh weight per plant (41.2% and 22.11%, respectively), water content percentage (1.02%), chlorophyll content (81.92%), carbohydrate content (24.65%), and protein content (79.14%) has also been observed. Hydroponically applied bio-Se-NPs produced using a leaf extract of barley plants drastically compensate for the adverse effect of salt stress (100 mM) in *Hordeum vulgare* that is correlated with declined malondialdehyde (MDA) level, significant accumulation of phenolic content, metabolic adjustment, and rising shoot dry weight (Habibi and Aleyasin 2020). Application of 120 mg L-1 Silica NPs (Si-NPs), as a foliar spray, obtained from rice husk has been investigated in three rice varieties (Pokkali, KDML105, and IR29) under salinity and observed stress alleviation by inducing net photosynthesis rate, lowering H_2O_2 content, increased activity of peroxidase, catalase, and ascorbate peroxidase (Larkunthod et al. 2022). Under a two-year field trial study with saline irrigation water, the application of Green nanosilica (GNS) as a foliar spray obtained from plant biowaste boosted fruit output, decreased leaf Na^+ concentrations, increased nutrient absorption, antioxidant, and osmoregulatory (such as proline and total sugar content), and imparted salt avoidance in *Musa* sp. (Ding et al. 2022). In maize plants, the restorative effect from salt stress is confirmed through the application of biologically synthesized copper NPs (Cu-NPs, 100 mg kg^{-1}) from *Klebsiella pneumonia* (strain NST2). The green Cu-NPs, when mixed with saline soil, recovered root and shoot length, fresh weight, and dry weight, neutralized the lipid peroxidation and oxidative damage by stimulating antioxidants and demoting the cellular

ROSlevels and Na + and Cl- content when compared to control (Noman et al. 2021). The biogenesis of titanium dioxide NPs (TiO_2-NPs, 40 mg/L) using the extract of *Buddleja asiatica* leaf has shown a substantial increase in dry weight, plant height, fresh weight, shoot, and root length, RWC, leaf count per plant, chlorophyll a and b, and total chlorophyll contents, thus proved to be favorable to augment agronomic growth and physiological attributes of two wheat varieties (Faisalabad-08 and NARC-11) under salinity (Mustafa et al. 2021). The salt tolerance potential was scored by applying a foliar spray of zinc oxide nanoparticles (ZnO-NPs) derived from *Moringa* leaf extract onto *Vicia faba* (cultivars: Giza-716 and Sakha 4). The results revealed significant enhancement in various plant growth parameters, photosynthetic pigments, proline and phenol levels, ions (Na^+, K^+, Ca^{2+}, and Zn^{2+}), pigments (chlorophyll and carotenoids), as well as enzyme activities (polyphenol oxidase—PPO, ascorbate peroxidase—APX, and catalase—CAT), when compared to control plants (Ragab et al. 2022; Mogazy and Hanafy 2022). The ameliorative role of 100 mg L^{-1} green Se-NPs synthesized by *Bacillus cereus* TAH examined in wheat seed germination under a salt-exposed environment has resulted in 25, 25, 39.4, and 11% enrichment of germination percent, mean germination time, vigor index, and germination rate index, respectively (Ghazi et al. 2022).The Se-NPs' treatment under high Ec values of 14 ds m^{-1} in a gnotobiotic sand system divulged marked increases by 22.8, 24.9, 19.2, and 20% of the shoot and root length, fresh and dry weight, respectively, compared to controls. Biogenic Se-NPs and ZnO-NPs out of an aqueous extract of the leaves of *Moringa* mitigated the negative effect of salinity on the growth, yield, antioxidant activity, and phytoconstituents accumulation in garlic plants (Sids 40) which have been associated with increased total phenolic and flavonoids compounds, enhanced H_2O_2 scavenging potential of antioxidants (El-Saber 2021). The positive effect of silver nanoparticles (AgNPs), fabricated using *Rosmarinus officinalis,* markedly elevated cellular levels of photosynthetic pigments, accumulated soluble sugars, proline, and soluble proteins, decreased H_2O_2 and malondialdehyde content with a concomitant increase in enzymatic and nonenzymatic antioxidants, thus bestowed with salt tolerance on *Linum usitatissimum* (Khalofah et al. 2021). Furthermore, exposure to various concentrations of AgNPs on *Triticum aestivum* and *Lathyrus sativus* stimulated fresh and dry weight, root and shoot length, seed sprouting, soluble sugar, total chlorophyll content, proline content, and antioxidant enzymes during salinity (Abasi et al. 2022). A comparative study has been done between green zinc NPs (Zn-GNPs) synthesized using the leaf extract of *Sorghum bicolor* L. and chemically synthesized Zn-CNPs produced by the co-precipitation method. It has been found that Zn-GNPs (0.3%) more efficiently triggered the salt tolerance response on the growth of Okra (*Abelmoschus esculentus*) under saline environment and resulted in significant enhancement of the fresh and dry weight of shoot and root, chlorophyll contents, and antioxidant activity (Zafar et al. 2021).

11.7.2 Drought Stress

Temperature dynamics, global warming, rainfall inconsistencies, shifts in monsoon patterns, and light intensity has resulted in inescapable stresses to the plant kingdom. Drought stress begins to manifest without prior indication, thereby impeding plant growth and crop yield and damaging plant morphological, physiological, biochemical, and molecular attributes, leading to reduced photosynthetic ability and energy production (Seleiman et al. 2021). Low photosynthesis is immediately followed by stomatal closure, membrane damage, disrupted various enzymes activities, impaired ATP synthesis, altered water relations, and reduced water retention capacity in plants that ultimately end up with the plant striving for more water and consequently aggravating permanent wilting (Farooq et al. 2012).

Drought adaptation through green NPs' applications became the most promising and environment-friendly strategy to compensate for the damaging effect of water stress through maintaining cellular homeostasis and is considered of great potential in agriculture. Recent studies explored the healing attributes of many Biogenic NPs to relieve the dangerous effects of drought conditions. For example, foliar spray of green ZnO-NPs (25 and 50 mg/L) on tomato plants significantly increased shoot and root biomass, shoot dry weight (2–2.5-fold), ascorbic acid, and free phenols, raised the activity of SOD, APX, and CAT, decreased MDA and H_2O_2 contents, thereby minimizing drought-induced oxidative stress in response to severe drought conditions (25%) compared to ZnO-NPs-untreated plants (El-Zohri et al. 2021). Green synthesized ZnO-NP-II (ZnO-NP-II; size = 75 nm) from *Lawsonia inermis* extract showed greater healing efficacy and post-stress recovery potential over chemical method (ZnO-NP-I; size = 100 nm) to mitigate the hazards brought on by water stress in rice (*Oryza sativa*) Kopilee cultivar seedlings under the hydroponic system (Shome et al. 2022). They have reached this conclusion by measuring the increase in fresh and dry mass, root and shoot length and decrease in H_2O_2 and O^2 contents due to augmentation of CAT, GPX, SOD, and GR activity. Moreover, foliar application of 100 ppm green ZnOx NPs synthesized using the leaf extract of *Camellia sennesis* encouraged the defensive system of *Coriander sativum* that helps them to withstand water stress by enhancing chlorophyll and proline content, CAT, SOD, and APX activity, declining MDA content, thus, restore agronomic attributes for high crop productivity (Khan et al. 2021b). The plants' defensive condition demonstrated the positive benefits of biosynthesizing Se-NPs produced from the buds of *Allium sativum* (Ikram et al. 2020). Application of 30 mg/L green Se-NPs exogenously on drought-tolerant (V1) and drought-susceptible (V2) wheat varieties at the trifoliate stage stemmed marked induction in plant height, shoot and root length, fresh weight, dry weight, leaf area, number, and length under water-deficient conditions. Investigations have been done with biogenic iron oxide NPs (Fe_3O_2-NPs) produced from ginger (*Zingiber officinale*) and cumin (*Cuminum cyminum*) seed extracts on wheat plants (Noor et al. 2022). The effectiveness of ginger-derived Fe_3O_2-NPs (0.6 mM) and cumin seed-derived Fe_3O_2-NPs (1.2 mM) in improving drought resistance in wheat plants has been demonstrated. These NPs have been found to stimulate germination and increase survival percentage. They also promote the accumulation of chlorophyll a, b, and carotenoids, as well as soluble sugars, proline content, and total iron content in both roots and shoots. Additionally, these NPs enhance the activity of SOD, peroxidase, and ascorbate peroxidase (APX) enzymes, while reducing lipid peroxidation and electrolyte leakage under drought stress, in comparison to the non-treated control group. Furthermore, 50 mg/L of biosynthesized magnetite (Fe_3O_4) NPs from leaves of *Polyalthia longifolia* when applied on two different varieties of *Trigonella foenum-graecum* (Afg 1 and Afg 3) contributed to better plant growth parameters, enhanced production of photosynthetic pigments, and overall photosynthetic performance, thus lessening drought stress response (Bisht et al. 2022). On the other hand, Fe_3O_4-NPs (both capped as well as bare) synthesized from a marine alga *Chaetomorpha antennina* (green algae) employed as nano-fertilizer on drought-stressed *Setaria italica* plants exhibited enhancement of overall plant growth (Sreelakshmi et al. 2021). They also suggested that iron uptaken by the plants facilitated the accumulation of photoassimilates, iron, chlorophyll, and soluble sugar content, thus confirming its ameliorative role in overcoming drought stress. Additionally, nanopriming and foliar application of phyto-synthesized FeONPs (100 ppm) using leaf extract of *Prosopis cineraria* at the seedling development stage (20 days) and tillering stage (30 days) of wheat (*Triticum aestivum*) plant encouragingly influenced all the morphological and yield attributes in the wheat crop and bestowed with drought resilience under rain-fed conditions in comparison to control (Singh et al. 2022).

11.7.3 Heavy Metal Stress

Heavy metals (HM), for instance, Manganese (Mn), Nickel (Ni), Iron (Fe), Copper (Cu), Cadmium (Cd), Cobalt (Co), Mercury (Hg) Zinc (Zn), and arsenic (As) are conventional elements which have been accumulated air, water, and soil through several anthropogenic activities, industrial trash. Although some of these metals function as micronutrients during normal plant growth and physiological processes, their surplus accrual in the environment compels the plant to reach a high risk (Ghori et al. 2019). Under prolonged toxic exposure in HM, plants experienced excessive oxidative stress for the excessive production of ROS that eventually showed detrimental effects on cellular components such as membranes, nucleic acids, proteins, pigments, and homeostasis between ROS and enzymatic or nonenzymatic antioxidants.

Several studies have been made to understand the fundamental mechanism of action of cheap and environmentally sound NPs that have been attributed as the savior for alleviating the toxic effect of HM in crop plants (Mathur et al. 2022; García-Ovando et al. 2022). AgNPs and CuO-NPs derived from the leaf extract of *Catharanthus roseus* have been utilized to wipe out chromium and cadmium, thus improving the present circumstances of metalloid pollution in soil and water environments (Verma and Bharadvaja 2022). Disk-shaped biogenic hydroxyapatite (HAP) nanoparticles (NPs), synthesized using *Aspergillus niger* fermentation broth, has applied to the habitat of mung-bean seedlings under Cd stress. HAP NPs' exposure in the presence of Cd stress demonstrated a drastic reduction of Cd content in the stem, a remarkable decline in H_2O_2 and MDA content, and a significant increase of SOD, CAT, and APX, thereby eliminating the oxidative stress due to Cd stress by blocking Cd translocation in mung-bean seedlings and restore seedling growth (Shen et al. 2022). External application of magnesium oxide nanoparticles (MgO-NPs) synthesized from an *Enterobacter* sp. strain RTN2 drastically improved rice plant resilience by minimizing the ill-effect of As-contaminated soil. Biogenic MgO-NPs (200 mg kg^{-1}) have resulted in significant induction of the plant biomass, antioxidant enzymatic contents, and reduction in ROS, As uptake, and translocation compared to the control treatment. It is also suggested to be used to formulate a nano-fertilizer for the sustainable production of rice (Ahmed et al. 2021). Synthesis of silicon nanoparticles (Bio-Si-NPs) has been performed using potassium silica fluoride substrate and the identified *Aspergillus tubingensis* AM11 strain and employed in 5.0 mmol/L concentration as a foliar spray on *Phaseolus vulgaris* to investigate its shielding effect under heavy metalscontaminated saline soil (El-Saadony et al. 2021). They observed notable convalescence in terms of plant growth and production, pigment contents (chlorophylls and carotenoids), rate of transpiration and net photosynthesis, stomatal conductance, relative water content (RWC), total soluble sugars, free proline contents, N, P, K, Ca^{2+}, K^+/Na^+ contents, and antioxidative enzymes' activities (peroxidase, CAT, APX, SOD). The remarkable decline in electrolyte leakage, MDA, H_2O_2, $O_2^{\bullet-}$, Na^+, Pb, Cd, and Ni contents in leaves and pods of *Phaseolus vulgaris* compared to control has also been discerned. The easing effect of green copper NPs (Cu-NPs) derived from a native strain of *Klebsiella pneumoniae* to relieve oxidative stress in wheat plants due to chromium (Cr) stress has been studied (Noman et al. 2020a, b). Soil fortification with bio-Cu-NPs (25 and 50 mg kg^{-1}) significantly enhances plant growth and biomass, along with cellular antioxidants, whereas it reduced the ROS levels and translocation of Cr from soil to plant body by immobilizing the Cr in the soil when compared to control. Additionally, they have examined the healing role of the Cu-NPs (100 mg kg^{-1}), synthesized from a bacterium *Shigella flexneri* SNT22 on wheat plants under cadmium (Cd) toxicity and recorded similar responses like increased plant length (44.4%), shoot dry weight (28.26%), nitrogen contents (41.60%), phosphorus contents (58.79%), P, N, Ca^{2+}, K^+, Ca^{2+}/Na^+, and K^+/Na^+ contents with a concomitant reduction in Na^+ content and acropetal Cd translocation (49.62%) in a wheat plant (Noman et al. 2020b). Further reports indicated that treatment with Bio-FeO-NPs (100 mg/L) produced from leaf extract of *Adiantum lunulatum* facilitated the rice plants to withstand the adverse effect owing to As stress by increasing percentage of seed germination, the growth, and vigor of the seedlings, reducing uptake and translocation of As, a decline in oxidative stress (Chatterjee et al. 2021). Combined application of the *Bacillus* sp. strain ZH16 with biogenic MoNPs considerably decreased plants' arsenic (As) translocation by 30.3% in As-contaminated agricultural soils. Furthermore, Bio-MoNPs exhibited biocompatibility with bacterial strain and stimulated indole-3-acetic acid synthesis, ACC deaminase activity, and phosphate solubilization, promoting the morphological parameters, nutrients content, and ionic balance of wheat plants under As-spiked conditions (Ahmed et al. 2022).

11.7.4 Other Abiotic Factors

Besides the salinity, drought, and heavy metal stress, green synthesized NPs have also acted as protective shields for many crop plants against many other abiotic factors. There are reports of application of 75 mg/l biosynthesized AgNPs generated using plant extract of *Moringa oleifera* on wheat plants at the trifoliate stage under heat stress in a range of 35–40 °C for three h/day for about three days (Iqbal et al. 2019). This investigation evidenced marked increase in plant root length (5.4%), shoot length (26.1%), root number (7.5%), plant fresh weight (2%), plant dry weight (0.60%), leaf area (33.8%), leaf number (4.8%), fresh leaf weight (0.15%), and leaf dry weight (0.18%) as compared over control under heat stress. Foliar application and soil irrigation of biogenic NPs, obtained from green tea (20 mg per plant), have been used as an enticing substitute that prohibits toxicity and injury brought on by oxidative stress as evidenced by fall in APX and CAT levels, rise in R-S-nitrosothiols (RSNOs), phenolic and total flavonoid content in lettuce (*Lactuca sativa*) (Kohatsu et al. 2021). Growth, physiology, antioxidant defense, and yield parameters' studies revealed that foliar administration of 25 mg/L biogenic AgNPs has been proved effective as a model anti-ozonant ethylene urea (EDU) against a phytotoxic pollutant, Tropospheric ozone (O_3) in two wheat cultivars (HD-2967 & DBW-17) at both vegetative and reproductive stages, and assigned as a promising ozone protectant agent (Kannaujia et al. 2022).

11.8 Challenges of Using Biogenic NPs

Recent advancement in the environmentally friendly synthesis of NPs and their possible applications in agricultural fields have become a major promising area with an endeavor to sustain crop yield and productivity worldwide. Enormous evidence has demonstrated their economic, non-toxic, and eco-friendly nature, compared to that of the conventional method of chemical synthesis of NPs. However, some challenges encumber the global synthesis of biogenic NPs and subsequent utilization. For instance, reactants (plant extract, microorganism inoculum, chemical compounds as oxidizing and reducing agents) and physical parameters of the reaction with reduced reaction time need to be optimized elaborately for controlling the shape, size, yield, and stability of the NPs. The physicochemical properties of NPs seek more characterization studies to guarantee quality assurance. Prioritization is required to scale up the commercial green synthesis of the NPs. Additional toxicological dissections are necessitated for the sprawling use of biogenic NPs on plants and animals. Moreover, large-scale production of biocompatible NPs from endemic flora is gaining huge encumbrance due to the interruption of raw material collection. In the coming future, it is essential to address all these limitations with momentous care to come up with a wide spectrum of utilizing biogenic NPs in various fields.

11.9 Conclusion

Global climate change, with steady temperature rise, water and land resources' scarcity due to anthropogenic activity, non-rhythmic seasonal

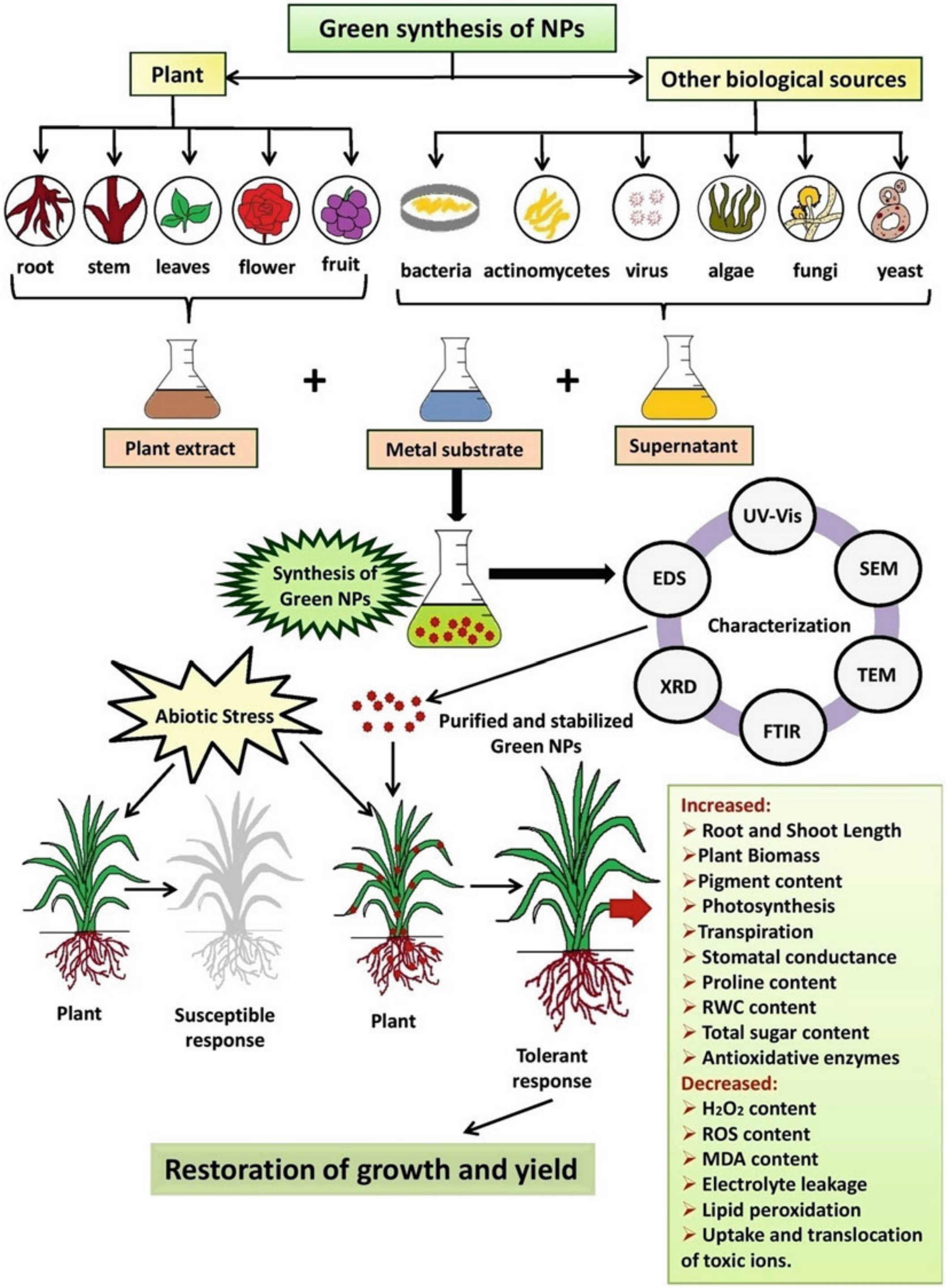

Fig. 11.1 Pictorial illustration of green synthesis of NPs from various biological sources and its amelioration impact on plants under abiotic stress conditions

oscillations, and other abiotic stressors challenge universal agricultural methods. This challenge necessitates the development of several sustainable and eco-friendly solutions to minimize the detrimental effect of stressors on field crops. Green nanotechnology is therefore considered as a viable alternative to traditional ones for alleviating abiotic stresses with minimum toxic environmental emissions. Green NP synthesis has evolved as a safe, low-cost, and environmentally friendly technique of NP synthesis. These bioinspired noble metals, due to their intrinsic stability, inertness, ease of accessibility, and environmentally benign nature, can be employed as reliable administrators of stress mitigation in crop plants, lowering the negative impacts of abiotic stressors. This chapter explored the potential applications of a wide range of biological sources as a precursor of biogenic NPs (Fig. 11.1). This chapter has also explored possible applications of the potential usages of a wide range of biological sources as a precursor of biogenic NPs (Fig. 11.1). In addition to that the most recent evidence exhibiting the positive impact of biogenic NPs restoring growth and production of crop plants in response to diverse abiotic stressors (Fig. 11.1) has been elaborated with citation of recent research trends. We also emphasized how the application of green synthesized NPs is accompanied by stress tolerance by acting as key players governing the underneath physiological and biochemical attributes like seedling germination, growth parameters, mineral uptake, photosynthetic efficiency, antioxidant defense system, accumulation of compatible solutes and ROS, membrane damage, etc. However, there are certain limitations of the green synthesis of NPs that should be dealt with the future researchers. Moreover, in the era of nanotechnology, the biogenesis of NPs can be served as an imperative development that demands global application in the upcoming years, encouraging the future agricultural community to improve the stress-resilience and sustainability of crop plants.

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