Review Article

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Potential applications of biogenic selenium nanoparticles in alleviating biotic and abiotic stresses in plants: A comprehensive insight on the mechanistic approach and future perspectives

https://doi.org/10.1515/gps-2021-0047
received May 27, 2021; accepted July 09, 2021

Abstract: In the present era, due to the increasing incidence of environmental stresses worldwide, the developmental growth and production of agriculture crops may be restrained. Selenium nanoparticles (SeNPs) have precedence over other nanoparticles because of the significant role of selenium in activating the defense system of plants. In addition to beneficial microorganisms, the use of biogenic SeNPs is known as an environmentally friendly and ecologically biocompatible approach to enhance crop production by alleviating biotic and abiotic stresses. This review provides the latest development in the green synthesis of SeNPs by using the results of plant secondary metabolites in the biogenesis of nanoparticles of different shapes and sizes with unique morphologies. Unfortunately, green synthesized SeNPs failed to achieve significant attention in the agriculture sector. However, research studies were performed to explore the application potential of plant-based SeNPs in alleviating drought, salinity, heavy metal, heat stresses, and bacterial and fungal diseases in plants. This review also explains the mechanistic actions that the biogenic SeNPs acquire to alleviate biotic and abiotic stresses in plants. In this review article, the future research that needs to use plant-mediated SeNPs under the conditions of abiotic and biotic stresses are also highlighted.

Keywords: biosynthesis, SeNPs, environmental stresses, reactive oxygen species

Abbreviations

Se	selenium
NPs	nanoparticles
SeNPs	selenium nanoparticles
ROS	reactive oxygen species
POD	peroxidase
SOD	superoxide dismutase
GPX	guaiacol peroxidase
CAT	catalase
POX	proline oxidase
APX	ascorbate peroxidase
MDA	malondialdehyde
GSH	glutathione
PCs	polyphenolic compounds
GR	glutathione reductase
ABA	abscisic acid
IAA	indole-3-acetic acid

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RWC	relative water content
SDW	shoot dry weight
RDW	root dry weight
CARs	carotenoids
Chl	chlorophyll
ATP	adenosine triphosphate
DPPH	2,2-diphenyl-1-picrylhydrazyl
ABTS	2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)

1 Introduction

Climate change is likely to exert a detrimental impact on productive resources and ultimately on agriculture production in developing countries worldwide [1]. Changes in climatic conditions have already affected the production of staple crops such as rice, wheat, and barley, and future climate change threatens to exacerbate this [2–4]. The major climatic stresses that exert pressure on agriculture are increasing temperature in arable areas, extreme events such as heat waves, drought, and accumulation of heavy metals, and various biotic stresses such as fungal and bacterial maladies [5,6]. Additionally, these devastating plant stresses could affect both crop quantity and quality worldwide. Moreover, these biotic and abiotic stresses have drastic effects on crop yields and cause the accumulation of various heavy metals in plant tissues that make them unsuitable for animals and humans and cause severe health issues [3]. In addition, biotic and abiotic stresses adversely affect the development and growth of agricultural and horticultural crops [7]. The environmental stress causes pollen sterility, produces shriveled seeds, disturbed photosynthetic and respiratory enzymes, and leads to the overproduction of reactive oxygen species (ROS) that pose detrimental effects on the cell membrane, lipids metabolisms, protein contents, and ultimately induces oxidative stress in plant species [2,4]. Surprisingly, in the recent past, selenium has been found to counteract the devastating effects of diverse environmental stressors, such as heavy metals, drought, salinity, high temperature, and bacterial and fungal pathogens [8]. Selenium (Se) is an essential trace element that is deliberately necessary for the normal regular functioning of the plants, which protects them from the detrimental effects of climatic stresses [9]. Moreover, selenium is a beneficial element for plants. It acts as an anti-oxidative agent at low concentrations and adequate doses; however, at high concentrations, it behaves like a pro-oxidant [9–12]. In addition, selenium at low concentrations can play a magnificent role in maintaining the structure and fluidity of the plastid membrane and chloroplast [13]. Besides, selenium at low concentrations can cause a decrease in metal genotoxicity, decrease electrolyte leakage, and improved cell integrity [14–16]. Furthermore, selenium can also play a significant role in the improvement of photosynthesis [17], delay senescence [18], and increase plant yield at low concentrations [19] In addition, selenium at low concentration regulated the production and quenching of ROS in plants.

Unfortunately, selenium at high concentrations in plant species can cause overproduction of ROS and induce oxidative stress [20]. In addition to the positive effects of selenium on plants, some studies also demonstrated that elevated levels of selenium could provoke oxidative stress and hence damage plant bodies [21]. Furthermore, in previous studies, it has been reported that selenium at high concentrations significantly causes a reduction in the leaf area, decreases plant biomass, and decreases seed formation, and its high exposure also disrupted the structural organization of plant cells [22–24]. Considering the above-described high-concentration selenium problems, nanobiotechnology has emerged as a 21st-century science that exhibits potential application in agriculture [25]. Selenium nanoparticles (SeNPs) have attracted considerable attention globally because of their significant potential application in alleviating biotic and abiotic stresses in plants [4,26]. Additionally, biogenic SeNPs have excellent potential application in the alleviation of drought stress [4], heat stress [27], salinity stress [28], and heavy metal stress [29]. Moreover, biogenic SeNPs have emerged as a strong antimicrobial agent to treat bacterial and fungal maladies in various crops [26,30].

Various chemical and physical methodologies have been explored as well as the use of several physical approaches and chemical compounds to prepare SeNPs. Unfortunately, these methodologies are very expensive and in the association of disastrous chemical residues with NPs, limit the applications of SeNPs in agriculture sectors to mitigate biotic and abiotic maladies. Surprisingly, various studies have been explored in the biogenic formation of SeNPs resulting in a nontoxic and environmentally friendly synthesis approach. The use of several extracts of medicinal plants in the green synthesis of SeNPs is cost-effective, simple, environmentally friendly, and a nontoxic approach as compared to other techniques by utilizing microorganisms such as bacteria and fungi. Several extracts of plant species have been utilized effectively and conveniently for the green synthesis of SeNPs [31–35]. Surprisingly, the plant extract contains alkaloids, tannin, cinnamic acid, sesquiterpenes, phenolic acid, monoterpenes, and secondary metabolites, which exhibit the ability of both potential stabilizing and reducing agents in the synthesis of biocompatible SeNPs [36]. This review paper focuses on the green synthesis approaches with special emphasis on the plant extract-mediated synthetic approaches, unique morphological importance, and varied application potential of biogenic SeNPs in agriculture. Furthermore, this review article also provides important information on mechanistic approaches that biogenic SeNPs adopt to mitigate biotic and abiotic stresses in agricultural crops. A detailed overview of the study is given in Scheme 1.

2 Different techniques for SeNPs synthesis

SeNPs can be synthesized by using various biological, physical, and chemical methods (Figure 1). Various techniques have been employed for the characterization of plant-mediated SeNPs. SeNPs can be characterized using UV-Visible (UV-Vis) spectroscopy, Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), and X-ray diffraction (XRD). The FTIR spectrum confirms the presence of various functional groups in the plant extract, which may possibly influence the

Scheme 1: Schematic overview of the study representing the efficacy of biogenic SeNPs to combat biotic and abiotic stresses (the inner circle) and their mechanistic actions (outer circle).

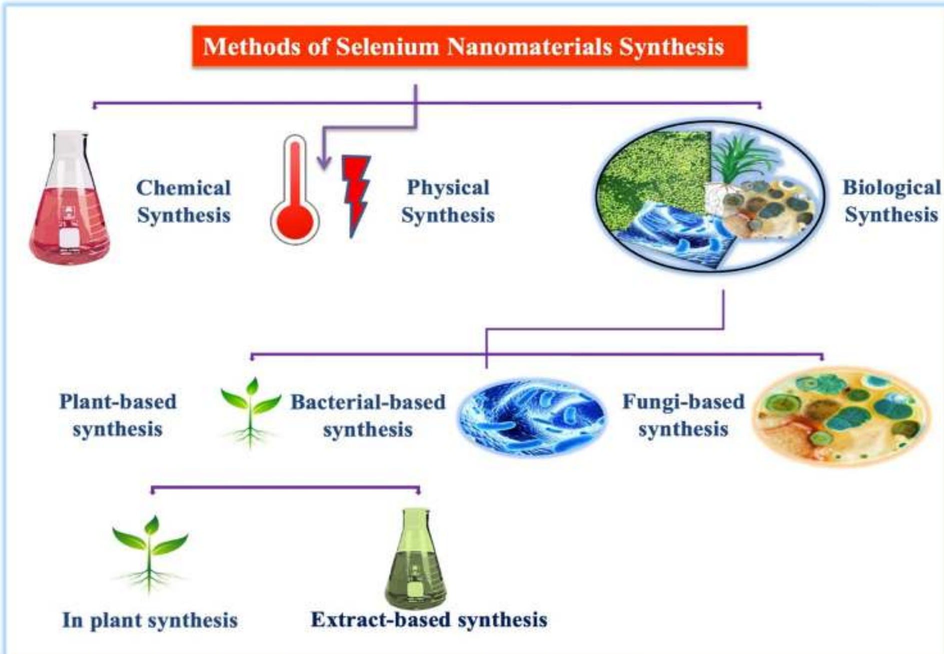

Figure 1: Various routes for the fabrication of SeNPs (adapted from ref. [11]).

reduction process and stabilization of nanoparticles [37]. Various research studies demonstrated the physical-method-based synthesis of SeNPs such as ultrasound-assisted synthesis and laser ablation strategy. The chemical-based fabrication of SeNPs requires several toxic chemical compounds to reduce sodium selenite salt into SeNPs [34,38,39]. Additionally, the previous studies explored the use of vitamin C solution in the presence of various polysaccharides for the reduction of selenious acid into SeNPs of various sizes with unique morphologies. Moreover, polysaccharides were used as a stabilizing agent, while vitamin C was used as a strong reducing agent [40]. Additionally, several other published studies reported the use of extracellular polymeric substances and quercetin gallic acids to synthesize SeNPs [39,41]. Another study reported the fabrication of SeNPs by reacting the ionic liquid with sodium selenosulfate in the presence of polyvinyl alcohol as a strong reducing agent [42] The other chemical and physical strategies for the fabrication of SeNPs also include temperature, sound, and light, which require reducing the sodium selenite salt in SeNPs [43]. Unfortunately, chemical- and physical-method-based synthesis of nanomaterial has been disfavored recently because of biosafety, cost ineffectiveness, and toxicological concerns [34].

To mitigate these emerging issues, the biogenic synthesis of SeNPs has been recommended by various researchers as the best conventional alternative strategy. The biogenic synthesis of SeNPs involves the synthesis of living organisms such as bacteria, fungi, and plants to reduce the sodium selenite salt to SeNPs [11,40], such as fungus *Mariannaea* for the biogenesis of SeNPs [40]. Moreover, it is reported that several kinds of bacterial strains such as *Klebsiella pneumoniae* [44] and *Pseudomonas aeruginosa* have been used for the biosynthesis of SeNPs [39,45] Among various biogenic synthesis methodologies, the plant-mediated biological synthesis of SeNPs has preference over conventional methods because of their outstanding antioxidant potential [32]. The green synthesis of SeNPs is an economic approach and environmentally friendly technique that requires the natural reducing, capping, and stabilizing agents (Figure 1). Although plant-based green synthesis of SeNPs started at the beginning of the twentieth century, various plants have been reported for their action capability to stabilize and reduce the SeNPs [46]. Moreover, some studies reported the use of *Aloe vera* plant extract for the biogenesis of SeNPs. It was revealed that the leaf extract of this plant has various natural stabilizers and reductants like vitamins, flavonoids, polysaccharides, organic acids, and phenolic compounds that are involved in the reduction of selenium salts into SeNPs. These substances play a remarkable role in the biogenic synthesis and stabilization of SeNPs [11,46]. Additionally, some other studies reported that biogenic synthesis of the SeNPs involves reduction, chelation, and stabilization of NPs with the various functional groups present in the plant extract such as secondary metabolites. The reduction of sodium selenite salt takes place by chemical oxidation–reduction chemical reactions that involves the selenium salt and plants' secondary metabolites. Various chemical reactions result in the formation of molecules and ions. Furthermore, during the phase of chelation, these molecules and ions coordinate with each other and result in the bonding of molecules and ions to the metals ions. However, the various functional groups present in the plant secondary metabolites cover the metallic core and help the green synthesis of nanoparticles with various shapes and sizes to remain stable for a longer time period. Thus, the clear and exact mechanism of the green synthesis of NPs by using plant extract materials still needs to be explored [47].

However, by keeping in mind the immense significance of biogenic synthesis of SeNPs, several laboratories have explored using the plant parts like shoot, stem, bark, root, and flowers. Other studies also explored the photosynthesis of SeNPs by using raisin extract as stabilizing, capping, and reducing agent [48] (Figure 1). Similarly, some other studies also reported the biogenesis of SeNPs in the presence of *Allium sativum* cloves extract [4]. In addition, various other researchers have been working to explore the biogenesis of SeNPs through the leaf extracts of *Spermacoce hispida* [49], *Zingiber officinale* fruit extract [50], *Citrus limon* fruit extract [51], *Prunus amygdalus* leaves extract [46], *Citrus reticulata* leaves [52], *Prunus amygdalus* leaves extract [53], and *Carica papaya* latex [54] (Table 1). The biocompatibility, stability, and versatility of SeNPs also depend upon the plant extract used for its effective concentration and physicochemical parameters representing various surface plasmon resonance bands [31].

Various physicochemical parameters such as the concentration of sodium selenite salt or selenium salt, pH, and temperature synergistically influence the enzymatic catalysis, reaction kinetics, protein confirmation, and molecular mechanisms that are responsible for affecting the shape, size, and biochemical corona of NPs. Moreover, physicochemical parameters also act as an important toolbox to carve the NPs of different functions [55]. The optimization of the abovementioned parameters varies from plant to plant species and depends on the concentration and the presence of plant metabolites. Furthermore, physicochemical parameters play a magnificent role in controlling the agglomeration, size, production, and shape of the nanoparticles. In addition, temperature plays a remarkable role in providing activation energy required to start a chemical reaction and it also favors the molecular collision that increases the potential of the reactants to convert into their products. Furthermore, various pH conditions have a significant influence on reaction kinetics and molecular dynamics. pH is also responsible to increase or decrease

Table 1: SeNPs synthesis by using various plant and bacterial species and their applications

Name of species	Extract type	Methods of characterization	Activity	Dimensions (nm)	Shape of NPs	Ref.
Allium sativum L.	Bud extract	UV-Vis, SEM, EDX, FTIR	Alleviation of drought stress	50–150	Spherical	[4]
Hordeum vulgare L.	Leaves	UV-Vis, SEM, EDX, FTIR	Alleviation of salinity stress	50–200	Spherical	[101]
Lactobacillus casei	Cell biomass	–	Alleviation of heat stress	50–200	–	[110]
Bacillus megaterium	Cell biomass	DLS, TEM, XRD	Antifungal potential	29.72–74.36	Spherical	[57]
Lactobacillus acidophilus ML14	Cell biomass	UV-Vis, TEM, XRD, DLS	Alleviation of drought and heat stress	46	Spherical	[58]
Aloe vera	Leaves	UV-Vis, TEM, XRD, DLS, FT-IR	Antifungal and antibacterial	50	Spherical	[59]
Pelargonium zonale	Leaves	FT-IR, UV-Vis, TEM, DLS	Antibacterial and antifungal activity	40–60	Spherical	[60]
Azolla pinnata	Leaves	UV-Vis, SEM, XRD, EDAX, FT-IR, XPS	Antimicrobial and antioxidant activity	36.45	Spherical	[61]
Zingiber officinale	Fruit	UV-Vis, SEM, XRD, AFM, FT-IR, TEM, EDAX	Antimicrobial and antioxidant activity	100–150	Spherical	[50]

the hydrogen ion concentration in the reaction mixture. In addition, the ratio of salt concentration acts in a synergistic fashion along with the pH and temperature [45,46,56].

However, the synthesis of plant-mediated SeNPs at the industrial level requires unique optimization of protocol to prepare nanomaterials of various sizes and unique morphologies. The shape, size, and biochemical corona of plant-mediated SeNPs determine their agriculture application potential, which depends on the reaction conditions. However, the biogenesis of plant-extract-assisted nanoparticles at the industrial level is still in the development process as it requires a wide understanding of the mechanism of reduction of selenium salts by utilizing secondary metabolites of plants and the synergistic response of various vital physicochemical parameters.

3 Efficacy of plant-based SeNPs to alleviate drought stress

Drought stress is one of the most critical agriculture problems that cause a reduction in crop yield and productivity worldwide [62]. Because of the continuous increase in the temperature and level of carbon dioxide in the atmosphere, the climate of the globe is drastically changing. This change in climate causes the uneven distribution of rainfall, leading to drought stress [63]. Under drought conditions, the physiologically available water to the plants is decreased and causes the death of the plant [64]. Drought disrupts the antioxidant function of plants by producing ROS and altering the function of stress-induced genes and proteins that cause modifications in the physiological, biochemical, and morphological characters of plants [65]. These changes cause variations in the quality and quantity of crops production by accumulating heavy metals into plant bodies and making them unhealthy for the consumption of living organisms giving rise to food insecurity at the global level [66–69].

The major cereal crops that are grown and consumed throughout the world are rice, wheat, and maize. These three crops account for more than 55% of food requirements. In these major crops, drought stress reduces the plant height, biomass, germination of seed, the establishment of seedling, and yield of grains [4,70]. It also makes the pollens sterile, gives rise to shriveled seeds, damages the respiratory and photosynthetic enzymes, and also causes the production of imprudent ROS that give rise to damaging effects on membrane lipids, DNA, protein, and carbohydrate contents, and ultimately impose oxidative stress in plants [4,71].

To alleviate such hazards caused by drought stress, various techniques are used such as genetic engineering, hybridization, locus mapping, etc. Unfortunately, all these modern and innovative techniques also have some adverse effects [2,72–74]. These techniques require proper technical experts and are not cost-effective. According to the current situation and demands, we require reasonable, cost-effective, and practical techniques that can overcome these adversities. Nanotechnology has gained a prominent role due to its various applications in the agriculture sector [75]. It has multiple applications in climate change, agriculture, and food security, and this technology is also utilized to create many tools such as nanofertilizers, nanopesticides, nanoherbicides, and nanomachines for controlled implementation of agrochemicals [76–79]. Surprisingly, selenium that emerged as an essential micronutrient that promotes plants' agronomic parameters, physiology, biochemistry, delay senescence, and maintained water status of plants exposed to the water-deficit condition [80–82]. In addition, it is reported that selenium induces stress resistance by enhancing the anti-oxidative potential of plant species. However, these beneficial impacts were observed at low doses of selenium concentrations since high selenium exposure could be toxic to plants [81,83]. Unfortunately, selenium at high concentrations interferes with sulfur metabolism and selenium-containing amino acids displaces sulfur-containing amino acids and proteins synthesized by them, which alters the morphology, physiology, and biochemistry of plants [17,84].

In this scenario, plant-based SeNPs provide an advantage to synthesize nanoparticles of remarkable biocompatible nature without additional capping and stabilizing agents. In addition, plant-based SeNPs because of their nontoxic nature can be one of the alternative approaches to control the drought stress problems in plants [4,11]. Unfortunately, there are only a few research studies exploring the role of plant-based SeNPs against drought stress. However, a recently published research study reported that *Allium sativum* L. gloves extract-assisted SeNPs were synthesized to study their impact on wheat plants under drought stress. Surprisingly, it was revealed that plant-mediated SeNPs at 30 mg/L concentration have improved the agronomic attributes (root length, shoot length, number of leaves per plant, and plant height) of wheat plants under drought stress [4]. This is because plant-based SeNPs increase the enzymatic activities under abiotic stresses. Moreover, biogenic SeNPs improved the antioxidant defensive system of plants under abiotic stress [85]. In addition, it is also reported that plant-mediated SeNPs significantly involve in quenching ROS and malondialdehyde (MDA) levels [27]. It is also reported that the excellent antioxidant potential of plant-based SeNPs against ROS is because of enhanced antioxidant enzymes including superoxide dismutase (SOD), guaiacol peroxidase (GPX), catalase (CAT), and proline oxidase (POX) [28,50,86]. Furthermore, in another study, it was also reported that selenium and silicon dioxide nanoparticles have improved photosynthetic pigments as compared to other treatments in strawberry fruits under drought stress. They also demonstrated that Se/SiO_2 nanoparticles at 100 mg/L concentration also increased membrane stability index, relative water content (RWC), and water use efficacy. Additionally, it was also reported that selenium and silicon dioxide nanoparticles increased drought tolerance by enhancing the potential of antioxidant enzymes including SOD, GPX, APX, and CAT and decreased lipids peroxidation and hydrogen peroxide contents [28,87–89]. In addition, in a recently published study, it is reported that SeNPs are remarkably effective in the mitigation of devastating effects of drought stress in pomegranate plants. It is also reported that 10 nm SeNPs improved the growth and yield of pomegranates plants under drought stress. Furthermore, SeNPs enhance photosynthetic pigments activity, better nutrient status, antioxidant activity, and total phenolic contents under drought stress. This is because foliar application alleviated many of the deleterious effects of drought stress in pomegranates fruits and leaves by reducing stress-induced lipid peroxidation and hydrogen peroxide contents by enhancing the potential of antioxidant enzymes [89]. By considering the excellent biocompatibility of green synthesized SeNPs, it is not extremely hard to believe that green synthesized SeNPs can be a systematic and promising vehicle in the future to mitigate drought stress problems in agricultural crops.

4 Efficacy of plant-based SeNPs to alleviate salinity stress

Climate has a significant environmental impact on the biological ecosystem. Climate change has caused notable serious changes by enhancing abiotic and biotic stresses, leading to dramatic changes in ecosystem processes [90]. The decline in freshwater resources is becoming a severe alarming crisis, especially in semi-arid and arid regions worldwide. Saline water may decrease plant developmental growth as it contains various ions and salts that can cause many devastating disorders in morpho-physiological and biochemical attributes of agricultural crops resulting in a reduction in growth, yield, and productivity of plants owing to an increase of chloride ions and sodium concentration [91,92]. Additionally, excessive accumulation of sodium and chloride ion concentration decreases the uptake of various essential nutrients (Ca, K, P, and Fe). Therefore, plants suffer from nutritional imbalance, membrane damage, enzymatic inhibition, and low crop yield and quality [92–94]. Salinity-induced oxidative stress is also associated with the overproduction of ROS that causes vital damage to proteins, membrane lipids, nucleic acids, and photosynthetic pigments [95,96]. Furthermore, salinity stress also decreases the photosynthetic activity of plants, which is related to the stomatal constraints like the closure of stomata and non-stomatal constraints including chlorophyll ultrastructure damage, chlorophyll degradation, and degradation of enzymatic and membrane proteins in the photosynthetic aperture [97]. Significant efforts have been made to increase plant salt tolerance by using exogenous substances like brassinolide, nitric acid, melatonin, silicon, polyamine, and selenium [98,99]. Among these, selenium is an essential micronutrient for both humans and animals and also seems to be a beneficial element for most plants suffering from biotic and abiotic stresses [85]. Selenium is also reported as a cofactor for glutathione peroxidase and important constituents of several selenoproteins and enzymes in the plants and human body and gives protection from environmental stresses and oxidative damages [11,100].

Additionally, selenium at low concentrations can regulate the water status of plants, act as an antioxidant, and cause mitigation of devastating oxidative damage posed by environmental stresses. Furthermore, selenium application at a low dose might stimulate developmental growth, enhance proline contents, protect cell membrane against lipid peroxidation, and increase crop productivity under stress conditions [101]. Surprisingly, selenium at a minimal dose is highly effective against salinity stress by maintaining the turgor pressure, accumulation of total sugars, amino acids, potential antioxidant enzymes, and improves the transpiration rate. Selenium also decreases chloride ion contents, ROS species, and membrane damage. In addition, selenium can cause decreases in sodium-ion accumulation and increases potassium ion accumulation, thus reducing the detrimental effects of salt stress on plants [102]. Unfortunately, high doses of selenium could lead to various abnormalities in plants resulting in low photosynthesis, overproduction of ROS, disturbed opening and closing of stomata, oxidative damage, and selenosis [103]. In this scenario, plant-mediated SeNPs have been introduced as highly stable nanoelement for use in various nutritional supplements for applications in medical therapy and their use as selenium fertilizer to enhance crop productivity and food security [104]. Furthermore, another study reported that barley (*Hordeum vulgare* L.) plant leaves-extract-mediated SeNPs were used to mitigate the devastating effects of salinity stress. They demonstrated that plant-mediated SeNPs showed remarkable bioavailability and less toxicity for enhancing agricultural productivity and crop yield under salinity stress [105].

In addition, researchers also demonstrated that plant-mediated SeNPs increased the leaf phenolic contents under extreme salinity stress. The excellent application potential of plant-mediated SeNPs against salinity stress might be due to their ability to reduce the content of hydrogen peroxide (H_2O_2) and malondialdehyde in the plants [28]. Unfortunately, there is minimal research exploring the impact of plant-mediated SeNPs against salinity stress. However, in another study, it was revealed that SeNPs at 50 mg/L concentration could mitigate the adverse effects of salinity stress in coriander plants by enhancing their vegetative growth and total chlorophyll contents. The notable potential of SeNPs against salinity stress is due to the fact that selenium increases the potassium ion concentration and binding of sodium to the cell wall and avoids sodium toxicity in the cytoplasm [87,88]. Another study demonstrated that SeNPs showed remarkable application potential against salinity stress in strawberry plants. They showed that salinity stress has devastating effects on the developmental growth, biochemistry, and physiological attributes of strawberry plants. Surprisingly, SeNPs increased growth performance and yield parameters of strawberry plants exposed to salinity stress. They also demonstrated that SeNPs activate the antioxidant defense system of plants to overcome the unsuitable effects of ROS [88] (Figure 2). Some studies also revealed that SeNPs at suitable doses can be effective to alleviate the effects of salinity stress by improving photosynthetic performance, ion homeostasis, salicylic acid (important signaling defensive hormone), and antioxidant machinery [106]. Unfortunately, the exact mechanism for the SeNPs to alleviate salt stress is still unknown and must be further explored. Keeping in mind the magnificent biocompatibility, bioavailability, and less toxicity of plant-based SeNPs, it is not difficult to accept that plant-mediated SeNPs can be a promising tool to mitigate the disastrous effects of salinity stress in plants. Additionally, plant-based SeNPs, due to their remarkable

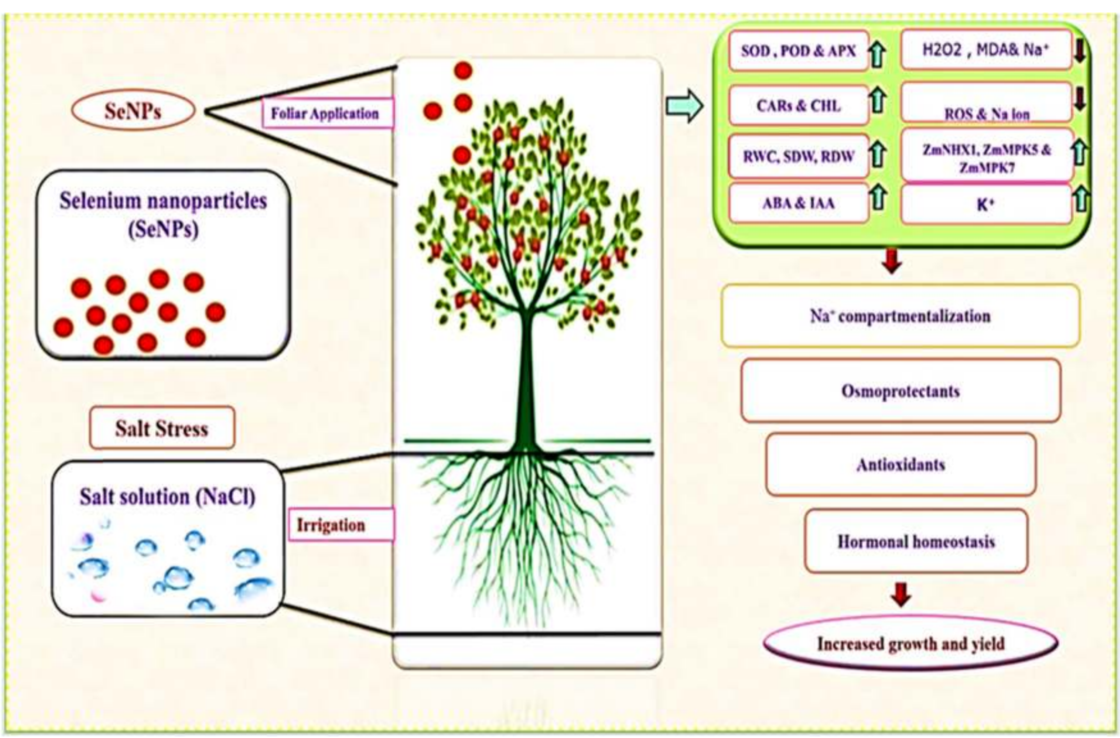

Figure 2: Schematic diagram demonstrating the possible mechanisms of salinity stress tolerance in plants induced by plant-mediated SeNPs. Under salinity stress, foliar applications of plant-mediated SeNPs on plants enhance growth and yield parameters by (i) protecting photosynthetic pigments to improve photosynthetic capacity; (ii) maintaining ROS homeostasis by activating antioxidant defense system-related enzymes, e.g., SOD, POD, and APX; (iii) upregulating the expression of salt stress-related genes ZmMPK5, ZmMPK7, and ZmCPK11; (iv) enhancing abscisic acid (ABA) and indole-3 acetic acid (IAA) concentrations for improvement of root biomass and continuation of the proper osmotic status of the cell; (v) inducing salt stress resistance by promoting RWC, shoot dry weight (SDW), and root dry weight (RDW), carotenoids (CARs), and chlorophyll (CHL) contents, (vi) increasing the uptake of potassium ions (K^+) and causing compartmentalization of sodium ions (Na^+) [28]. Upward arrows show an increase and the downward arrows indicate a decrease in the respective content.

eco-friendly nature, can be used as nanofertilizer and nano-biofortifying agents in agriculture fields to mitigate abiotic stresses.

5 Efficacy of plant-based SeNPs to alleviate heat stress

Agriculture is considered the backbone of most developing countries. Unfortunately, various abiotic stresses such as extreme salinity, water deficit, and high temperature adversely affect the developmental growth, yield, and productivity of agricultural crops such as wheat, barley, etc. [107,108]. Among these abiotic stresses, the extreme temperature is a primary concern for crop production worldwide. Furthermore, heat stress is responsible for growth retardation by decreasing cell elongation and cell division resulting in a reduction in plant growth, root diameter, number of roots, plant height, and productivity of crops [109]. In addition, photosynthesis is vital among the plant cellular functioning that is extremely subjected to heat stress. Moreover, the primary sites of targets of heat stress are photosystem II; Rubisco, cytochrome b559, and plastoquinone are also affected resulting in the reduction of crop yield and production [110]. To minimize the devastating effects of heat stress and other biotic stresses in agricultural crops, various techniques have been employed such as genetic engineering, hybridization, quantitative trait locus mapping, molecular-assisted selection are commonly in use [111]. Unfortunately, these approaches have some problems in operation, technical expertise, and are of high cost.

In this scenario, there is an inevitable need for affordable, practical, and feasible approaches to minimize these shortcomings. Surprisingly, nanobiotechnology has emerged as an ebullient sphere of science having applications in the agriculture and medical sectors [112]. Selenium is a natural element in soil and is considered a vital nutrient for plants, humans, and animals. The foliar biofortification of various crops has been introduced as an alternative approach for enhancing selenium intake in the human diet [113]. Additionally, there is much evidence confirming the benefits of a low dose of selenium on the developmental growth, physiology, and biochemistry of agricultural crops such as wheat, soybean, and mung bean under biotic and abiotic stresses such as heat stress [112]. Unfortunately, high doses of selenium negatively impacted the plant growth, physiological, and biochemical profiling of crops resulting in less production. In this scenario, SeNPs have emerged as a remarkable biofortifying agent alternative to various fertilizers. Unfortunately, there is limited research exploring the potential plant-mediated SeNPs to combat high-temperature stress in plants. However, some studies showed the potential application of green synthesized SeNPs against heat stress in various crops. In a recently published research study, it was reported that SeNPs were fabricated by using *Lactobacillus casei* bacterial strain having the dimension between 50 and 100 nm. They demonstrated that biogenic SeNPs ameliorate the growth, physiological, and biochemical profiling of two sensitive chrysanthemum cultivars (i.e., sensual and Francofone) under heat stress (up to 41.6°C) [114]. Moreover, they also revealed that biogenic SeNPs up to 150 mg/L improved heat resistance in chrysanthemum by enhancing the potential of antioxidant enzymes including peroxidase and catalase and decreasing electrolyte leakage and polyphenol oxidase at a concentration of 200 mg/L [114]. The application potential of biogenic SeNPs may be due to some reasons such as SeNPs promote the antioxidant defense system of plants and also maintained the integrity of the thylakoid membrane under abiotic stresses [115]. In addition, another study reported that SeNPs alleviate the adverse effects of heat stress in grain sorghum. They revealed that foliar applications of 10 mg/L SeNPs during the booting stage of sorghum under heat stress enhanced the anti-oxidative defense system by ameliorating the antioxidant enzyme action potential. Additionally, SeNPs decreased the concentration of ROS (Figure 3). Moreover, SeNPs alleviate the high-temperature stress by increasing pollen germination, seed set percent, seed yield, photosynthetic rate, and decreased oxidative stress [27]. In another study, it was also reported that SeNPs at low concentration induced alterations in salicylic acid, jasmonic acid, phytohormones, and ethylene and their signaling provoke modifications in metabolism, as well as expression of defensive genes [116]. Additionally, another study also demonstrated that SeNPs significantly modified the expression pattern of the heat shock factor HSFA4A, thereby triggering specific signaling pathways and altering metabolism. Moreover, unfortunately, there is very limited research available exploring the mechanism of action of biogenic SeNPs to mitigate heat stress in plants [117].

To increase our understanding of the mechanistic action of SeNPs in plants, the detailed SeNPs metabolism has to be studied. This endeavor will require detailed physiological and biochemical profiling as well as the study of vital genes involved in the transport, uptake, and assimilation of biogenic SeNPs. Keeping in mind the notable importance of biogenic SeNPs, it is not extremely hard to believe that plant-mediated SeNPs owing to

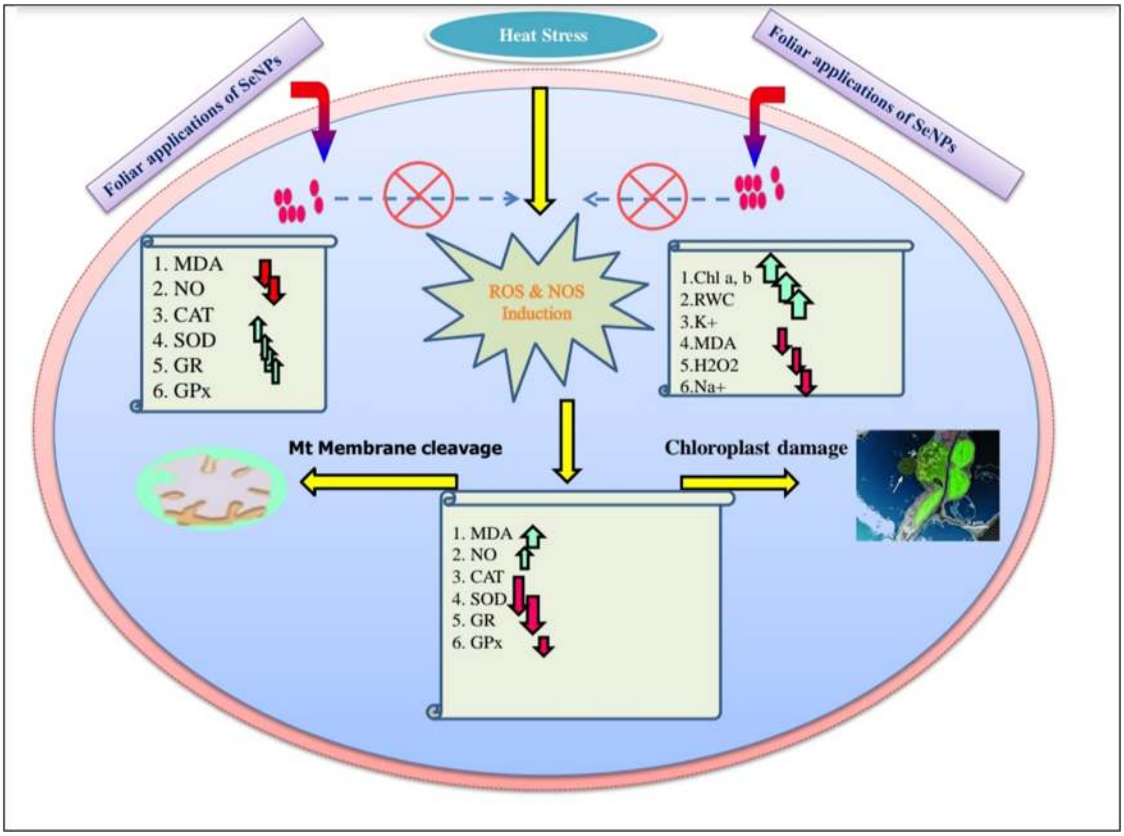

Figure 3: Possible heat tolerance mechanism in plants exposed to biogenic SeNPs. Upward arrows show an increase and downward arrows show a decrease in the respective content.

their excellent biocompatibility, antioxidant potential, nontoxicity, bioavailability, and stability may be an excellent futuristic candidate to mitigate the devastating effects of heat stress in agricultural crops.

6 Efficacy of plant-based SeNPs to combat plant microbes

Agriculture provides the basis for food production on a global scale. The world population will increase to approximately eight billion people in 2025 and almost nine billion people in 2050, this will require increasing agriculture production to feed a growing world population. Sustainable agriculture tries to maintain or improve the quality of food without damaging the environment; unfortunately, sessile organism's plants are susceptible to various biotic stresses and contact with other living microorganisms [118].

Unfortunately, food security is threatened by less crop production due to attacks of various pathogens including fungus and bacterial strains. It is estimated that around one-third of crop production is lost annually because of devastating plant diseases worldwide [119]. To control the devastating effects of plant pathogens, various chemicals are available that have been designed to control various plant diseases by killing or inhibiting the growth of diseases caused by pathogens [120]. In addition, some chemicals such as bactericides, fungicides, and nematicides are commonly used to control the disastrous effects of these pathogenic maladies in agricultural crops. Unfortunately, these chemicals, as mentioned earlier, cause environmental deterioration, and have nontarget effects on animals and plants. Furthermore, overuse of these harmful chemicals is also responsible for resistance development in pathogens, affecting photosynthetic processes and various hazards to humans and other living creatures [121].

In this scenario, nanobiotechnology can be employed to improve the developmental growth, yield, and productivity of plants under devastating biotic stresses [57]. Among various nanoparticles, plant-mediated SeNPs have emerged as strong antimicrobial and biofortifying agents to mitigate the disastrous effects of plant pathogenic species. In addition, SeNPs prepared from biogenic sources have been shown to have excellent biocompatibility, less toxicity, biodegradability, and bioavailability and ecofriendly nature [46,122]. Furthermore, biogenic SeNPs have shown remarkable antimicrobial potential against various pathogenic microorganisms such as bacteria and fungi [46,123]. Furthermore, in another study, biogenic SeNPs showed magnificent antimicrobial potential against bacteria and fungus species. They demonstrated that biogenic SeNPs showed excellent antifungal potential against *Rhizoctonia solani* pathogen [57]. Surprisingly, they revealed that biosynthesized SeNPs caused a significant increase in chlorophyll and carotenoid contents of diseased plants as compared to control plants. Moreover, foliar applications of SeNPs induce responses regarding the total phenolic contents and total protein contents as compared to healthy plants. Furthermore, biogenic SeNPs act as promoters and enhance the antioxidant defense system of plants, leading to the improvement of plant resistance under biotic stress [89,124,125]. Another study reported that biosynthesized SeNPs suppress growth, spore viability, sporulation, and proliferation of *Sclerospora graminicola*. *Sclerospora graminicola* is a plant pathogen infecting pearl millet and maize crops [126]. However, another study showed that biogenic SeNPs have remarkable antimicrobial potential against an *Alternaria solani*, which caused early blight disease on potatoes. They revealed that biogenic SeNPs exert gradual inhibiting effects on the growth of the abovementioned pathogenic fungus [124]. In addition, another study reported that biomolecules-assisted SeNPs also inhibit the growth of *Aspergillus flavus*, a pathogenic and saprotrophic fungus with a cosmopolitan distribution. It is well known for its devastating effects on cereal grains, tree nuts, and legumes.

The exact mechanism of action of SeNPs is still unidentified. However, it is reported that SeNPs generate ROS that damage the pathogen cell wall, cell membrane integrity, and inhibit the activity of ATP synthetase [26,127]. Additionally, another study reported that *Pelargonium zonale* leaf-extract-mediated SeNPs showed magnificent potential against *Penicillium digitatum*. It is also reported that *Penicillium digitatum* is a plant pathogen that commonly causes post-harvest fungal diseases of citrus known as green mold [46]. Surprisingly, plant-based SeNPs significantly inhibit the growth of this fungus species in *in vitro* conditions. Because of excellent biocompatibility, plant-mediated SeNPs may be effective and economical alternatives for treating fungal plant pathogens. The possible antimicrobial potential of biogenic SeNPs may be because of some reasons such as the production of ROS or through damaging of the plasma membrane functioning and integrity. Another possible mechanism of biogenic SeNPs is to inhibit the microorganism growth by damaging the cell wall and then attaching to the cell membrane and altering the deoxyribonucleic acid replication, protein synthesis

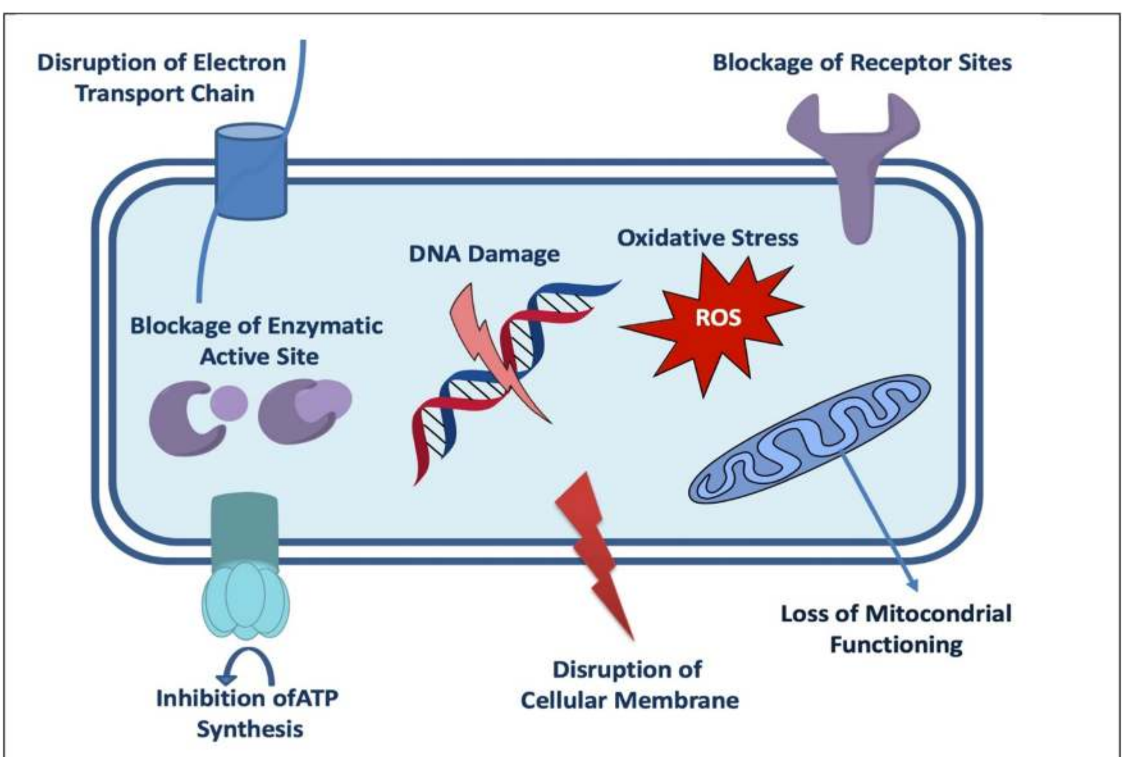

Figure 4: Possible antimicrobial mechanism of plant-mediated SeNPs (adopted from ref. [11]).

process, and food metabolism cycle; then ultimately binds to the thiol groups present in the membrane proteins and cause cell death of microorganisms [26,30,128] (Figure 4). In another study, it is also reported that SeNPs act as an insecticidal agent against various insects. The insecticidal potential of SeNPs may be attributed to the reaction of NPs with phosphorus-containing compounds such as DNA and RNA, which denatured these organelles. Moreover, on the other hand, SeNPs may cause the inactivation of essential enzymes and caused cell death [129,130].

By considering the excellent antimicrobial potential of biosynthesized SeNPs *in vitro* and *in vivo*, it is not exceedingly difficult to believe that plant extract-mediated SeNPs can be an excellent nanoproduct to kill these devastating plant pathogens. Unfortunately, there is limited research that has been explored on plant-based SeNPs in the agricultural sectors. So, it is essential need to explore the application potential of green synthesized SeNPs against devastating plant pathogens to protect the plants.

7 Antioxidant potential of biogenic SeNPs

Antioxidants are substances that can prevent the cells or tissues from disastrous effects of free radicals and unstable molecules that the organism's body produces during environmental stresses. They are also sometimes known as free radical scavengers. Additionally, antioxidants are natural or synthetic substances that prevent or delay cell damage caused by several oxidants such as nitrogen oxide species, reactive nitrogen species, and other unstable molecules. Antioxidants maintained oxidative stress and played a great potential in the treatment of radicals induced by various devastating effects during biotic and abiotic stresses [131]. However, synthetic and natural antioxidants have less effectiveness because of their deficient absorption, difficulty to cross the selectively permeable membranes, and their degradation resulting in limited bioavailability. In addition, plant-extract-assisted nanoparticles (NPs) have important antioxidant functional groups with excellent stability, biocompatibility, and control liberation with superior antioxidant profiling [50]. The plant-based SeNPs are prominent for their remarkable antioxidant activity, as reported in earlier studies, where plant-assisted SeNPs are well explored to efficiently scavenge the DPPH (2,2-diphenyl-1-picrylhydrazyl) and ABTS (2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) free radicals in less time [132,133]. The significant antioxidant activity of plant-mediated SeNPs might be due to an elevated level of Se that plays an essential role in an upturn of selenoenzymes like GPX that protect the plants from damaging effects of free radicals [134–136]. Furthermore, another study demonstrated that *Aloe vera* and *Mucuna pruriens* mediated SeNPs showed significant anti-oxidative potential in the protection of cells from the damaging effects of ROS. The significant antioxidant activity of plant-mediated SeNPs might be due to selenium. It is a vital component of essential selenoproteins that protects the cells from oxidative damage [50,59]. Additionally, another study reported that ginger-root-extract-mediated SeNPs showed marvelous antioxidant potential. The results revealed that plant-mediated SeNPs are scavengers or free radical inhibitors acting possibly as primary antioxidants. The antioxidant application potential of plant-mediated SeNPs could be attributed to the various functional groups bound to SeNPs, originating from ginger root extract involved in the capping, stabilizing, and bioreduction of SeNPs [39,137,138]. Furthermore, another study reported that exogenous applications of plant-mediated SeNPs induced the expression of antioxidant-defense-related genes and eventually increased the potential of SOD, ascorbate peroxidase, and catalase in maize and strawberry plants ultimately leading to enhance the resistance against biotic and abiotic stresses [139]. However, another study reported that exogenous foliar application of SeNPs improved the salt stress in strawberry plants by reducing hydrogen peroxide and lipid peroxidation contents by enhancing the potential of antioxidant enzymes such as peroxidase and SOD [28]. By considering the magnificent antioxidant potential of plant-based SeNPs *in vitro* and *in vivo*, it is not difficult to accept that biogenic SeNPs may be an excellent futuristic candidate to mitigate the adverse effects of harmful ROS produced under environmental stresses in plants.

8 Potential applications of biogenic SeNPs in the removal of life-threatening heavy metals from contaminated agriculture ecosystem

In the last few decades, because of the speedy development of industries, more and more lethal heavy metals are been released into the ecosystem. Agriculture land in many parts of the world is moderately or slightly contaminated by heavy metal toxicity such as Zn, Ni, Cr, Cd, As, and Pb [140]. Unfortunately, this could lead to long-term exposure to sewage sludge application, industrial waste, phosphatic fertilizer, and bad watering practices in the agricultural soil. Additionally, contamination of agricultural land by the accumulation of heavy metals has become a serious environmental problem because of their detrimental ecological effects. These toxic elements are considered soil pollutants because of worldwide occurrence and their chronic and acute effects on plant growth resulting in less crop production [141,142]. Additionally, heavy metals are primarily carcinogenic, highly toxic, and nonbiodegradable, and can quickly enter the food chain even at exceptionally low concentrations. Hence, it is an inevitable and emergency need to get rid of lethal heavy metals from the underground water reservoirs and also soil [29,143]. For example, cadmium (Cd) is a lethal heavy metal that enters into the ecosystem via photography, electroplating, metals formation, and the manufacture of batteries. In earlier studies, it has been demonstrated that continuous exposure to cadmium can lead to toxicity in plants and animals. Moreover, plants exposed to elevated levels of cadmium cause a decrease in water uptake, nutrient uptake, and photosynthesis rate. Plants grown in cadmium-affected soil show symptoms of chlorosis, browning of root tips, and growth inhibition leading to plant death [144,145]. According to the Department of Environment, Food and Rural Affairs, UK, cadmium is the most dangerous substance. It has been added to the black list and is also among the red list of priority pollutants [29].

Furthermore, the vulnerability to nickel (Ni) compounds cause various harmful effects in plants and humans. It is reported that plants grown in nickel-containing soil showed impairment of severe nutrient imbalance and significantly affected cell membrane integrity. Additionally, nickel also affected the H-ATPase activity of the cell membrane and lipid peroxidation. It is also reported that nickel enhanced MDA contents in the plants resulting in less crop production [146]. Therefore, there are a variety of methods for remediation of heavy metals from wastewater including electrolysis, adsorption, coagulation, flocculation, membrane filtration, etc. [147]. Among all these methods, adsorption is a more convenient method with low operational value and remarkable efficiency in removing heavy metal ions from solutions. It has been studied in recent decades; there are many types of adsorbents like root cell walls [148], bamboo charcoal [148], and activated carbon [149]. But, these adsorbents are mostly less effective and less efficient. However, considerable research is necessary to examine the adsorbents with more adsorption capacity, faster kinetics, and lower cost. In the last few decades, biogenic SeNPs have captivated a great deal of attention from researchers. Recently, some researchers described the use of SeNPs as a fertilizer, sensor, semiconductor, and antimicrobial agent. It has also been described that SeNPs can be used as an efficient adsorbent to eliminate heavy metals from the contaminated solution because of their nanoscopic size, large specific surface area, and negative charge [150]. It was reported that the green synthesized SeNPs have been used efficiently to eliminate cadmium, nickel, copper, and zinc from contaminated soil [151–154]. In another study, it was also reported that SeNPs ameliorated the growth of *Brassica napus* L. under cadmium stress. It is also reported that SeNPs decreased cadmium-induced ROS production by inhibiting the expression of NADPH oxidases and glycolate oxidase thereby decreasing oxidative protein and membrane lipid damage [155]. Unfortunately, there is no scientific research reported to explore the effect of plant-based SeNPs on heavy metal bioremediation. However, in recent studies, biogenic SeNPs have been used to eliminate elemental mercury from the soil and air. Furthermore, it has been reported that bio-synthesized SeNPs are also used to eradicate elemental mercury from the ground water [153]. Because of the nontoxic nature and biocompatibility of SeNPs, it is believed that biosynthesized SeNPs can be used as a substituent method to eliminate the lethal heavy metals from the contaminated air, soil, and water.

9 Lethality of biogenic SeNPs

Phyto-nanotechnology has been growing rapidly with utilization in a wide range of commercial production materials in the agriculture and medical sectors worldwide. The plant-mediated SeNPs, because of their outstanding antioxidant and antimicrobial potential are so far becoming the most promising candidate for their use in the alleviation of abiotic and biotic stresses in agricultural crops. However, there is still a lack of information and knowledge concerning the increase of plants and ecological exposure of nanoparticles, especially SeNPs and their associated potential risks related to long and short time toxicity [88,124]. This section is devoted to reviewing all possible dangerous effects of biogenic SeNPs on different agricultural crops and plant pathogens responsible for devastating diseases in plants *in vitro*. Additionally, another study reported that *Allium sativum* gloves extract mediated SeNPs at 30 mg/L concentration ameliorates the agronomic parameters of wheat plants. Unfortunately, the plant agronomic parameters gradually decreased at elevated levels (40 mg/L) in wheat crop varieties under drought stress [4].

In addition, another study, L-cysteine and tannic acid capped and stabilized biosynthesized SeNPs showed toxic signs in the *Lemna minor* plants. It is reported that biogenic L-cysteine-mediated SeNPs decreased chlorophyll a and b contents at 40 and 80 mg/L, respectively.

Furthermore, it is also reported that tannic acid capped SeNPs minimize the chlorophyll a and b contents at 20 and 80 mg/L, respectively. This is because of the generation of ROS by biogenic SeNPs, resulting in increased MDA and hydrogen peroxide levels and decreased antioxidant defense enzymes such as POD [156]. Another examination also reported that at high concentrations, nanoparticles themselves generate ROS resulting in mitochondrial damage. Additionally, in other studies, it was also reported that plant-based SeNPs showed severe toxicity at 50 mg/L by decreasing the growth of *M. officinalis* plants. Furthermore, it was described that SeNPs at a high concentration significantly reduced the potassium contents in the leaves by 27% [104]. Unfortunately, there is very minimal research on plant-based SeNPs in alleviating biotic and abiotic stresses in plants. Here, we discussed the lethality of some biosynthesized SeNPs when they were used at higher concentrations. Furthermore, in comparison, plant-mediated SeNPs have advantageous over other nanoparticles because of their excellent biocompatibility, bioavailability, and biodegradability, less toxicity, and eco-friendly nature [46,133]. Keeping in view the slight lethality of plant-mediated SeNPs, it is not too difficult to believe that these can be a futuristic candidate to ameliorate the developmental growth, physiological profiling of agricultural crops resulting in excellent crop production. However, there is an inevitable need for time to optimize the concentration of SeNPs, which can be nontoxic and without detrimental effects, and safe to use for agriculture purposes.

10 Conclusion and future perspectives

Agriculture is a supreme sector of most developing countries. Agriculture is essential for the survival of humanity on the Earth because with the increasing population, the latest innovative technologies in agriculture are required that can meet the higher demands in the future. Furthermore, agriculture provides raw materials and supplies food and fibers [157]. Unfortunately, climate change is likely to disturb food security at the regional, global, and local levels. In addition, climate change can disturb food quality, food availability, and reduce access to food. Moreover, any climate-related disturbance such as drought, salinity, heat waves, heavy metal accumulation, and various bacterial and fungal attacks are responsible for reducing food quality, yield, and productivity of crops [158]. Surprisingly, in this scenario, the biogenic synthesis of nano-based material to emerge formulations hold remarkable possibilities in the 21st century to mitigate detrimental effects of biotic and abiotic stresses. It is well known that a significant number of nanotechnology-based products are available in the markets worldwide. Looking at the importance of plant-based SeNPs and green synthesis routes for biosafety and biocompatibility, it is anticipated that plant-mediated SeNPs have been developed as a significant scientific tool that has the application potential to overcome the devastating effects of climate change in the agriculture sector to ensure food security.

This study systematically reviewed the potential applications of plant-mediated SeNPs through previously published articles and provided valuable preliminary evidence representing the potentiality of biogenic SeNPs as a futuristic candidate to mitigate biotic and abiotic stresses in agricultural crops. Moreover, by analyzing the extraordinary biocompatibility and potency and at the same time biofortification and antifungal potential against various biotic and abiotic stresses, it is not exceedingly difficult to believe that biogenic SeNPs may seem productive to develop commercialized products that may revolutionize the agricultural sector. Plant-mediated SeNPs act as integral parts for many different antioxidant defensive enzymes, and it is also anticipated that SeNPs may reform the agriculture sector by developing selenium-based antimicrobial and biofortifying products. Indeed, the plant-extract-assisted SeNPs hold a significant rationale behind many explored studies. However, detailed biological research and investigation are indispensable to realize the bridge between selenium-based nanoparticles and selenium and molecular modifications that are responsible for enhancing the antioxidant and antimicrobial potential of crop plants under biotic and abiotic stresses. Moreover, it is very compulsory to understand the diversity or kinetics of selenoproteins which provides protection to plants against oxidative damage. In addition, collaborative efforts are required from plant physiologists, biochemists, molecular biologists, and nanotechnologists to understand the *in vivo* mechanism approach that plant-based SeNPs have adopted to tackle environmental stresses. Such efforts will likely increase the consumption of SeNPs and decrease the lethality of plant-based SeNPs in the agriculture industry to design customized Nano products.

Funding information: Authors state no funding involved.

Author contributions: Muhammad Ikram and Efat Zohra devised the study. Muhammad Ikram and Efat Zohra wrote the first draft. Ahmad Omar and Seema Hassan Satti edited and reviewed the manuscript. Mujahid Hussain and Maria Ehsan revised the manuscript. Naveed Iqbal Raja and Zia-Ur-Rehman Mashwani provided guidance and supervision. All authors reviewed and endorsed the final version of the manuscript for submission.

Conflict of interest: The authors state no conflict of interest.

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