agriculture

MDPI

Review

Appraisal of Functions and Role of Selenium in Heavy Metal Stress Adaptation in Plants

Mohd Asgher [1,*], Abdul Rehaman [1], Syed Nazar ul Islam [1], Mohd Arshad [1] and Nafees A. Khan [2,*]

[1] Plant Physiology and Biochemistry Laboratory, Department of Botany, Baba Ghulam Shah Badshah University, Rajouri 185234, India
[2] Plant Physiology and Biochemistry Laboratory, Department of Botany, Aligarh Muslim University, Aligarh 202002, India
* Correspondence: asghermohd@gmail.com (M.A.); naf9.amu@gmail.com (N.A.K.)

Abstract: Heavy metals (HMs) contamination is one of the main abiotic factors affecting crop productivity and also threatens human health via consuming metal-contaminated crops as a food source. Over the past few years, HMs have drawn a lot of attention due to their increased use for commercial purposes and their harmful effects on plants and other life forms, thus threatening human survival. However, several methods have been adopted in recent years to combat the harsh effects of HMs. After phytohormones, the use of mineral nutrients such as selenium (Se) in the prevention of HM stress has been explored by researchers more recently. Selenium is an important micronutrient widely known for its antioxidant properties in plants and animals. Exogenous Se inhibits metal uptake and translocation and improves the antioxidant system, thus imparting resistance to HM toxicity in plants. Moreover, Se also regulates the production of various osmolytes in cells, which helps develop cell osmolarity. Selenium also produces different secondary metabolites in plants' defense mechanisms against different stresses. The uptake of mineral nutrients is a vital process for plant growth and development, which is also positively correlated with Se under metalloid toxicity. However, to understand the exact mechanism of Se in HM tolerance, different metabolic processes stimulated by Se and their pathways need to be explored. Hence, this review focuses on the role of Se on nutritional status, antioxidant metabolism, interaction with phytohormones and its role in the regulation of various genes involved in Se-induced HM tolerance. Thus, this study will help researchers in the future for the improvement of HM tolerance via Se application in plants.

Keywords: heavy metal; mineral nutrition; phytohormones; selenium

check for updates

Citation: Asgher, M.; Rehaman, A.; Islam, S.N.u.; Arshad, M.; Khan, N.A. Appraisal of Functions and Role of Selenium in Heavy Metal Stress Adaptation in Plants. *Agriculture* **2023**, *13*, 1083. https://doi.org/10.3390/agriculture13051083

Academic Editor: Bernhard Huchzermeyer

Received: 19 April 2023
Revised: 12 May 2023
Accepted: 17 May 2023
Published: 18 May 2023

1. Introduction

Heavy metal (HM) pollution is one of the significant obstructions in determining the productivity of crops at the worldwide level [1–3]. The issue of HM stress has become a prominent concern in various soils and aquatic ecosystems worldwide [4]. Heavy metals are inorganic chemicals non-biodegradable and persistent, causing mutagenic, cytotoxic, and genotoxic effects on plants, humans, and animals. They contaminate soil and water ecosystems and enter food chains [5]. HMs are typically described as metals or metalloids with a higher density (5 g cm^{-3}). For a plant to flourish, certain heavy metals (Fe, Mn, Zn, Cu, Mo, and Ni) must be present in the ideal concentrations as critical micronutrients. While cadmium (Cd), lead, and mercury (Hg) are non-essential and have harmful effects when present in amounts that are beyond the tolerance limit of plants [6]. Exposure to HMs induces plant oxidative stress due to forming free radicals, which alter plant morpho-physiological and biochemical mechanisms at cellular and tissue levels. As a result of their stunted growth and development, plants raised in soils contaminated with HM produce less crops [7]. Heavy metals enter the plant through the root from soil deposits and significantly negatively impact several essential plant functions, including mineral nutrition, photosynthesis, water uptake and ion distribution [8–11]. Reports suggest that a higher concentration of HMs in the soil increases its uptake and accumulation in several commercial crops such as rice [12–14]. However, the increasing concentrations of HMs in agricultural land have negatively impacted the productivity of crops [14,15]. Recently, it has been reported that toxicity reduced photosynthetic functions and nitrogen assimilation, affecting the overall growth of *Oryza sativa* [11,14]. Besides mineral elements, plants also require a limited number of HMs for their normal functioning and metabolic activities. To prevent crops from metal toxicity, several essential elements have been made, and, among them, Se is widely used because of its various beneficial roles and potential to trigger HM tolerance in plants. Mineral nutrition is one of the key processes that is directly involved in the growth and development of plants. Plants under stressful conditions produce different types of signaling molecules to overcome stress [16]. Selenium is a chief element for plants. Selenium is a broadly distributed trace element with toxic and beneficial effects on plants, humans, and animals. Se might be useful for plant growth and development at low concentrations under optimum and unfavorable conditions [17]. However, the agglomeration of Se on the surface of water or soil may become a source of toxicity for plants. For this reason, most research on plant Se resistance has emphasized Se interaction with sulfur (S) metabolisms [18]. The addition of Se limits the uptake of metals by roots and their translocation to shoots by synthesizing various growth regulators, one of plants' indispensable stress tolerance mechanisms [19]. The low concentration (<1000 mg Se/kg DW) of Se can reduce metals' toxic effects on plants and develop tolerance against stress by inducing different metabolic processes [20]. However, at higher concentration (>1000 mg Se/kg DW), Se affects plant growth and decrease the level of organogenesis, nucleic acid synthesis and protein synthesis. The uptake of Se from the soil is controlled by edaphic and plant factors. Primarily, soil is the most common factor controlling Se entry into the plant body [21]. Selenium application reduces the adverse effects of both biotic and abiotic stresses by adjusting different mechanisms like secondary metabolites and antioxidant systems [17]. Selenium application enhanced photosynthesis by activating antioxidant enzymes involved in ROS detoxification under Cd stress in *Capsicum annuum* L. [22]. Studies have also shown that selenium decreased the levels of ROS and induced lignification of cell walls under cadmium stress in *Oryza sativa* [23]. However, the detoxification action of Se on the growth of garlic plants under Cd stress was also investigated [24]. Osmolytes, also important components of plant defense systems, are synthesized under stress conditions. Further, the application of Se also induced the production of some amino acids, such as proline (Pro), glycine betaine (GB), etc., under metal stress [25,26]. Nanoparticle treatment of Se also regulates the accumulation of Pro, GB, and sugars in response to HMs stress [27,28]. These amino acids act as osmolytes that help develop tolerance to stress conditions by maintaining their osmotic balance. Moreover, plants also secrete important compounds that participate in plant secondary defense against biotic and abiotic stress conditions. These secretions are commonly known as secondary metabolites (SMs). Among all the classes of SMs, phenolics are one of the major classes of SMs that participate in plant secondary defense. However, the exogenous supply of Se significantly enhanced the levels of phenolic metabolites under different types of metal stresses [17,29–31]. Furthermore, antagonistic results of Se on the production of glucosinolates (GLS) were also observed in plants when exposed to metalloid toxicity [32–34]. Accumulation of HMs in soil badly affects the uptake of mineral elements from the soil, thereby affecting plants' overall growth and metabolism. However, the exogenous treatment of Se enhances the uptake of the elements by interfering with metal uptake and hence improves the nutritional status of plants [35–37]. Furthermore, Se application also accumulates large amounts of Se in grains under metal stress, thus helping in developing nutritional-rich crop variety [38]. Plant hormones collaborate with the changing environment and are necessary for stress tolerance and crop production [22]. Selenium can occur in soil in four forms: Se, Selenate, Selenite, and inorganic selenide [39]. Under HM stress conditions, the endogenous production of various signalling molecules like ABA, ETH, SA, brassinosteroid (BRs) and JA increased, while auxin (AUX), gibberellins (GA) and cytokinin (CK) levels decreased [40–42]. However, the interaction between ETH and ROS was effective in *Solanum lycopersicum* under HM stress [42]. Ethylene is among the crucial plant stress hormones under adverse environmental conditions. Reports also suggest that Se (10 µM, 5 µM) induced production of ETH is controlled by the type of Se form supplied [43,44]. SeNPs are typically much smaller and have a more uniform size distribution and large surface area than conventional Se preparations. However, the increased levels of ABA and GA in response to selenium nanoparticles (SeNPs) treatment were also observed in *Brassica napus* [45]. In Cd-stressed *Nicotiana tabacum*, exogenous Se (10 µM) treatment increased the levels of indole acetic acid (IAA) [46]. However, seed priming with GA and SA showed stimulatory effects on the growth and metabolism of mung bean under Cd stress conditions [47]. Furthermore, the role of JA and GA in inducing tolerance to Cd stress is also explored in *Cicer arietinum* [48]. However, the interactive role of ETH on Se mediated antioxidant system under Cd stress is studied in *Solanum tuberosum* [49]. Phytohormones (exogenous/endogenous) alone play a major role in HM tolerance at the molecular level by regulating different defense mechanism genes that contribute to developing tolerance against HM toxicity in plants [50]. However, the information regarding the interaction of Se and phytohormones under HM stress is very scanty. Thus, the present review summarizes the mechanism of Se-induced tolerance to metal stress via regulating different processes such as Se uptake and translocation, antioxidant metabolism and mineral nutrition. This review also highlights the role of Se towards secondary metabolites production and its interaction with phytohormones under metal stress.

The data consolidated in the Figures 1 and 2 were extracted from the subsequent Dimensions software 2.6.0 (https://www.dimensions.ai/). The data were exported on 10 May 2023 using search terms" selenium", "heavy metal stress," "stress tolerance," and "plant" in the dataset. The data retrieved were further filtered by the year-wise distribution of articles published between 2010–2022 and country-wise publications in the past eight years, illustrated in Figures 1 and 2, respectively.

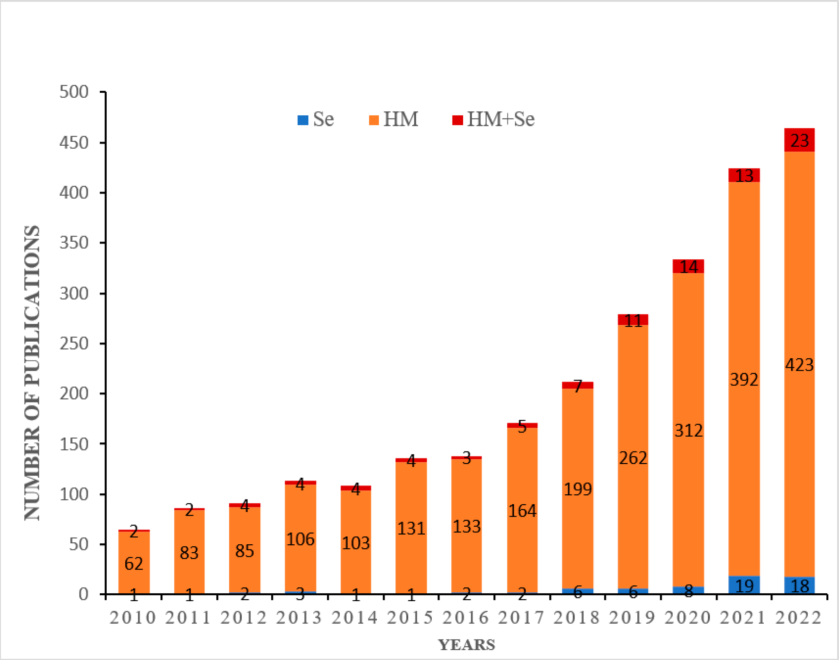

Figure 1. The number of publications in the literature on the effect of Se, HMs and their coordinated role in plants from 2010–2022.

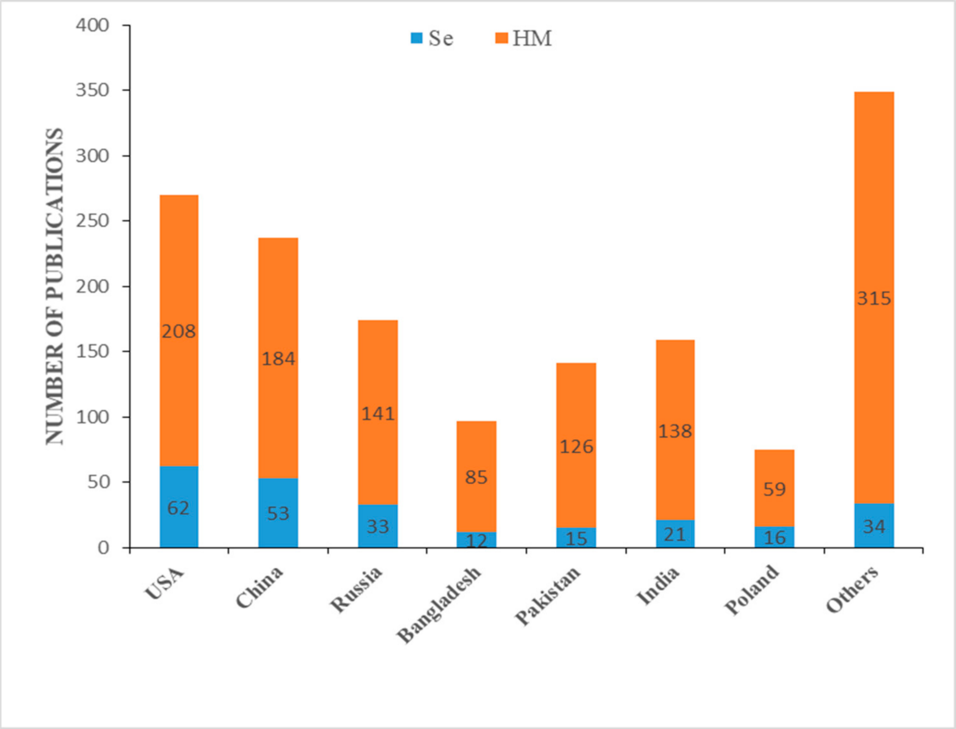

Figure 2. The number of publications country-wise that have studied the effect of selenium and HMs on plants in the last eight years.

2. Methodology

The review article covers the literature available from 1982 to 2023. The research papers were collected from scientific journals, books, and reports through electronic search PubMed, Google Scholar, and Science Direct, Scopus using keywords. Documentation of the information from these sources helped in drafting the different sections of the manuscript.

3. Selenium Uptake and Translocation

Selenium is a metalloid occurring naturally in sedimentary rocks in dry areas of the world [51]. The inorganic forms of Se i.e., Selenite (SeO_3^{2-}) and Selenate (SeO_4^{2-}), are the two main forms of Se which remain available to plants through soil. Selenite and selenate are present in anoxic and oxic soils [52]. Selenium chemically resembles sulfur(S), hence taken up inside the plants via S transporters located in the root plasma membrane [53]. Many species of plants have been identified as Se hyperaccumulators which can accumulate high concentrations of Se, such as *Stanleya pinnata* [54]. Selenium uptake differs from species to species, soil type, soil concentrations, and form of Se supplied [55]. Selenate absorption by plants is a well-established mechanism. The high-affinity sulphate transporters help in the absorption of selenate by roots. However, the selectivity of various plant species for sulphate and selenate varies [56,57]. On the other hand, nothing is understood about the process behind selenite uptake by plants. It has been observed that plant roots absorb selenite through passive diffusion [58]. Several species of plants belonging to the families Asteraceae, Brassicaceae and Fabaceae absorb higher concentrations of Se in hair-like epidermal appendages called trichomes [59]. The metabolism of Se in higher plants is closely associated with that of S due to their chemical analogy. Both ions SeO_3^{2-} and SeO_4^{2-} are absorbed by the plants via roots, and SeO_4^{2-} is taken via sulphate transporters (SULTRs). This relationship is demonstrated by the fact that Se is taken up by the plants via sulphate transporters and SeO_3^{2-} via aquaporins and phosphate transporters [52,57,60]. However, considerable differences in the uptake and transport mechanisms of inorganic forms are found in plants [61]. Selenate is uptake by plant roots in an active manner and leads to increased Se concentrations in the roots. However, selenite is not normally concentrated in roots [61]. Selenium is metabolized by S assimilation enzymes resulting in the synthesis of organic forms of Se, i.e., selenocysteine (SeCys) and selenomethionine (SeMT). However, Se uptake can also be increased from the soil via aquaporins by maintaining the pH of apoplastic space through H^+-ATPases [62]. Moreover, in rice, it was observed that selenite and SeNPs were accumulated in roots, whereas selenate is more stored in shoots [63]. Selenium uptake can also be enhanced by regulating the expression of SLUTRs [64]. Thus, from the above paragraph, it can be concluded that plants uptake different forms of Se from the soil using different transporters, such as sulfur and phosphate transporters. However, plants also promote the uptake of some forms of Se in an energy-independent manner via aquaporins. Moreover, the organs for different forms of Se accumulation and its transport also vary based on Se accumulated.

4. Selenium and Heavy Metals

Selenium is an essential nutrient for plants which is a foe to some living organisms like bacteria, humans, and most of the chlorophyte species [65–67]. Even Se is crucial for oxidative stress resistance, immunity enhancement, and antipathy of heavy metal toxicity [68,69]. Metalloid toxicity is now emerging as a significant concern to both humans and the environment [11,14]. Globally anthropogenic activities are the main cause of metal toxicity in agricultural lands. Heavy metals are non-biodegradable, accumulate in higher trophic levels of the food chain (biomagnification) and threaten biotic forms and their environment [70,71]. In *Lactuca sativa*, adding selenite significantly reduced the agglomeration of Pb and Cd and, at the same time, increased the uptake of some essential elements, including Se [72]. Selenium promotes the growth of plants and may act as a heavy metal opponent as it is a necessary micronutrient with some anti-oxidative and physiological properties [73,74]. The cadmium existing in water, soil, and the atmosphere can cause serious problems to all organisms and its bioaccumulation in the food chain can be highly hazardous [75]. The presence of Se may affect the distribution of elements which are necessary for plant growth and metabolism. The Se functions to reduce metal toxicity and regulate micronutrient levels by modifying soil conditions like pH, adsorption, and organic matter. It is vital in enhancing metal chelation and improving ROS scavenging mechanism [74,76–78]. The beneficial impact of Se on plants is often described as its ability to increase the anti-oxidative capacity of their cells. Se enhances the cellular anti-oxidative mechanism by elevating the enzymatic activity of CAT, GR, SOD and APX, which protects the plant cellular membranes against oxidation [79,80]. An appropriate concentration of Se can delay senescence, improve photosynthesis, and antioxidant capacity, induces auxin levels and promote plant growth [46,81,82]. Selenium application at optimum concentration improved the growth and biomass of *Cucumis sativus* plants under heavy metals stress (Cd, Pb, Ni) by detoxifying ROS-induced damages via regulation of activities of various antioxidant enzymes [83]. Application of 2 µM Se improved root growth and decreased oxidative stress in Al-treated *Lolium perenne* [84]. Exogenous treatment of Se reduced As-induced toxicity in *Phaseolus aureus* by interfering with its uptake and improved plant growth by activating the antioxidant system under As toxicity [85]. However, the application of Se in Pb-stressed *Vicia faba* plants reduced the accumulation of ROS via enhancement in the activities of various antioxidant enzymes [86]. The application of Se reduced the oxidative stress caused by the combined treatment of Cd and Pb in *Brassica napus* by minimizing the uptake and accumulation of both Cd and Pb [87]. Selenium plays a pivotal role in neutralizing abiotic stresses in plants. However, the role of Se in response to antioxidant metabolism has been studied under HM stress (Table 1) and found to induce tolerance to different HMs discussed below:

Table 1. Role of Selenium under HM stress conditions.

Species	Heavy Metal Conc.	Se Conc.	Effect of Se on Antioxidants Metabolism	Reference(s)
Brassica napus	5 µM Cd 500 µM Pb	15 µM	Enhanced SOD and GSH-Px levels to minimize Cd/Pb-induced oxidative stress	[87]
Brassica juncea	300 µM Cr	4 µM	Strengthen the inheretent defense system by inducing the expression of SOD, CAT, APX, GPOX, GR, GST, DHAR M-DHAR, AsA and GSH against Cr stress.	[31]
Brassica juncea	100 or 200 µM Cd	50 µM	Increment in CAT, APX and GR activity was observed	[88]
Brassica spp.	50 µM Cd	3 µM	Induced ROS detoxification, maintained the levels of SOD, CAT and POD	[89]
Glycine max	As 25 µM	25 µM	Reduced As toxicity by improving photosynthesis, antioxidants, and regulation of some defense genes	[27]
Vicia faba	50 µM Pb	6 µM	Up-regulated CAT, GPOX and GSH-Px levels	[86]
Phaseolus aureus	10 µM As	5 µM	Reduced As-induced oxidative stress by increasing CAT, APX GR, AsA and GSH levels	[85]
Satureja hortensis	150 µM Cd	40 µM	Elevated the levels of CAT and POD and reduced Cd toxicity.	[90]
Cucumus sativus	25 µM Cd 200 µM Ni 100 µM Pb	8 µM	Stimulated antioxidant system by enhancing the activity of CAT, APX and GPOX	[83]
Triticum aestivum	Cd 50 µM	5 and 10 µM	Down-regulation of genes of Cd uptake and transport	[91]
Oryza sativa	As 100 µM	25 µM	Up-regulated various As-tolerant genes and also induced the antioxidant expression	[92]
Oryza sativa	20 µM Cd	1 µM	Up-regulated CAT and GSH-Px activity and reduced lipid oxidation	[93]
Oryza sativa	25 µM As	25 µM	Positively enhanced the activities of CAT, APX, GSH-Px, GR, GST and GSH	[94]
Lolium perenne	0.2 µM Al	5 µM	Reduced lipid peroxidation by Increasing SOD and APX activity	[84]

Selenium application is involved in the recovery of chloroplast injuries caused due to Cd stress in *Cucumus sativus* by increasing starch content in leaves [95]. Exogenous Se (4 µM) alleviated Zn stress by improving growth and photosynthesis in *Billbergia zebrina* [96]. SeMT (3 µM) mitigated Cd toxicity in mustard species by enhancing enzymatic antioxidants and preventing Cd aggregation in cell organelles [89]. Further, leaf spraying of Se (10, 20, and 40 µM) reduced Cd toxicity by limiting Cd uptake by roots and improved photosynthetic attributes, osmoprotectants and antioxidant levels in *Satureja hortensis* [90]. However, Se application significantly increased the accumulation of organic Se in grains but also affected the uptake and translocation of other HMs in *Triticum aestivum* [97]. More interestingly, exogenous supplementation of Se is also involved in promoting flowering in *Cucumis sativus,* which was delayed by Cd and maintained the sex ratio in plants [98]. Foliar spraying of Se in wheat leaves inhibited metal uptake and enhanced the nutritional status of wheat by accumulating more Se in the grains [38].

Moreover, the application of SeNPs ameliorated the toxic effects of Cd by enhancement in the production of some essential SMs and osmoprotectants in *Coriandrum sativum* [26]. Supplementation of Se considerably reduced Cd stress in *Raphanus sativus* by improving photosynthetic attributes, antioxidants level and micro-essential nutrients [35]. In plants, Se has a dual function. At low concentrations, it acts as an antioxidant, but at enormous doses, it generates ROS and impairs several cellular activities. Se affects plant growth, physiology, and antioxidant machinery at various concentration levels [99]. Foliage application of SeNPs alleviated both Cd and Pb toxicity in *Salvia officinalis* and decreased lipid peroxidation of membranes [100]. Both foliar and root applications of Se enhance plant growth, development, and tolerance. But the foliar application is considered more efficient than the root application [101]. Selenium treatment reduced ROS accumulation in the reproductive parts of rice and increased pollen viability and germination under Cd stress [102]. Researchers revealed that using elements with antioxidant properties can abate the hazardous effects of heavy metal stresses [103]. Figure 3 shows the mechanism of HM-induced changes in the growth and metabolism of plants and the role of Se in alleviating HM-induced oxidative stress by triggering various defense processes in plants. (ROS: reactive oxygen species, PCD: programmed cell death).

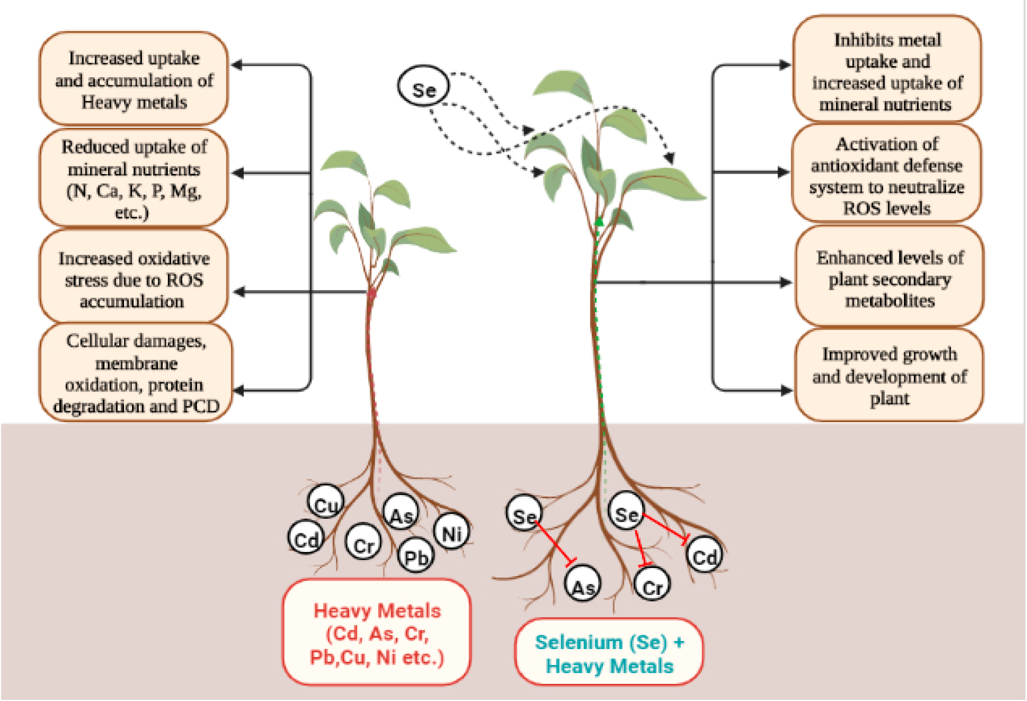

Figure 3. Role of selenium in the mitigation of heavy metals stress.

Some researchers reported that Se application reduced Cd accumulation and decreased toxicity in pepper by enhancing chlorophyll contents and overall antioxidant activity [104]. In rice seedlings, Se increases the absorption of Cd in the cell wall and vacuoles and decreases the amount of Cd in its toxic form [93]. Optimal doses of Se were known to cope with various biotic and abiotic stresses, including exposure to HMs, by regulating the antioxidant system [105]. Selenium is also a fundamental part of some antioxidant enzymes, which shield cells from ROS damage [29,106]. Additionally, reports also showed that an ideal concentration of Se (1/2 μM) enhanced the antioxidant capabilities of photosynthetic pigments and slowed the ageing of leaf tissues in *Brassica oleracea* and strawberries [29,107]. Furthermore, adding Se reduced oxidative stress by stimulating the ROS scavenging system and synchronized Cd accumulation in shoots and roots in *Brassica juncea* [88]. Recent reports also confirm that all the Se (SeNPs, inorganic and organic) forms contribute to HM tolerance by inducing the activities of various antioxidants and other biochemical parameters in *Oryza sativa* under Cd stress [93].

Selenium plays a significant role in the mitigation of metal-induced toxicity by the improvement in the overall growth and metabolism of plants. Primarily, Se reduces metal uptake and transport by changing root architecture, stimulating different types of antioxidants and PCs, and producing many other types of defensive compounds in plants to increase the tolerance potential of plants against metal toxicity.

5. Selenium Interaction with Osmolytes under Heavy Metal Stress

To avoid cellular damage due to the accumulation of ROS, plants deposit some compatible solutes known as "osmolytes" to protect the cellular machinery from several environmental stresses. Among all the osmolytes, Pro, GB, polyamines, and sugars are the common osmolytes that plants accumulate under stressful conditions and play an essential role in osmoregulation. However, plants synthesize different types of osmolytes under different environmental constraints, and their exogenous supply may also enhance the production of other osmolytes, such as proline application relieved As-induced oxidative damages by improving other osmolytes concentration in mung bean crops [108]. Increment in the levels of Pro and GB with the application of Se (10 µM) demonstrates its role in providing membrane stability in *Solanum lycopersicum* under Cd stress [25]. Increased production of osmolytes, including Pro, GB, and sugars, protect the cells from damage against stress conditions by developing osmotic potential and regulating other defense mechanisms [88,109]. It has also been reported that Se supplementation to Cd-challenged tomato plants promoted the production of compatible solutes and stress markers, which relieves Cd toxicity [26]. However, applying SeNPs increased Pro accumulation in *Coriandrum sativum* under Cd stress [26]. However, the leaf spraying of Se elevated leaves Pro content and grain Se concentration in wheat cultivars [110]. Application of SeNPs increased the content of Pro and GB in *Glycine max* subjected to As stress [27]. Selenium at optimal concentration positively regulated the synthesis of essential osmoprotectants such as Pro and sugars [111]. An increased level of important compatible solute Pro was also observed in *Triticum aestivum* in response to Se under Cd stress [28]. Osmolytes are essential in maintaining osmoregulation in plants under various stress conditions. These osmolytes, also called osmoprotectants, are synthesized in plants and help develop tolerance to plants against different stresses. Pro, GB, and sugars are the most synthesized osmolytes in plants under stress conditions. However, it has also been observed that Se regulates the biosynthesis of these osmolytes under stress conditions. These osmolytes protect the plants against HM toxicity by maintaining osmolarity and membrane stability and strengthening the antioxidant defence system to minimize ROS-induced damages.

6. Selenium Interplay with Phytohormones under Heavy Metal Stress

Phytohormones have gained much attention over the last two decades due to their wide use in plants against many abiotic stresses. However, their role in ameliorating different strains attracted researchers to more and more use of these signaling molecules. In recent years, much work has been carried out to elaborate on the role of phytohormones against HM stress. These signaling molecules protect plants against HMs by regulating different physiological and biochemical processes that help develop tolerance strategies against stresses [112]. Moreover, their role, along with Se, in alleviating HM stress is the least studied so far. Exogenous application of AUX affected the uptake of Cd and reduced Cd stress by improving photosynthesis and antioxidant system and raising the level of endogenous nitric oxide (NO) in tomatoes [6]. Furthermore, the role of GA application in mitigating Nickel (Ni) toxicity was also observed in mung beans by improving growth and biomass and reducing Ni uptake [113]. However, Se interferes with HMs by regulating the endogenous production of phytohormones [19]. Reports also suggest that inorganic forms of Se negatively affect the production of ethylene [43]. However, their organic forms, such as SeMT, positively regulated ethylene biosynthesis but also affected AUX transport in rice [44]. Moreover, it has been also noticed that optimal concentration of Se induces tolerance to Cd and low phosphorous stress in *Nicotiana tabacum* by regulating AUX biosynthesis and transport genes [46,114]. However, pretreatment of mung bean seeds with GA and SA improved overall growth and antioxidant system and prevented Cd-induced alterations in roots under Cd stress conditions [47]. Furthermore, applying JA and GA mitigated Cd-induced toxicity in *Cicer arietinum* by minimizing ROS accumulation via increased antioxidants and osmolytes production under Cd stress [48]. Besides organic and inorganic forms of Se, it can also be applied exogenously as nanoparticles (NPs). However, the literature available on Se so far indicates the effectiveness of Se in the removal of various abiotic stresses. Reports further enlightened that supplementation of SeNPs and ZnONPs (Zinc oxide) in combination improved germination rate and seedling growth by inducing the endogenous levels of ABA and GA in *Brassica napus* [45]. However, applying these signaling molecules (Phytohormones) impart tolerance to various abiotic stresses through interaction with other signaling molecules and promoting signal transduction cascades in plants [115]. Biochemical and molecular studies have revealed that defense response facilitated by phytohormones such as ETH and JA play an essential role in Se resistance and accumulation [116]. Reports suggest that selenite has been shown to decrease NO levels in a concentration-dependent manner in Arabidopsis root [117]. It has also been reported that the application of NO and SeNPs regulated the expression of the DREB1A gene in *Cichorium intybus* [118]. However, the endogenous production of ABA under Cd stress also plays a role in the regulation of various Cd-responsive genes such as HsfA4c, HMA4 in roots and HMA2, HMA3CAD and NAS, suggesting its role in the accumulation of more Cd in apoplast region [119].

Studies also emphasized the role of Se and AUX on morphological and biochemical attributes and genotoxicity under As stress in rice plants [120]. It has been reported that the presence of PGRs in the external growth medium of plants has altered ion homeostasis (K^+, Na^+, Ca^{2+}) in the root tissues and mesocotyle [21]. Reports also indicated that JA and ETH are essential for Se resistance in Arabidopsis plants [18]. Exogenous GR24, a source of strigolactone, also reduced Cd toxicity by inducing NO production and elevated the levels of different antioxidants in *Hordeum vulgare* [121]. The application of IAA also increased the phytoextraction of Cd/U from the soil in *Helianthus annuus* [122]. The roots are the foremost organ of plants that reflect heavy metal stress. Thus, the knowledge about the interaction between heavy metal stress and AUX homeostasis is of utmost significance. The involvement of phytohormones in the amelioration of HM stress and their response to different HMs has been studied (Table 2) and discussed in detail below:

Table 2. Role of phytohormones under heavy metals stress.

Species	HM Conc.	Phytohormones Conc.	Response	Reference(s)
Brassica juncea	24 µM As	200 µL/L Ethephon	Improvement of photosynthetic attributes by reduced As and ABA accumulation, increment in antioxidant activity	[123]
Sedum alfredii	100 µM Cd	0.2 mg/L ABA	Exogenous ABA enhanced endogenous ABA production, which is involved in Cd tolerance by regulating the expression of Cd tolerance genes	[119]
Populus × *Canescens*	3 µM Pb	10 µM ABA	Ameliorated the toxic effects of Pb by minimizing oxidative stress and induced expression of genes responsible for Pb resistance	[124]
Oryza sativa	150 µM As	3 µM IAA	Improved growth by accumulating more amino acids, proteins etc.	[120]
Cajanus cajan	5 µM Cu^{2+}	1 nM JA	Improved photosynthesis, antioxidative system and reduced oxidative stress	[125]
Solanum lycopersicum	3 µM Cd	10 nM HBL	Improved overall growth and productivity of plants, positively regulated N-metabolism.	[126]
Zea mays	50 µM Cd	10^{-9} M IBA	Reduced Cd toxicity by inducing ROS detoxification and improved nutrient status of plants	[127]
Vigna radiata	60 µM Ni	10^{-4} M GA_3	Improved growth and biomass of plants by reducing the uptake of Ni from soil	[113]
Helianthus annuus	4 µM U/Cd	500 mg/L IAA	ROS detoxification by inducing antioxidants, increased uptake of U/Cd from soil	[122]

Table 2. *Cont.*

Species	HM Conc.	Phytohormones Conc.	Response	Reference(s)
Brassica juncea	50 µM Cd	200 µL/L Ethephon	Improved growth, induced antioxidants, and amino acids accumulation	[128]
Brassica juncea	1.2 µM Cr	200 µL/L Ethephon	Mitigated Cr stress by improving photosynthesis, reduced oxidative stress, and also enhanced proline accumulation	[15]
Hordeum vulgare	10 µM Cd	1 µM GR24 (strigol analogue)	Reduced Cd toxicity by improving photosynthesis, uptake of essential nutrients, and inducing stress markers	[121]
Panicum virgatum	10 µM Cd	1 µM GR24 (strigol analogue)	Increment in photosynthetic parameters, stimulation of antioxidant system and improvement in the mineral status of plants	[129]
Solanum lycopersicum	150 µM Cd	100 µM NO	Positive effect on photosynthesis and improved growth, antioxidant system, osmoprotectants and secondary metabolites accumulation, hence involved in Cd tolerance.	[130]
Oryza sativa	5 µM Cr	0.1 nM 24-EBL	Induced Cd detoxification by enhancing photosynthesis and regulating the genes expression	[131]

In recent times, the participation of plant growth regulators (PGRs) in the establishment and activation of plant defense mechanisms to HMs exposure has been largely studied [132–134]. Accumulating evidence indicates that exogenous ABA can stimulate the transport of Pb^{2+} from underground to aerial parts of herbaceous plants [124]. Exogenous ABA addition enhanced the activities of enzymatic antioxidants that relieve oxidative stress by scavenging ROS produced due to Pb toxicity in *Atractylodes macrocephala* [135]. SA interacts with other plant hormones, such as AUX, ABA, and GA and encourages the production of antioxidant chemicals and enzymes in response to stress, particularly HM stress [136]. The combined application of Se and phytohormones represents a promising strategy to ameliorate HM toxicity by reducing the uptake of HMs, activating various defense systems in plants as illustrated in Figure 4.

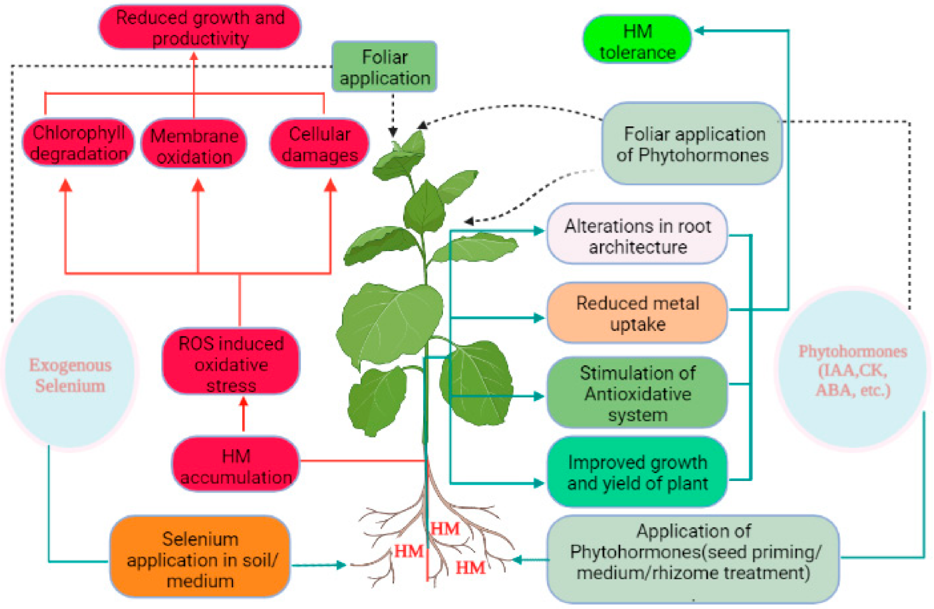

Figure 4. Supplementation of Se and phytohormones ameliorated heavy metal toxicity via reduced uptake of HMs and activation of various defence systems.

Phytohormones play a crucial role in the growth and developmental processes of plants when exposed to a variety of abiotic stresses. Some of these signaling molecules are produced endogenously during stress conditions. However, their exogenous application to different abiotic stresses, including HM stress, significantly contributes to developing tolerance. Primarily, PGRs interfere with metal uptake via altering root architecture, thus resisting the uptake and accumulation of metals in the plant body. Moreover, Se supplementation also induces the endogenous production of different growth regulators under different stresses. Thus, both Se and PGRs help develop tolerance to stress conditions by regulating different plant mechanisms to minimize oxidative damage.

7. Molecular and Proteomic Interaction of Selenium under Heavy Metals

Work on Se indicated that Se plays a beneficial role in enhancing abiotic stress tolerance [17]. Proteomics is acknowledged as an effective method for understanding how plants respond to abiotic stress, comprising toxic metals such as Cu, As, Al, Cr etc. [137,138]. Analysis of more than a hundred (110) proteins to understand the proteomic response of rice seedlings under different levels of Cr stress was carried out by [139]. In a recent study, RNA sequencing, proteome profiling, and a morphological demonstration were conducted to explore molecular cross-talk of Se mediated As stress amelioration [92]. There are numerous transporters family that play crucial roles in response to As stress in plants, specifically for uptake of As in root, phloem movements, xylem loading and unloading in cells and subcellular organelles specific distribution [92]. The Germin protein family participates in numerous metabolic and stress tolerance mechanisms. Selenium helps plants to cope with As stress by regulating various stress-responsive genes [92]. When exposed to Cd, rice developed Cd-responsive miRNA. The translational levels of several targeted genes were inversely linked with the corresponding miRNA, suggesting the molecular role of HM stress resistance in plants [140]. At the molecular level, Se also plays an essential role in developing HMs tolerance in plants by regulating numerous stress-related genes. However, the involvement of ETH and Se in the regulation of genes which encode enzymes of antioxidants has been observed in mustard subjected to As stress [123]. Significant enhancement in the regulation of WRKY1, PAL and 4CL genes was observed in *Mimordica charantia* when exposed to slightly higher concentrations of nano-Se [141]. Increased expression of antioxidant genes, PAL and CHS was also noticed in Cr stressed mustard [142]. Selenium treatment significantly up-regulated the expression of S transporters (SLUTs) genes involved in the transport of Se [143]. Application of Se at 25 μM in broccoli has shown negative effects at both translational and transcriptional levels. Proteins of the BIN family, which express during stress conditions and heat shock proteins (HSPs), were badly affected in Se-treated plants.

Moreover, down-regulation of different transcription genes such as MYB (28, 34), BCAT4, MAM1, CYP79B2 and FMO2 was also detected in Se-treated plants [32]. Regulation of various antioxidant and thiol metabolism genes in response to Se was also observed in *Oryza sativa* exposed to As stress [94]. Exogenous Se considerably increased the expression levels of the NtPT2 gene in tobacco [114]. Selenium also up-regulated genes responsible for seed germination and seedling growth in rapeseed [45]. In *Glycine max*, SeNPs treatment significantly upregulated various stress marker genes in response to As stress [27]. However, the addition of Se in rice cell culture in the presence of Cd positively up-regulated OsHMA3 and OsPAL, OsCoMT and Os4CL3 genes responsible for Cd accumulation in the vacuole and lignin biosynthesis. On the other hand, Se also represses the expression of genes (OsNramp5, OsLCT1) involved in Cd uptake and transport [23]. Moreover, the expression of SBP1 protein in arabidopsis seedlings indicated its role in alleviating Cd-induced oxidative stress by promoting its binding to Cd [144]. Furthermore, foliar treatment of Se (10 μM) induced genes responsible for Se accumulation and transport to shoots and differentially expressed the proteins related to Se uptake, aggregation, antioxidants, and heat shock proteins [145]. Meanwhile, Se treatment upregulated genes responsible for cell wall lignification and triggered resistance to Cd by inducing the expression of BZR1, LOX3, and NCDE1 genes [22]. Selenium (5, 10 µM) supplementation negatively affected the expression of genes (TaNramp5, TaHMA2) responsible for Cd uptake and translocation but also up-regulated TaHMA3-gene required for Cd translocation to the vacuole in both roots and shoot in wheat [91].

An important area of the plants to respond or increase tolerance potential to stresses, including HM, is the regulation of genes at both transcriptional and translational levels. During stress conditions, activation/expression of different stress-responsive proteins or genes occurs, which help the plant to generate tolerance for survival against stress. In response to metalloid toxicity, Selenium application down-regulates various genes responsible for the uptake and transport of HM in plants, thus indicating its importance in plant stress tolerance. Moreover, Se also regulates the expression of various antioxidant genes that are significant players in developing the tolerance and hence protection of plants against abiotic stress.

8. Selenium Interplay with Secondary Metabolites (Phenolics, N-Containing Metabolites and Terpenes)

In the era of climate change, abiotic stress hampered the growth and development of plants. Plants develop several defense mechanisms to cope with such conditions. Plant secondary metabolites display their functions against stresses [146,147]. The amounts of SMs under stress conditions are slightly higher and are involved in signaling, thereby regulating the activity of genes responsible for plant defense [148]. Among different SMs, terpenes, phenolics and nitrogen compounds are widely known for their protective effects against various environmental constraints [149]. To investigate the role of these compounds in plant defense, the exogenous use of monoterpenoid on *Quercus suber* leaves indicated its role in endogenous terpene accumulation and improved photosynthesis of plants subjected to heat stress [150]. The production of plant metabolites is regulated genetically, environmental factors and also the mineral status of the plant [151]. Plants accumulate different types of metabolites under varying conditions. For instance, the production of flavonoids during drought stress in *Arabidopsis thaliana* is thought to be involved in drought tolerance [152]. *Matricaria chamomilla* plants subjected to copper (Cu) and Cd stress have shown more phenolic content than the non-stressed plants [153].

Similarly, increased levels of phenolics were observed in *Vaccinium corymbosum* plants facing Cd stress [154]. Increased biosynthesis of phenolics was also observed in *Kandelia obovata* under HM stress [155]. Increased accumulation of different types of SMs was also noticed in *Brassica juncea*, which has a higher Cd tolerance capability without external mitigators [156]. To overcome plant metal toxicity, the use of elicitors can be done to enhance SMs production [157]. The effect of Se on SMs production and their function in plants has been studied (Table 3) and discussed in detail below:

Table 3. Effect of Se on the production of secondary metabolites.

Plant Species	Se Dose	Secondary Metabolites	Response	Reference(s)
Mentha suaveolens	10 µM	Production of essential oils such as piperitenone oxide, limonene, jasmone etc.	Enhanced growth and SMs production	[158]
Brassica juncea	4 µM	Enhanced levels of phenols, flavonoids, and anthocyanins	Improvement in the photosynthesis thereby growth of plant by inducing the accumulation of antioxidants, SMs, etc., against Cr stress	[31]
Brassica oleracea	25 µM	Affected the production or accumulation of glucoraphanin, an important glucosinolate	Reduced content of glucosinlates precursors, Suppressed the expression of genes involved in glucosinlates biosynthesis	[32]

Table 3. *Cont.*

Plant Species	Se Dose	Secondary Metabolites	Response	Reference(s)
Melissa officinalis	5 µM	Increased the accretion of essential oils such as z-citral, citral and geranyl acetate	Positive effect on the growth at low concentration	[20]
Brassica oleracea	10 µM	Increment in the levels of phenolic compounds and glucosinolates	Improved growth and yield characteristics of plants by inducing antioxidant and SMs levels	[30]
Zea mays	10 µM	Enhancement of phenols and flavonoids content	Induced accumulation of proteins, sugars and SMs	[159]
Oryza sativa	25 µM	Induced the accumulation of essential phenolics such as gallic, protocatechuic and ferulic (acids)	Increased the uptake of nutrients from the soil and regulated SMs production, hence reducing As toxicity	[160]
Brassica juncea	50 µM	Enhanced phenolic content	Reduced Cd stress by inducing the antioxidant system and SMs status of plants	[88]
Allium sativum	4 µM	Increased total phenolic content	Increased tolerance ability of garlic to salt stress by preventing membrane oxidation, phenols accumulation and regulation of phenylalanine ammonia-lyase activity	[161]
Vallerianella locusta	5 µM	Enhanced the endogenous levels of flavonoids and phenolics	Improved growth, antioxidant activity and accumulation of SMs	[162]

Research on selenium has shown that it plays a crucial part in plant metal tolerance by limiting the uptake of metals from the soil by changing the root architecture system and preventing their translocation to leaves [19]. Selenium at low concentrations benefits plant secondary metabolites, as it enhances the levels of carotenoids and phenolic compounds in rice [163]. Selenium nanoparticles supplementation in bitter melon induced the activity of phenylalanine ammonia-lyase (PAL), an important enzyme involved in the biosynthesis of phenolic compounds [141]. The addition of Se upregulated PAL and Chalcone synthase genes and increased the contents of phenolics, flavonoids and anthocyanin compounds in mustard under chromium (Cr) stress [17,31]. The report showed that Se decreased the accumulation of glucosinolates (GLS) in broccoli [33]. In Se-treated *Arabidopsis thaliana*, a reduction in GLS and carotenoid content was observed in shoots by suppressing their biosynthetic genes [34]. Selenium application negatively affected the accretion of GLS by suppressing genes involved in GLS biosynthesis and their precursors in broccoli [32]. An increment in the levels of plant essential oils (secondary metabolites) in response to Se was also observed in *Melissa officinalis* [20]. However, the supplementation of Se at low doses increased the accumulation of GLS in *Brassica oleracea* [29]. In *Allium sativum*, treatment with Se improved PAL activity and increased the content of phenolics under salt stress [161]. Selenium application increased the levels of total phenolics and flavonoids in *Zea mays* and *Valerianella locusta* [159,162]. Recently, it has been reported that spraying of SeNPs on the leaves of *Mentha suaveolens* induced the accumulation of various types of essential oils under salt stress [158]. Reports also indicate that Se ameliorated the Cd toxicity of *Brassica juncea* by improving its antioxidant system and SMs status [88]. Selenium also enhances the biosynthesis of flavonoids and tocopherols, which are also involved in relieving oxidative stress of different abiotic stresses [80]. Selenium also attenuated As toxicity in *Oryza sativa* by inducing the aggregation of phenolics in both underground and aerial parts of the plant [160]. Secondary metabolites are an important class of plant defense compounds synthesized by plants as a response to different types of stress conditions that can cause harm to plants. Plant exudates such as tannins, resins, gums etc., are the common secretions mostly related to stress factors, i.e., both biotic and abiotic. However, the root exudates also limit the uptake and translocation of HMs, thus helping protect plants against HMs toxicity.

Based on the results of the aforesaid studies on Se and secondary metabolites, it has been concluded that Se is involved in improving the antioxidant system of plants by enhancing the synthesis of different types of SMs, which play an essential part in the plant defense system. As per the literature, the effect of SMs on forming other SMs can vary depending on the specific metabolites involved, the plant species and the environmental conditions.

In some cases, the synthesis of one SM may stimulate or inhibit the synthesis of another metabolite. Conversely, it is also possible that the synthesis of one SM may not affect the production of another. Overall, the interactions between different SMs in plants are still not fully understood, and more research is needed to determine the specific effects of each compound on the synthesis of others.

9. Selenium Interaction with Mineral Nutrients under Heavy Metal Stress

Selenium is an essential plant micro-nutrient vital in various metabolic pathways in plant life. However, its accumulation in plants varies from species to species. Moreover, at high concentrations, Se shows toxic effects on plants, but at optimal concentrations, it is reported to be safe for plants. However, some plant species can accumulate higher concentrations of Se in their body. Selenium is known for its both beneficial and toxic effects on plants. Apart from developing resistance to metal/metalloid uptake, it is also known to increase nutrient absorption and accumulation in plants. Reports indicated that the coordinative supply of Se and S in mung bean increased the uptake of various mineral nutrients such as NPK, Fe, Zn and S under drought stress [36]. Selenium helps plants relieve oxidative stress by acting as an antioxidant that also improves their nutritional status by enhancing the uptake and aggregation of mineral nutrients [164]. A significant increment in the uptake of some nutrients such as Fe, Mn and Cu was also observed in radishes subjected to Cd stress in the presence of Se [35]. However, the supplementation of Se in the nutrient solution favoured more uptakes of P and Ca from the media, indicating its role in maintaining mineral nutrition in *Zea mays* [165]. Application of Se significantly enhanced the uptake of micro-nutrients that regulated various metabolic processes to develop tolerance against As stress [160]. Moreover, Se treatment improves the nutritional quality of crops by accumulating more Se in edible parts of plants [38]. Supplementation of Se at different concentrations showed fluctuations in the contents of both macro and microelements in different species [166].

Furthermore, Se at higher concentrations affected the uptake of micronutrients in *Eruca sativa* [167]. However, improvement in N and Ca content was also observed in wheat subjected to exogenous Se treatment [168]. Selenium supplementation significantly up-regulated various essential mineral elements uptake in *Brassica campestris* by modifying root architecture to reduce Cr uptake [169]. Introducing the biosynthetic form of SeNPs to different HMs (Cd, Pb, Hg), stress improved the nutritional status of *Brassica chinensis* by enhancing the uptake of nutrient elements [37].

Availability of mineral nutrients is one of the chief processes in the life cycle of a plant to regulate all its growth and developmental processes. However, the uptake of these mineral elements is severely affected by the soils contaminated with metals, thus affecting the overall growth and metabolism of plants. On the other hand, Se is directly involved in the uptake of these nutrients from the soil by inhibiting metal uptake and therefore helps the plants to restore the activities of all their physiological, biochemical, and developmental processes to withstand such harsh environmental constraints.

10. Conclusions

Rising concentrations of HMs in the soil and their alarming negative effects on plants and, thus, on other living life forms attracted scientists in the field of research more towards this environmental constraint in the present era of science. Due to its increasing threat to the agronomy field, various methods have been adopted by scientists to overcome this problem. Exogenous supplementation of Se in the form of selenite, selenate, SeCys, SeMT and SeNPs has been successfully done to cope with the harsh effects of HM stress in plants. Selenium is directly involved in alleviating HM toxicity by inhibiting or limiting its uptake and translocation from soil to aerial parts of plants. Primarily, Se is involved in improving plants' growth and photosynthesis by improving nutritional status, osmoprotectants concentration, antioxidant metabolism and secondary metabolites under metal stress conditions.

Further, the crosstalk between HMs, Se and phytohormones is needed to be understood. By understanding this problem, it will become more feasible to overcome such threats, and crops with higher nutritional quality and yield can be produced in the future. And hence, this approach can also become helpful in reducing global food scarcity/hunger. Therefore, future research in this area is likely to shed new light on the molecular, physiological, and ecological mechanisms underlying Se-mediated stress tolerance and to identify new opportunities for the development of sustainable and effective strategies for crop improvement.

Author Contributions: Conceptualization, M.A. (Mohd Asgher) and N.A.K. Validation, A.R., S.N.u.I. and M.A. (Mohd Arshad). Writing—Original Draft, M.A. (Mohd Asgher), A.R., S.N.u.I. and M.A. (Mohd Arshad). Writing and editing, M.A. (Mohd Asgher), N.A.K., A.R., S.N.u.I. and M.A. (Mohd Arshad) Supervision M.A. (Mohd Asgher) and N.A.K.; funding acquisition, M.A. (Mohd Asgher). All authors read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Hasan, M.M.; Uddin, M.N.; Ara-Sharmeen, F.I.; Alharby, H.; Alzahrani, Y.; Hakeem, K.R. Assisting phytoremediation of heavy metals using chemical amendments. *Plants* **2019**, *8*, 295. [CrossRef]
2. Rather, B.A.; Mir, I.R.; Masood, A.; Anjum, N.A.; Khan, N.A. Nitric oxide pre-treatment advances seed germination and alleviates copper-induced photosynthetic inhibition in Indian mustard. *Plants* **2020**, *9*, 776. [CrossRef]
3. Tripathi, D.K.; Rai, P.; Guerriero, G.; Sharma, S.; Corpas, F.J.; Singh, V.P. Silicon induces adventitious root formation in rice under arsenate stress with involvement of nitric oxide and indole-3-acetic acid. *J. Exp. Bot.* **2021**, *72*, 4457–4471. [CrossRef] [PubMed]
4. Alsafran, M.; Saleem, M.H.; Al Jabri, H.; Rizwan, M.; Usman, K. Principles and applicability of integrated remediation strategies for heavy metal Removal/Recovery from contaminated environments. *J. Plant Growth Regul.* **2022**. [CrossRef]
5. Sharma, J.K.; Kumar, N.; Singh, N.P.; Santal, A.R. Phytoremediation technologies and their mechanism for removal of heavy metal from contaminated soil: An approach for a sustainable environment. *Front. Plant Sci.* **2023**, *14*, 1076876. [CrossRef]
6. Khan, M.Y.; Prakash, V.; Yadav, V.; Chauhan, D.K.; Prasad, S.M.; Ramawat, N.; Sharma, S. Regulation of cadmium toxicity in roots of tomato by indole acetic acid with special emphasis on reactive oxygen species production and their scavenging. *Plant Physiol. Biochem.* **2019**, *142*, 193–201. [CrossRef]
7. Noor, I.; Sohail, H.; Sun, J.; Nawaz, M.A.; Li, G.; Hasanuzzaman, M.; Liu, J. Heavy metal and metalloid toxicity in horticultural plants: Tolerance mechanism and remediation strategies. *Chemosphere* **2022**, *303*, 135196. [CrossRef]
8. Asgher, M.; Khan, M.I.R.; Anjum, N.A.; Khan, N.A. Minimising toxicity of cadmium in plants—Role of plant growth regulators. *Protoplasma* **2015**, *252*, 399–413. [CrossRef] [PubMed]
9. Emamverdian, A.; Ding, Y.; Mokhberdoran, F.; Xie, Y. Heavy metal stress and some mechanisms of plant defense response. *Sci. World J.* **2015**, *1*, 1–18. [CrossRef]
10. Saini, S.; Kaur, N.; Pati, P.K. Phytohormones: Key players in the modulation of heavy metal stress tolerance in plants. *Ecotoxicol. Environ. Saf.* **2021**, *223*, 112578. [CrossRef] [PubMed]
11. Asgher, M.; Ahmed, S.; Sehar, Z.; Gautam, H.; Gandhi, S.G.; Khan, N.A. Hydrogen peroxide modulates activity and expression of antioxidant enzymes and protects photosynthetic activity from arsenic damage in rice (*Oryza sativa* L.). *J. Hazard. Mater.* **2021**, *401*, 123365. [CrossRef] [PubMed]
12. Upadhyay, M.K.; Majumdar, A.; Barla, A.; Bose, S.; Srivastava, S. An assessment ofarsenic hazard in groundwater–soil–rice system in two villages of Nadia district, West Bengal, India. *Environ. Geochem. Health* **2019**, *41*, 2381–2395. [CrossRef]
13. Tyagi, N.; Raghuvanshi, R.; Upadhyay, M.K.; Srivastava, A.K.; Suprasanna, P.; Srivastava, S. Elemental (As, Zn, Fe and Cu) analysis and health risk assessment of rice grains and rice based food products collected from markets from different cities of Gangetic basin, India. *J. Food Compos. Anal.* **2020**, *93*, 103612. [CrossRef]
14. Asgher, M.; Sehar, Z.; Rehaman, A.; Rashid, S.; Ahmed, S.; Per, T.S.; Alyemeni, M.N.; Khan, N.A. Exogenously-applied L-glutamic acid protects photosynthetic functions and enhances arsenic tolerance through increased nitrogen assimilation and antioxidant capacity in rice (*Oryza sativa* L.). *Environ. Pollut.* **2022**, *301*, 119008. [CrossRef]

15. Asgher, M.; Khan, M.I.R.; Anjum, N.A.; Verma, S.; Vyas, D.; Per, T.S.; Khan, N.A. Ethylene and polyamines in counteracting heavy metal phytotoxicity: A crosstalk perspective. *J. Plant Growth Regul.* **2019**, *37*, 1050–1065. [CrossRef]
16. Hasan, M.M.; Alharbi, B.M.; Alhaithloul, H.A.S.; Abdulmajeed, A.M.; Alghanem, S.M.; Al-Mushhin, A.A.M.; Jahan, M.S.; Corpas, F.J.; Fang, X.-W.; Soliman, M.H. Spermine-mediated tolerance to selenium toxicity in wheat (*Triticum aestivum* L.) depends on endogenous nitric oxide synthesis. *Antioxidants* **2021**, *10*, 1835. [CrossRef] [PubMed]
17. Hasanuzzaman, M.; Bhuyan, M.H.M.B.; Raza, A.; Hawrylak-Nowak, B.; Matraszek-Gawron, R.; Mahmud, J.A.; Nahar, K.; Fujita, M. Selenium in plants: Boon or Bane? *Environ. Exp. Bot.* **2020**, *178*, 104170. [CrossRef]
18. Tamaoki, M.; Freeman, J.L.; Pilon-Smits, E.A.H. Cooperative ethylene and jasmonic acid signaling regulates selenite resistance in Arabidopsis. *Plant Physiol.* **2008**, *146*, 1219–1230. [CrossRef]
19. Hasanuzzaman, M.; Nahar, K.; García-Caparrós, P.; Parvin, K.; Zulfiqar, F.; Ahmed, N.; Fujita, M. Selenium supplementation and crop plant tolerance to metal/metalloid toxicity. *Front. Plant Sci.* **2022**, *12*, 792770. [CrossRef]
20. Tavakoli, S.; Enteshari, S.; Yousefifard, M. The effect of selenium on physiologic and morphologic properties of *Melissa officinalis* L. *Iran. J. Plant Physiol.* **2020**, *10*, 3125–3134.
21. Pazurkiewicz-Kocot, K.; Galas, W.; Kita, A. The effect of selenium on the accumulation of some metals in *Zea mays* L. plants treated with indole-3-acetic acid. *Cell. Mol. Biol. Lett.* **2003**, *8*, 97–104.
22. Li, D.; Zhou, C.; Ma, J.; Wu, Y.; Kang, L.; An, Q.; Pan, C. Nanoselenium transformation and inhibition of cadmium accumulation by regulating the lignin biosynthetic pathway and plant hormone signal transduction in pepper plants. *J. Nanobiotech.* **2021**, *19*, 316. [CrossRef] [PubMed]
23. Cui, J.; Liu, T.; Li, Y.; Li, F. Selenium reduces cadmium uptake into rice suspension cells by regulating the expression of lignin synthesis and cadmium-related genes. *Sci. Total Environ.* **2018**, *644*, 602–610. [CrossRef] [PubMed]
24. Sun, H.W.; Ha, J.; Liang, S.X.; Kang, W.J. Protective role of selenium on garlic growth under cadmium stress. *Commun. Soil Sci. Plan.* **2010**, *41*, 1195–1204. [CrossRef]
25. Alyemeni, M.N.; Ahanger, M.A.; Wijaya, L.; Alam, P.; Bhardwaj, R.; Ahmad, P. Selenium mitigates cadmium-induced oxidative stress in tomato (*Solanum lycopersicum* L.) plants by modulating chlorophyll fluorescence, osmolyte accumulation, and antioxidant system. *Protoplasma* **2018**, *255*, 459–469. [CrossRef]
26. Babashpour-Asl, M.; Farajzadeh-Memari-Tabrizi, E.; Yousefpour-Dokhanieh, A. Foliar-applied selenium nanoparticles alleviate cadmium stress through changes in physio-biochemical status and essential oil profile of coriander (*Coriandrum sativum* L.) leaves. *Environ. Sci. Pollut. Res.* **2022**, *29*, 80021–80031. [CrossRef]
27. Zeeshan, M.; Hu, Y.X.; Iqbal, A.; Salam, A.; Liu, Y.X.; Muhammad, I.; Ahmad, S.; Khan, A.H.; Hale, B.; Wu, H.Y.; et al. Amelioration of AsV toxicity by concurrent application of ZnO-NPs and Se-NPs is associated with differential regulation of photosynthetic indexes, antioxidant pool and osmolytes content in soybean seedling. *Ecotoxicol. Environ. Saf.* **2021**, *225*, 112738. [CrossRef] [PubMed]
28. Atarodi, B.; Fotovat, A.; Khorassani, R.; Keshavarz, P. Study of wheat (*Triticum aestivum* L.) response to selenium application under cadmium stress. *Environ. Stress. Crop Sci.* **2019**, *12*, 291–305.
29. Saeedi, M.; Soltani, F.; Babalar, M.; Izadpanah, F.; Wiesner-Reinhold, M.; Baldermann, S. Selenium fortification alters the growth, antioxidant characteristics and secondary metabolite profiles of cauliflower (*Brassica oleracea* var. botrytis) cultivars in hydroponic culture. *Plants* **2021**, *10*, 1537. [CrossRef]
30. Chu, J.; Yao, X.; Zhang, Z. Responses of wheat seedlings to exogenous selenium supply under cold stress. *J. Biol. Trace Elem. Res.* **2010**, *136*, 355–363. [CrossRef]
31. Handa, N.; Kohli, S.K.; Sharma, A.; Thukral, A.K.; Bhardwaj, R.; Abd Allah, E.F.; Alqarawi, A.A.; Ahmad, P. Selenium modulates dynamics of antioxidative defence expression, photosynthetic attributes and secondary metabolites to mitigate chromium toxicity in *Brassica juncea* L. *Environ. Exp. Bot.* **2019**, *161*, 180–192. [CrossRef]
32. Tian, M.; Xu, X.; Liu, F.; Fan, X.; Pan, S. Untargeted metabolomics reveals predominant alterations in primary metabolites of broccoli sprouts in response to pre-harvest selenium treatment. *Food Res. Int.* **2018**, *111*, 205–211. [CrossRef]
33. Barickman, T.C.; Kopsell, D.A.; Sams, C.E. Selenium influences glucosinolate and isothiocyanates and increases sulfur uptake in Arabidopsis thaliana and rapid-cycling *Brassica oleracea*. *J. Agric. Food Chem.* **2013**, *61*, 202–209. [CrossRef]
34. Sams, C.E.; Panthee, D.R.; Charron, C.S.; Kopsell, D.A.; Yuan, J.S. Selenium regulates gene expression for glucosinolate and carotenoid biosynthesis in Arabidopsis. *J. Am. Soc. Hortic. Sci.* **2011**, *136*, 23–34. [CrossRef]
35. Amirabad, A.S.; Behtash, F.; Vafaee, Y. Selenium mitigates cadmium toxicity by preventing oxidative stress and enhancing photosynthesis and micronutrient availability on radish (*Raphanus sativus* L.) cv. Cherry Belle. *Environ. Sci. Pollut. Res.* **2020**, *27*, 12476–12490. [CrossRef] [PubMed]
36. Aqib, M.; Nawaz, F.; Majeed, S.; Ghaffar, A.; Ahmad, K.S.; Shehzad, M.A.; Usmani, M.M. Physiological insights into sulfate and selenium interaction to improve drought tolerance in mung bean. *Physiol. Mol. Bio. Plants* **2021**, *27*, 1073–1087. [CrossRef]
37. Zhu, Y.; Dong, Y.; Zhu, N.; Jina, H. Foliar application of biosynthetic nano-selenium alleviates the toxicity of Cd, Pb, and Hg in *Brassica chinensis* by inhibiting heavy metal adsorption and improving antioxidant system in plant. *Ecotoxicol. Environ. Saf.* **2022**, *240*, 113681. [CrossRef]
38. Gu, X.; Wen, X.; Yi, N.; Liu, Y.; Wu, J.; Li, H.; Liu, G. Effect of foliar application of silicon, selenium and zinc on heavy metal accumulation in wheat grains in field studies. *Environ. Pollut. Bioavail.* **2022**, *34*, 246–252. [CrossRef]

39. Hasanuzzaman, M.; Hossain, M.A.; Fujita, M. Selenium in higher plants: Physiological role, antioxidant metabolism and abiotic stress tolerance. *J. Plant Sci.* **2010**, *5*, 354–375. [CrossRef]
40. Atici, O.; Agar, G.; Battal, P. Changes in phytohormone contents in chickpea seeds germinating under lead or zinc stress. *Algologia* **2005**, *49*, 215–222. [CrossRef]
41. Maksymiec, W.; Krupa, Z. The effects of short-term exposition to Cd, excess Cu ions and jasmonate on oxidative stress appearing in *Arabidopsis thaliana*. *Environ. Exp. Bot.* **2006**, *57*, 187–194. [CrossRef]
42. Nguyen, T.Q.; Sesin, V.; Kisiala, A.; Emery, R.N. Phytohormonal roles in plant responses to heavy metal stress: Implications for using macrophytes in phytoremediation of aquatic ecosystems. *Environ. Toxicol. Chem.* **2021**, *40*, 7–22. [CrossRef]
43. Malheiros, R.S.P.; Costa, L.C.; Ávila, R.T.; Pimenta, T.M.; Teixeira, L.S.; Brito, F.A.L.; Ribeiro, D.M. Selenium downregulates auxin and ethylene biosynthesis in rice seedlings to modify primary metabolism and root architecture. *Planta* **2019**, *250*, 333–345. [CrossRef]
44. Malheiros, R.S.P.; Gonçalves, F.C.M.; Brito, F.A.L.; Zsögön, A.; Ribeiro, D.M. Selenomethionine induces oxidative stress and modifies growth in rice (*Oryza sativa* L.) seedlings through effects on hormone biosynthesis and primary metabolism. *Ecotoxicol. Environ. Saf.* **2020**, *189*, 109942. [CrossRef]
45. El-Badri, A.M.; Batool, M.; Wang, C.; Hashem, A.M.; Tabl, K.M.; Nishawy, E.; Wang, B. Selenium and zinc oxide nanoparticles modulate the molecular and morpho-physiological processes during seed germination of *Brassica napus* under salt stress. *Ecotoxicol. Environ. Saf.* **2021**, *225*, 112695. [CrossRef]
46. Luo, Y.; Wei, Y.; Sun, S.; Wang, J.; Wang, W.; Han, D.; Fu, Y. Selenium modulates the level of auxin to alleviate the toxicity of cadmium in tobacco. *Int. J. Mol. Sci.* **2019**, *20*, 3772. [CrossRef]
47. Hassan, M.; Israr, M.; Mansoor, S.; Hussain, S.A.; Basheer, F.; Azizullah, A.; Ur Rehman, S. Acclimation of cadmium-induced genotoxicity and oxidative stress in mung bean seedlings by priming effect of phytohormones and proline. *PLoS ONE* **2021**, *16*, e0257924. [CrossRef]
48. Ahmad, P.; Raja, V.; Ashraf, M.; Wijaya, L.; Bajguz, A.; Alyemeni, M.N. Jasmonic acid (JA) and gibberellic acid (GA3) mitigated Cd-toxicity in chickpea plants through restricted Cd uptake and oxidative stress management. *Sci. Rep.* **2021**, *11*, 19768. [CrossRef]
49. Alves, L.R.; Dos Reis, A.R.; Prado, E.R.; Lavres, J.; Pompeu, G.B.; Azevedo, R.A.; Gratao, P.L. New insights into cadmium stressful-conditions: Role of ethylene on selenium-mediated antioxidant enzymes. *Ecotoxicol. Environ. Saf.* **2019**, *186*, 109747. [CrossRef]
50. Rahman, S.U.; Li, Y.; Hussain, S.; Hussain, B.; Riaz, L.; Ashraf, M.N.; Cheng, H. Role of phytohormones in heavy metal tolerance in plants: A review. *Ecol. Indic.* **2023**, *146*, 109844. [CrossRef]
51. Frankenberger, J.W.T.; Karlson, U. Campaigning for bioremediation. *Chemtech* **1994**, *24*, 45–51.
52. White, P.J. Selenium metabolism in plants. *Biochim. Biophys. Acta-Gen. Subj.* **2018**, *1862*, 2333–2342. [CrossRef] [PubMed]
53. Gupta, M.; Gupta, S. An overview of selenium uptake, metabolism, and toxicity in plants. *Front. Plant Sci.* **2017**, *7*, 2074. [CrossRef]
54. Parker, D.R.; Feist, L.J.; Varvel, T.W. Selenium phytoremediation potential of *Stanleya pinnata*. *Plant Soil* **2003**, *249*, 157–165. [CrossRef]
55. Zayed, A.; Lytle, C.M.; Terry, N. Accumulation and volatilization of different chemical species of selenium by plants. *Planta* **1998**, *206*, 284–292. [CrossRef]
56. White, P.J.; Bowen, H.C.; Parmaguru, P.; Fritz, M.; Spracklen, W.P.; Spiby, R.E.; Meacham, M.C.; Mead, A.; Harriman, M.; Trueman, L.J.; et al. Interactions between selenium and sulfur nutrition in *Arabidopsis thaliana*. *J. Exp. Bot.* **2004**, *55*, 1927–1937. [CrossRef]
57. Sors, T.G.; Ellis, D.R.; Salt, D.E. Selenium uptake, translocation, assimilation and metabolic fate in plants. *Photosynth. Res.* **2005**, *86*, 373–389. [CrossRef]
58. Arvy, M.P. Selenate and selenite uptake and translocation in bean plants (*Phaseolus vulgaris*). *J. Exp. Bot.* **1993**, *44*, 1083–1087. [CrossRef]
59. Freeman, J.L.; Quinn, C.F.; Marcus, M.A.; Fakra, S.; Pilon-Smits, E.A. Selenium-tolerant diamondback moth disarms hyperaccumulator plant defense. *Curr. Biol.* **2006**, *16*, 2181–2192. [CrossRef]
60. Dumont, E.; Vanhaecke, F.; Cornelis, R. Selenium speciation from food source to metabolites: A critical review. *Anal. Bioanal. Chem.* **2006**, *385*, 1304–1323. [CrossRef]
61. Brown, T.A.; Shrift, A. Selenium: Toxicity and tolerance in higher plants. *Biol. Rev.* **1982**, *57*, 59–84. [CrossRef]
62. Zhang, L.; Chu, C. Selenium uptake, transport, metabolism, reutilization, and biofortification in rice. *Rice* **2022**, *15*, 30. [CrossRef] [PubMed]
63. Wang, K.; Wang, Y.; Li, K.; Wan, Y.; Wang, Q.; Zhuang, Z.; Guo, Y.; Li, H. Uptake, translocation and biotransformation of selenium nanoparticles in rice seedlings (*Oryza sativa* L.). *J. Nanobiotechnol.* **2020**, *18*, 103. [CrossRef]
64. Trippe, R.C., III; Richard, C.; Pilon-Smits, E.A.H. Selenium transport and metabolism in plants: Phytoremediation and biofortification implications. *J. Hazard. Mater.* **2021**, *404*, 124178. [CrossRef]
65. Lobanov, A.V.; Hatfield, D.L.; Gladyshev, V.N. Eukaryotic selenoproteins and selenoproteomes. *Biochim. Biophys. Acta-Gen. Subj.* **2009**, *1790*, 1424–1428. [CrossRef]
66. Nancharaiah, Y.V.; Lens, P.N.L. Selenium biomineralization for biotechnological applications. *Trends Biotechnol.* **2015**, *33*, 323–330. [CrossRef]

67. Costa, L.C.; Luz, L.M.; Nascimento, V.L.; Araujo, F.F.; Santos, M.N.S.; França, C.F.M.; Silva, T.P.; Fugate, K.K.; Finger, F.L. Selenium-ethylene interplay in postharvest life of cut flowers. *Front. Plant Sci.* **2020**, *11*, 584698. [CrossRef]
68. Conte, F.; Copat, C.; Longo, S.; Oliveri Conti, G.; Grasso, A.; Arena, G.; Ferrante, M. First data on trace elements in *Haliotistuberculata* (Linnaeus, 1758) from southern Italy: Safety issues. *Food Chem. Toxicol.* **2015**, *81*, 143–150. [CrossRef] [PubMed]
69. Copat, C.; Grasso, A.; Fiore, M.; Cristaldi, A.; Zuccarello, P.; Signorelli, S.S.; Ferrante, M. Trace elements in seafood from the Mediterranean sea: An exposure risk assessment. *Food Chem. Toxicol.* **2018**, *115*, 13–19. [CrossRef] [PubMed]
70. Guo, W.; Zhao, R.; Zhao, W.; Fu, R.; Guo, J.; Bi, N.; Zhang, J. Effects of arbuscular mycorrhizal fungi on maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L. Moench) grown in rare earth elements of mine tailings. *Appl. Soil Ecol.* **2013**, *72*, 85–92. [CrossRef]
71. Angulo-Bejarano, P.I.; Puente-Rivera, J.; Cruz-Ortega, R. Metal and metalloid toxicity in plants: An overview on molecular aspects. *Plants* **2021**, *10*, 635. [CrossRef]
72. He, P.; Lv, X.; Wang, G. Effects of Se and Zn supplementation on the antagonism against Pb and Cd in vegetables. *Environ. Int.* **2004**, *30*, 167–172. [CrossRef]
73. Nawaz, F.; Ashraf, M.Y.; Ahmad, R.; Waraich, E.A.; Shabbir, R.N. Selenium (Se) regulates seedling growth in wheat under drought stress. *Adv. Chem.* **2014**, *2014*, 143567. [CrossRef]
74. Gui, J.Y.; Rao, S.; Huang, X.; Liu, X.; Cheng, S.; Xu, F. Interaction between selenium and essential micronutrient elements in plants: A systematic review. *Sci. Total Environ.* **2022**, *853*, 158673. [CrossRef]
75. Ismael, M.A.; Elyamine, A.M.; Moussa, M.G.; Cai, M.; Zhao, X.; Hu, C. Cadmium in plants: Uptake, toxicity, and its interactions with selenium fertilizers. *Metallomics* **2019**, *11*, 255–277. [CrossRef]
76. Filek, M.; Koscielniak, J.; Labanowska, M.; Bednarska, E.; Bidzinska, E. Selenium-induced protection of photosynthesis activity in rape (*Brassica napus*) seedlings subjected to cadmium stress:Fluorescence and EPR measurements. *Photosynth. Res.* **2010**, *105*, 27–37. [CrossRef]
77. Feng, R.; Wei, C.; Tu, S. The roles of selenium in protecting plants against abiotic stresses. *Environ. Exp. Bot.* **2013**, *87*, 58–68. [CrossRef]
78. Tobiasz, A.; Walas, S.; Filek, M.; Mrowiec, H.; Samsel, K.; Sieprawska, A.; Hartikainen, H. Effect of selenium on distribution of macro- and micro-elements to different tissues during wheat. *Biol. Plant.* **2014**, *58*, 370–374. [CrossRef]
79. Hasanuzzaman, M.; Hossain, M.A.; Fujita, M. Exogenous selenium pretreatment protects rapeseed seedlings from cadmium-induced oxidative stress by upregulating antioxidant defense and methylglyoxal detoxification systems. *Biol. Trace Elem. Res.* **2012**, *49*, 248–261. [CrossRef]
80. Lanza, M.G.D.B.; Reis, A.R.d. Roles of selenium in mineral plant nutrition: ROS scavenging responses against abiotic stresses. *Plant Physiol. Biochem.* **2021**, *164*, 27–43. [CrossRef] [PubMed]
81. Kaur, N.; Sharma, S.; Kaur, S.; Nayyar, H. Selenium in agriculture: A nutrient or contaminant for crops? *Arch. Agron. Soil Sci.* **2014**, *60*, 1593–1624. [CrossRef]
82. Cakir, O.; Candar-Cakir, B.; Zhang, B.H. Small RNA and degradome sequencing reveals important microRNA function in *Astragalus chrysochlorus* response to selenium stimuli. *Plant Biotechnol. J.* **2016**, *14*, 543–556. [CrossRef]
83. Aroiee, H.; Shekari, L.; Mirshekari, A. Effects of selenium on damage of heavy metals in germination, growth and antioxidant activities of cucumber (*Cucumis sativus* L.) seedling. *Iran. J. Seed Sci. Res.* **2019**, *6*, 269–286. [CrossRef]
84. Cartes, P.; Jara, A.A.; Pinilla, L.; Rosas, A.; Mora, M.L. Selenium improves the antioxidant ability against aluminium-induced oxidative stress in ryegrass roots. *Ann. Appl. Biol.* **2010**, *156*, 297–307. [CrossRef]
85. Malik, J.A.; Kumar, S.; Thakur, P.; Sharma, S.; Kaur, N.; Kaur, R.; Pathania, D.; Bhandhari, K.; Kaushal, N.; Singh, K.; et al. Promotion of growth in mungbean (*Phaseolus aureus* Roxb.) by selenium is associated with stimulation of carbohydrate metabolism. *Biol. Trace Elem. Res.* **2011**, *143*, 530–539. [CrossRef]
86. Mroczek-Zdyrska, M.; Strubińska, J.; Hanaka, A. Selenium improves physiological parameters and alleviates oxidative stress in shoots of lead-exposed *Vicia faba* L. minor plants grown under phosphorus-deficient conditions. *J. Plant Growth Regul.* **2017**, *36*, 186–199. [CrossRef]
87. Wu, Z.; Yin, X.; Bañuelos, G.S.; Lin, Z.Q.; Liu, Y.; Li, M.; Yuan, L. Indications of selenium protection against cadmium and lead toxicity in oilseed rape (*Brassica napus* L.). *Front. Plant Sci.* **2016**, *7*, 1875. [CrossRef]
88. Ahmad, P.; Abd Allah, E.F.; Hashem, A.; Sarwat, M.; Gucel, S. Exogenous application of selenium mitigates cadmium toxicity in *Brassica juncea* L. (Czern and Cross) by up-regulating antioxidative system and secondary metabolites. *J. Plant Growth Regul.* **2016**, *35*, 936–950. [CrossRef]
89. Zhang, Z.W.; Dong, Y.Y.; Feng, L.Y.; Deng, Z.L.; Xu, Q.; Tao, Q.; Wang, C.Q.; Chen, Y.E.; Yuan, M.; Yuan, S. Selenium enh;nces cadmium accumulation capability in two mustard family species—*Brassica napus* and *B. Juncea*. *Plants* **2020**, *9*, 904. [CrossRef]
90. Azizi, I.; Esmaielpour, B.; Fatemi, H. Effect of foliar application of selenium on morphological and physiological indices of savory (*Satureja hortensis*) under cadmium stress. *Food Sci. Nutr.* **2020**, *8*, 6539–6549. [CrossRef]
91. Zhu, J.; Zhao, P.; Nie, Z.; Shi, H.; Li, C.; Wang, Y.; Qin, S.; Qin, X.; Liu, H. Selenium supply alters the subcellular distribution and chemical forms of cadmium and the expression of transporter genes involved in cadmium uptake and translocation in winter wheat (*Triticum aestivum*). *BMC Plant Boil.* **2020**, *20*, 550.
92. Chauhan, R.; Awasthi, S.; Indoliya, Y.; Chauhan, A.S.; Mishra, S.; Agrawal, L.; Tripathi, R.D. Transcriptome and proteome analyses reveal selenium mediated amelioration of arsenic toxicity in rice (*Oryza sativa* L.). *J. Hazard. Mater.* **2020**, *390*, 122122. [CrossRef] [PubMed]

93. Xu, H.; Yan, J.; Qin, Y.; Xu, J.; Shohag, M.J.I.; Wei, Y.; Gu, M. Effect of different forms of selenium on the physiological response and the cadmium uptake by rice under cadmium stress. *Int. J. Environ. Res. Public Health* **2020**, *17*, 6991. [CrossRef] [PubMed]
94. Kumar, A.; Singh, R.P.; Singh, P.K.; Awasthi, S.; Chakrabarty, D.; Trivedi, P.K.; Tripathi, R.D. Selenium ameliorates arsenic induced oxidative stress through modulation of antioxidant enzymes and thiols in rice (*Oryza sativa* L.). *Ecotoxicology* **2014**, *23*, 1153–1163. [CrossRef] [PubMed]
95. Sun, H.; Wang, X.; Li, H.; Bi, J.; Yu, J.; Liu, X.; Rong, Z. Selenium modulates cadmium-induced ultrastructural and metabolic changes in cucumber seedlings. *RSC Adv.* **2020**, *10*, 17892–17905. [CrossRef]
96. Martins, J.P.R.; Souza, A.F.C.; Rodrigues, L.C.A.; Braga, P.C.S.; Gontijo, A.B.P.L.; Falqueto, A.R. Zinc and selenium as modulating factors of the anatomy and physiology of *Billbergia zebrina* (Bromeliaceae) during in vitro culture. *Photosynthetica* **2020**, *58*, 1068–1077. [CrossRef]
97. Liu, Y.; Huang, S.; Jiang, Z.; Wang, Y.; Zhang, Z. Selenium biofortification modulates plant growth, microelement and heavy metal concentrations, selenium uptake, and accumulation in black-grained wheat. *Front. Plant Sci.* **2021**, *12*, 748523. [CrossRef]
98. Shekari, L.; Aroiee, H.; Mirshekari, A.; Nemati, H. Protective role of selenium on cucumber (*Cucumis sativus* L.) exposed to cadmium and lead stress during reproductive stage role of selenium on heavy metals stress. *J. Plant Nutr.* **2019**, *42*, 529–542. [CrossRef]
99. Naseem, M.; Anwar-ul-Haq, M.; Wang, X.; Farooq, N.; Awais, M.; Sattar, H.; Ahmed Malik, H.; Mustafa, A.; Ahmad, J.; El-Esawi, M.A. Influence of selenium on growth, physiology, and antioxidant responses in maize varies in a dose-dependent manner. *J. Food Qual.* **2021**, *2021*, 1–9. [CrossRef]
100. Bakhtiari, M.; Raeisi Sadati, F.; Raeisi Sadati, S.Y. Foliar application of silicon, selenium, and zinc nanoparticles can modulate lead and cadmium toxicity in sage (*Salvia officinalis* L.) plants by optimizing growth and biochemical status. *Environ. Sci. Pollut. Res.* **2023**, *30*, 54223–54233. [CrossRef]
101. Ros, G.H.; Van Rotterdam, A.M.D.; Bussink, D.W.; Bindraban, P.S. Selenium fertilization strategies for bio-fortification of food: An agro-ecosystem approach. *Plant Soil* **2016**, *404*, 99–112. [CrossRef]
102. Barman, F.; Kundu, R. Foliar application of selenium affecting pollen viability, grain chalkiness, and transporter genes in cadmium accumulating rice cultivar: A pot study. *Chemosphere* **2023**, *313*, 137538. [CrossRef]
103. Rostami, M.; Abbaspour, H. Effect of selenium on growth and physiological traits of basil plant (*Ocimum basilicum* L.) under arsenic stress conditions. *Rev. Agric. Neotrop.* **2019**, *6*, 30–37. [CrossRef]
104. Mozafariyan, M.; Shekari, L.; Hawrylak-Nowak, B.; Kamelmanesh, M.M. Protective role of selenium on pepper exposed to cadmium stress during reproductive stage. *Biol. Trace Elem. Res.* **2014**, *160*, 97–107. [CrossRef] [PubMed]
105. Feng, R.; Wang, L.; Yang, J.; Zhao, P.; Zhu, Y.; Li, Y. Underlying mechanisms responsible for restriction of uptake and translocation of heavy metals (metalloids) by selenium via root application in plants. *J. Hazard. Mater.* **2020**, *402*, 23570. [CrossRef]
106. Kieliszek, M. Selenium–fascinating microelement, properties and sources in food. *J. Mol.* **2019**, *24*, 1298. [CrossRef]
107. Zahedi, S.M.; Abdelrahman, M.; Hosseini, M.S.; Hoveizeh, N.F.; Tran, L.S.P. Alleviation of the effect of salinity on growth and yield of strawberry by foliar spray of selenium-nanoparticles. *Environ. Pollut.* **2019**, *253*, 246–258. [CrossRef]
108. Alam, M.Z.; McGee, R.; Hoque, M.A.; Ahammed, G.J.; Carpenter-Boggs, L. Effect of arbuscular mycorrhizal fungi, selenium and biochar on photosynthetic pigments and antioxidant enzyme activity under arsenic stress in mung bean (*Vigna radiata*). *Front. Physiol.* **2019**, *10*, 193. [CrossRef]
109. Ahanger, M.A.; Agarwal, R.M. Salinity stress induced alterations in antioxidant metabolism and nitrogen assimilation in wheat (*Triticum aestivum* L) as influenced by potassium supplementation. *Plant Physiol. Biochem.* **2017**, *115*, 449–460. [CrossRef]
110. Sajedi, N. Evaluation of selenium and salicylic acid effect on physiological and qualitative characteristics of dry-land wheat cultivars. *Iran Agric. Res.* **2017**, *36*, 91–100.
111. Khalofah, A.; Migdadi, H.; El-Harty, E. Antioxidant enzymatic activities and growth response of quinoa (*Chenopodium quinoa* Willd) to exogenous selenium application. *Plants* **2021**, *10*, 719. [CrossRef]
112. Sytar, O.; Kumari, P.; Yadav, S.; Brestic, M.; Rastogi, A. Phytohormone priming: Regulator for heavy metal stress in plants. *J. Plant Growth Regul.* **2019**, *38*, 739–752. [CrossRef]
113. Ali, M.A.; Asghar, H.N.; Khan, M.Y.; Saleem, M.; Naveed, M.; Niazi, N.K. Alleviation of nickel-induced stress in mungbean through application of gibberellic acid. *Int. J. Agric. Biol.* **2015**, *17*, 990–994. [CrossRef]
114. Jia, H.; Song, Z.; Wu, F.; Ma, M.; Li, Y.; Han, D.; Yang, Y.; Zhang, S.; Cui, H. Low selenium increases the auxin concentration and enhances tolerance to low phosphorous stress in tobacco. *Environ. Exp. Bot.* **2018**, *153*, 127–134. [CrossRef]
115. Alhaithloul, H.A.S.; Abu-Elsaoud, A.M.; Soliman, M.H. Abiotic stress tolerance in crop plants: Role of phytohormones. In *Abiotic Stress in Plants*; Fahad, S., Saud, S., Chen, Y., Wu, C., Wang, D., Eds.; IntechOpen: London, UK, 2020. [CrossRef]
116. Tamaoki, M.; Freeman, J.L.; Marquès, L.; Pilon-Smits, E.A.H. New insights into the roles of ethylene and jasmonic acid in the acquisition of selenium resistance in plants. *Plant Signal. Behav.* **2008**, *3*, 865–867. [CrossRef]
117. Kolbert, Z.; Ortega, L.; Erdei, L. Involvement of nitrate reductase (NR) in osmotic stress-induced NO generation of *Arabidopsis thaliana* L. roots. *J. Plant Physiol.* **2010**, *167*, 77–80. [CrossRef]
118. Abedi, S.; Iranbakhsh, A.; Oraghi-Ardebili, Z.; Ebadi, M. Nitric oxide and selenium nanoparticles confer changes in growth, metabolism, antioxidant machinery, gene expression, and flowering in chicory (*Cichorium intybus* L.): Potential benefits and risk assessment. *Environ. Sci. Pollut. Res. Int.* **2021**, *28*, 3136–3148. [CrossRef]

119. Lu, Q.; Chen, S.; Li, Y.; Zheng, F.; He, B.; Gu, M. Exogenous abscisic acid (ABA) promotes cadmium (Cd) accumulation in *Sedum alfredii* Hance by regulating the expression of Cd stress response genes. *Environ. Sci. Pollut. Res.* **2020**, *27*, 8719–8731. [CrossRef]
120. Pandey, C.; Gupta, M. Selenium and auxin mitigates arsenic stress in rice (*Oryza sativa* L.) by combining the role of stress indicators, modulators and genotoxicity assay. *J. Hazard. Mater.* **2015**, *287*, 384–391. [CrossRef]
121. Qiu, C.W.; Zhang, C.; Wang, N.H.; Mao, W.; Wu, F. Strigolactone GR24 improves cadmium tolerance by regulating cadmium uptake, nitric oxide signaling and antioxidant metabolism in barley (*Hordeum vulgare* L.). *Environ. Pollut.* **2021**, *273*, 116486. [CrossRef]
122. Chen, L.; Hu, W.; Long, C.; Wang, D. Exogenous plant growth regulator alleviate the adverse effects of U and Cd stress in sunflower (*Helianthus annuus* L.) and improve the efficacy of U and Cd remediation. *Chemosphere* **2020**, *262*, 127809. [CrossRef] [PubMed]
123. Sehar, Z.; Iqbal, N.; Fatma, M.; Rather, B.A.; Albaqami, M.; Khan, N.A. Ethylene suppresses abscisic acid, modulates antioxidant system to counteract arsenic-inhibited photosynthetic performance in the presence of selenium in mustard. *Front. Plant Sci.* **2022**, *13*, 852704. [CrossRef]
124. Shi, W.G.; Liu, W.; Yu, W.; Zhang, Y.; Ding, S.; Li, H.; Mrak, T.; Kraigher, H.; Luo, Z.B. Abscisic acid enhances lead translocation from the roots to the leaves and alleviates its toxicity in *Populus* × *canescens*. *J. Hazard. Mater.* **2019**, *362*, 275–285. [CrossRef] [PubMed]
125. Poonam, S.; Kaur, H.; Geetika, S. Effect of jasmonic acid on photosynthetic pigments and stress markers in *Cajanus cajan* (L.) Mill sp. seedlings under copper stress. *Am. J. Plant Sci.* **2013**, *4*, 817–823. [CrossRef]
126. Singh, S.; Prasad, S.M. Effects of 28-homobrassinoloid on key physiological attributes of *Solanum lycopersicum* seedlings under cadmium stress: Photosynthesis and nitrogen metabolism. *Plant Growth Regul.* **2017**, *82*, 161–173. [CrossRef]
127. Šípošová, K.; Labancová, E.; Kučerová, D.; Kollárová, K.; Vivodová, Z. Effects of exogenous application of indole-3-butyric acid on maize plants cultivated in the presence or absence of cadmium. *Plants* **2021**, *10*, 2503. [CrossRef] [PubMed]
128. Khan, N.A.; Asgher, M.; Per, T.S.; Masood, A.; Fatma, M.; Khan, M.I. Ethylene potentiates sulfur-mediated reversal of cadmium inhibited photosynthetic responses in mustard. *Front. Plant Sci.* **2016**, *7*, 1628. [CrossRef]
129. Tai, Z.; Yin, X.; Fang, Z.; Shi, G.; Lou, L.; Cai, Q. Exogenous GR24 alleviates cadmium toxicity by reducing cadmium uptake in switchgrass (*Panicum virgatum*) seedlings. *Int. J. Environ. Res. Public Health* **2017**, *14*, 852. [CrossRef]
130. Ahmad, P.; Ahanger, M.A.; Alyemeni, M.N.; Wijaya, L.; Alam, P. Exogenous application of nitric oxide modulates osmolyte metabolism, antioxidants, enzymes of ascorbate-glutathione cycle and promotes growth under cadmium stress in tomato. *Protoplasma* **2018**, *255*, 79–93. [CrossRef]
131. Sharma, P.; Kumar, A.; Bhardwaj, R. Plant steroidal hormone epibrassinolide regulate–Heavy metal stress tolerance in *Oryza sativa* L. by modulating antioxidant defense expression. *Environ. Exp. Bot.* **2016**, *122*, 1–9. [CrossRef]
132. Bücker-Neto, L.; Paiva, A.L.S.; Machado, R.D.; Arenhart, R.A.; Margis-Pinheiro, M. Interactions between plant hormones and heavy metals responses. *Genet. Mol. Biol.* **2017**, *40*, 373–386. [CrossRef]
133. Rajewska, I.; Talarek, M.; Bajguz, A. Brassinosteroids and response of plants to heavy metals action. *Front. Plant Sci.* **2016**, *7*, 629. [CrossRef]
134. Sah, S.K.; Reddy, K.R.; Li, J. Abscisic acid and abiotic stress tolerance in crop plants. *Front. Plant Sci.* **2016**, *7*, 571. [CrossRef]
135. Wang, J.; Chen, J.; Pan, K. Effect of exogenous abscisic acid on the level of antioxidants in *Atractylodes macrocephala* Koidz under lead stress. *Environ. Sci. Pollut. Res.* **2013**, *20*, 1441–1449. [CrossRef]
136. Sharma, A.; Sidhu, G.P.S.; Araniti, F.; Bali, A.S.; Shahzad, B.; Tripathi, D.K.; Landi, M. The role of salicylic acid in plants exposed to heavy metals. *Molecules* **2020**, *25*, 540. [CrossRef]
137. Ahsan, N.; Renaut, J.; Komatsu, S. Recent developments in the application of proteomics to the analysis of plant responses to heavy metals. *Proteomics* **2009**, *9*, 2602–2621. [CrossRef]
138. Hossain, Z.; Komatsu, S. Contribution of proteomic studies towards understanding plant heavy metal stress response. *Front. Plant Sci.* **2013**, *3*, 310. [CrossRef]
139. Zeng, F.; Wu, X.; Qiu, B.; Wu, F.; Jiang, L.; Zhang, G. Physiological and proteomic alterations in rice (*Oryza sativa* L.) seedlings under hexavalent chromium stress. *Planta* **2014**, *240*, 291–308. [CrossRef]
140. Thapa, G.; Sadhukhan, A.; Panda, S.K. Molecular mechanistic model of plant heavy metal tolerance. *Biometals* **2012**, *25*, 489–505. [CrossRef]
141. Behbahani, S.R.; Iranbakhsh, A.; Ebadi, M.; Majd, A.; Ardebili, Z.O. Red elemental selenium nanoparticles mediated substantial variations in growth, tissue differentiation, metabolism, gene transcription, epigenetic cytosine DNA methylation, and callogenesis in bittermelon (*Momordica charantia*); an in vitro experiment. *PLoS ONE* **2020**, *15*, e0235556. [CrossRef]
142. Handa, N.; Kohli, S.K.; Thukral, A.K.; Arora, S.; Bhardwaj, R. Role of Se(VI) in counteracting oxidative damage in *Brassica juncea* L. under Cr(VI) stress. *Acta Physiol. Plant.* **2017**, *39*, 51. [CrossRef]
143. Schiavon, M.; Berto, C.; Malagoli, M.; Trentin, A.; Sambo, P.; Dall'Acqua, S.; Pilon-Smits, E.A.H. Selenium biofortification in radish enhances nutritional quality via accumulation of methyl-selenocysteine and promotion of transcripts and metabolites related to glucosinolates, phenolics, and amino acids. *Front. Plant Sci.* **2016**, *7*, 1371. [CrossRef]
144. Dutilleul, C.; Jourdain, A.; Bourguignon, J.; Hugouvieux, V. The Arabidopsis putative selenium-binding protein family: Expression study and characterization of SBP1 as a potential new player in cadmium detoxification processes. *Plant Physiol.* **2008**, *147*, 239–251. [CrossRef] [PubMed]
145. Feng, X.; Ma, Q. Transcriptome and proteome profiling revealed molecular mechanism of selenium responses in bread wheat (*Triticum aestivum* L.). *BMC Plant Biol.* **2021**, *21*, 584. [CrossRef]

146. Kumar, I.; Sharma, R.K. Production of secondary metabolites in plants under abiotic stress: An overview. *Significances Bioeng. Biosci.* **2018**, *2*, 196–200. [CrossRef]
147. Akula, R.; Ravishankar, G.A. Influence of abiotic stress signals on secondary metabolites in plants. *Plant Signal. Behav.* **2011**, *6*, 1720–1731. [CrossRef]
148. Akhi, M.Z.; Haque, M.M.; Biswas, M.S. Role of secondary metabolites to attenuate stress damages in plants. In *Antioxidants-Benefits, Sources, Mechanisms of Action*; IntechOpen: London, UK, 2021.
149. Ahanger, M.A.; Bhat, J.A.; Siddiqui, M.H.; Rinklebe, J.; Ahmad, P. Silicon and secondary metabolites integration in plants: A significant association in stress tolerance. *J. Exp. Bot.* **2020**, *71*, 6758–6774. [CrossRef]
150. Delfine, S.; Csiky, O.; Seufert, G.; Loreto, F. Fumigation with exogenous monoterpenes of a non-isoprenoid-emitting oak (*Quercus suber*): Monoterpene acquisition, translocation, and effect on the photosynthetic properties at high temperatures. *New Phytol.* **2000**, *146*, 27–36. [CrossRef]
151. Hassan, A. Effects of mineral nutrients on physiological and biochemical processes related to secondary metabolites production in medicinal herbs. *Med. Arom. Plant Sci. Biotechnol.* **2012**, *6*, 105–110.
152. Nakabayashi, R.; Mori, T.; Saito, K. Alternation of flavonoid accumulation under drought stress in *Arabidopsis thaliana*. *Plant Signal. Behav.* **2014**, *9*, e29518. [CrossRef]
153. Kováčik, J.; Grúz, J.; Bačkor, M.; Strnad, M.; Repčák, M. Salicylic acid-induced changes to growth and phenolic metabolism in Matricaria chamomilla plants. *Plant Cell Rep.* **2009**, *28*, 135–143. [CrossRef]
154. Manquián-Cerda, K.M.; Escudey, G.; Zúñiga, N.; Arancibia-Miranda, M.; Molina, E.C. Effect of cadmium on phenolic compounds, antioxidant enzyme activity and oxidative stress in blueberry (*Vaccinium corymbosum* L.) Plantlets grown in vitro. *Ecotoxicol. Environ. Saf.* **2016**, *133*, 316–326. [CrossRef]
155. Chen, S.; Wang, Q.; Lu, H.; Li, J.; Yang, D.; Liu, J.; Yan, C. Phenolic metabolism and related heavy metal tolerance mechanism in *Kandelia obovata* under Cd and Zn stress. *Ecotoxicol. Environ. Saf.* **2019**, *169*, 134–143. [CrossRef]
156. Tan, P.; Zeng, C.; Wan, C.; Liu, Z.; Dong, X.; Peng, J.; Lin, H.; Li, M.; Liu, Z.; Yan, M. Metabolic profiles of *Brassica juncea* roots in response to cadmium stress. *Metabolites* **2021**, *11*, 383. [CrossRef]
157. Anjitha, K.S.; Sameena, P.P.; Puthur, J.T. Functional aspects of plant secondary metabolites in metal stress tolerance and their importance in pharmacology. *Plant Stress* **2021**, *2*, 100038. [CrossRef]
158. Kiumarzi, F.; Morshedloo, M.R.; Zahedi, S.M.; Mumivand, H.; Behtash, F.; Hano, C.; Chen, J.T.; Lorenzo, J.M. Selenium nanoparticles (Se-NPs) alleviates salinity damages and improves phytochemical characteristics of pineapple mint (*Mentha suaveolens* Ehrh.). *Plants* **2022**, *11*, 1384. [CrossRef]
159. Gul, H.; Kinza, S.; Shinwari, Z.K.; Hamayun, M. Effect of selenium on the biochemistry of *Zea mays* under salt stress. *Pak. J. Bot.* **2017**, *49*, 25–32.
160. Chauhan, R.; Awasthi, S.; Tripathi, P.; Mishra, S.; Dwivedi, S.; Niranjan, A.; Tripathi, R.D. Selenite modulates the level of phenolics and nutrient element to alleviate the toxicity of arsenite in rice (*Oryza sativa* L.). *Ecotoxicol. Environ. Saf.* **2017**, *138*, 47–55. [CrossRef]
161. Astaneh, R.K.; Bolandnazar, S.; Nahandi, F.Z.; Oustan, S. Effect of selenium application on phenylalanine ammonia-lyase (PAL) activity, phenol leakage and total phenolic content in garlic (*Allium sativum* L.) under NaCl stress. *Inf. Process. Agric.* **2018**, *5*, 339–344. [CrossRef]
162. Skrypnik, L.; Styran, T.; Savina, T.; Golubkina, N. Effect of selenium application and growth stage at harvest on hydrophilic and lipophilic antioxidants in lamb's lettuce (*Valerianella locusta* L. Laterr.). *Plants* **2021**, *10*, 2733. [CrossRef]
163. Chomchan, R.; Siripongvutikorn, S.; Puttarak, P.; Rattanapon, R. Influence of selenium bio-fortification on nutritional compositions, bioactive compounds content and anti-oxidative properties of young ricegrass (*Oryza sativa* L.). *Funct. Foods Health Dis.* **2017**, *7*, 195–209. [CrossRef]
164. Farman, M.; Nawaz, F.; Majeed, S.; Ahmad, K.S.; Rafeeq, R.; Shehzad, M.A.; Shabbir, R.N.; Usmani, M.M. Interplay between selenium and mineral elements to improve plant growth and development. In *Handbook of Bioremediation*; Academic Press: Cambridge, MA, USA, 2021; pp. 221–236.
165. Hawrylak-Nowak, B. Effect of selenium on selected macronutrients in maize plants. *J. Elem.* **2008**, *13*, 513–519.
166. Drahoňovský, J.; Száková, J.; Mestek, O.; Tremlová, J.; Kaňa, A.; Najmanová, J.; Tlustoš, P. Selenium uptake, transformation and inter-element interactions by selected wildlife plant species after foliar selenate application. *Environ. Exp. Bot.* **2016**, *125*, 12–19. [CrossRef]
167. Khattab, H. Metabolic and oxidative responses associated with exposure of *Eruca sativa* (Rocket) plants to different levels of selenium. *Int. J. Agric. Biol.* **2004**, *6*, 1101–1106.
168. Elkelish, A.A.; Soliman, M.H.; Alhaithloul, H.A.; El-Esawi, M.A. Selenium protects wheat seedlings against salt stress-mediated oxidative damage by up-regulating antioxidants and osmolytes metabolism. *Plant Physiol. Biochem.* **2019**, *137*, 144–153. [CrossRef]
169. Zhao, Y.; Hu, C.; Wang, X.; Qing, X.; Wang, P.; Zhang, Y.; Zhang, X.; Zhao, X. Selenium alleviated chromium stress in chinese cabbage (*Brassica campestris* L. ssp. Pekinensis) by regulating root morphology and metal element uptake. *Ecotoxicol. Environ. Saf.* **2019**, *173*, 314–321. [CrossRef]