Zinc and Selenium Mitigate Abiotic Stresses in Plants

Subjects: Plant Sciences

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Abiotic stress factors are considered a serious threat to various growth parameters of crop plants. Stressors such as drought, salinity, and heavy metals (HMs) hamper the chlorophyll content in plants, resulting in low photosynthesis, hinder the integrity of cell membranes, reduce biomass, and overall growth and development of crops which ultimately results in the sharp decline of crop yield. Under such stressful conditions, various strategies are employed to overcome hazardous effects. Application of Zinc (Zn) or Selenium (Se) in different forms is an effective way to alleviate the abiotic stresses in plants. Zn and Se play a pivotal role in enhancing the chlorophyll level to improve photosynthesis, reducing oxidative stress by limiting reactive oxygen species (ROS) production, controlling HMs absorption by plant roots and their accumulation in the plant body, maintaining homeostasis, and alleviating all the detrimental effects caused by abiotic stress factors.

abiotic stress drought heavy metals salinity selenium zinc plant health Sustainable agriculture plant nutrition

1. Zinc (Zn) and Selenium (Se) Absorption and Transport in Plants

In normal soil conditions, Zn can react with hydroxides, carbonates, and phosphates to form insoluble precipitates. However, a gradual increase in the soil pH decreases the solubility of Zn. Plants can be able to increase their capacity for Zn uptake by gradual acidification of the rhizosphere. The uptake of Zn depends mainly on two key factors, the type of plant species and the composition of the Zn in media. Translocation of Zn takes place via both the symplast and apoplast pathways from the roots to other plant tissues [1]. In most cases, Zn is absorbed by the plant roots in bivalent forms (Zn^{2+}). However, in some cases, roots take up Zn in the form of ligand–Zn complexes. Among several approaches to Zn absorption, the first significant one is the outflow of organic acids and hydrogen ions (H^+), inducing the liberation of Zn^{2+} ions for the roots of the epidermis to absorb. Another approach is the release of phytosiderophore compounds, which helps in the easy absorption of Zn^{2+} ions by the roots of cereal crops by making stable complexes [2].

There are some dictatorial proteins that help in Zn transportation, such as the ZIP family protein, the heavy metal ATPase (HMA) and metal tolerant proteins (MTP). Among these three kinds of transport protein groups, the ZIP family proteins are known to regulate the absorption of Zn into the cytosol of the cell. On the other hand, members of the MTP protein family promote the segregation of Zn into the vacuoles and endoplasmic reticulum (ER), whereas transportation of Zn^{2+} ions through the apoplast pathway is mediated by the HMA group of transport proteins [3]. Hyperpolarization of root hair cell plasma membrane (RCPM) is the main energy source for the absorption of Zn^{2+} ions, mediated by the action of RCPM H^+/ATPase. Such action enhances the external pumping of H^+ ions in the rhizosphere, which, in turn, hyperpolarizes RCPM and lowers the pH of the soil, resulting in an increased rate of cation intake [4]. As the transporter proteins are not closely linked to the disintegration of ATP, the mechanism of passive Zn intake (through nonselective channels of cations) is more efficient than the active Zn uptake mechanism [5].

Zn transport through roots starts from the epidermal layer and, after that, reaches the endodermis. From the endodermis, Zn^{2+} ions pass the barriers of the Casparian strip zone and enter the zone of living tissue (pericycle and xylem parenchyma) following the symplast pathway. This living zone of the xylem parenchyma allows continuous functioning of the H^+/ATPase system, which eventually induces hyperpolarization of RCPM, resulting in the restriction in Zn^{2+} ion efflux of the cytosol [6].

Se exists in nature in both organic and inorganic forms. Inorganic forms are elemental Se, selenite (SeO_3^{2-}), selenate (SeO_4^{2-}), and selenide (Se^{2-}). On the other hand, major organic forms are SeMet and SeCys [7]. It shares chemical properties with elemental sulfur and thereby can be taken up via sulfate transporters present in the root cells' plasma membrane and assimilated by sulfur-assimilating pathways inside the plants [7]. Finally, it can be volatilized as either Dimethyldiselenide (DMDSe) or Dimethylselenide (DMSe) into the atmosphere [8]. As per the capacity to hold Se inside the cell, plants can be broadly classified into non-accumulator (can accumulate less than 100 mg Se per kg dry weight), secondary accumulator (can accumulate 100–1000 mg Se per kg dry weight), and hyperaccumulator (can accumulate more than 1000 mg Se per kg dry weight) [8]. Younger leaves show higher Se content than older leaves [9], and the vacuole is the main storehouse of Se inside the plant cell [10]. The uptake and distribution of Se in the plant tissue need further investigation to find their transporter proteins and other related factors. The simplest possible routes of Zn and Se uptake and their downstream movement in plants are depicted in **Figure 1**.

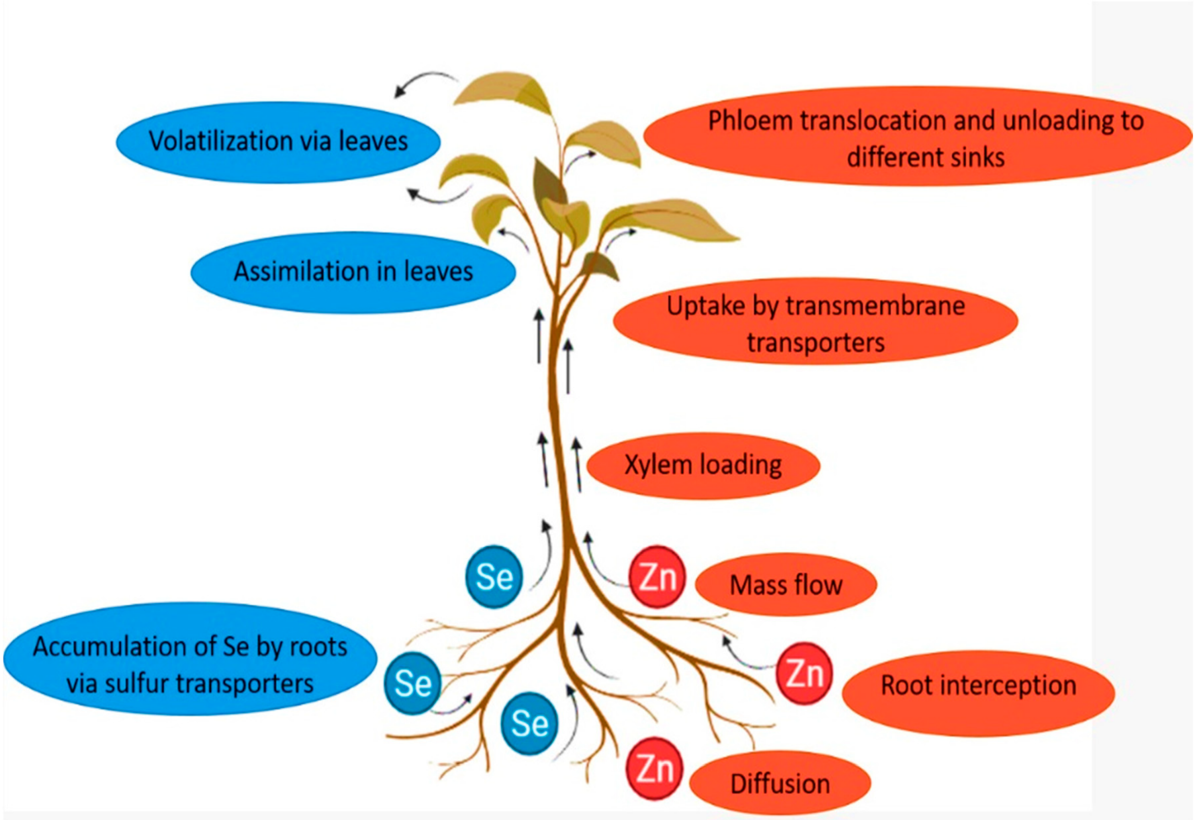

Figure 1. Zinc and selenium uptake and transport in plants.

2. Importance of Zinc and Selenium and the Effects of Their Deficiency on Plants

Zinc and Selenium are the most important micronutrients for plant growth and crop productivity (**Figure 2**). The average requirement of Zn by the plants lies between 15 and 55 ppm [1]. However, in Se-rich soil, the plant is able to intake 55–200 µg per day [8]. Improvement in the quality and quantity of the crops has been noticed after the application of Zn or Se to the soil [11][12][13]. The deficiency of Zn or Se in the soil affects the quality of the crop and also its yield [14]. The application of Zn directly on the leaves of wheat seedlings promotes plant growth and development under critical conditions [15]. It is also helpful in enhancing the chlorophyll content and the rate of photosynthesis in cauliflower plants, consequently advancing plant growth [16]. Similar to Zn, Se promotes the content of chlorophyll and overall growth by reducing oxidative damage in plants. At low concentrations, Se plays an important role in regulating the structure of chloroplast and the fluidity of plasma membrane [17] and delaying senescence. Se induces the absorption of essential macro- and micronutrients in plants. Zn and Se are both considered excellent stress-managing nutrients for a wide variety of crops. They are able to mitigate several abiotic stresses such as salinity [18][19], drought [20], and heavy metal [21], and biotic stresses such as herbivores and pathogens [22]. The positive effects of Zn and Se have been summarized in **Figure 2**.

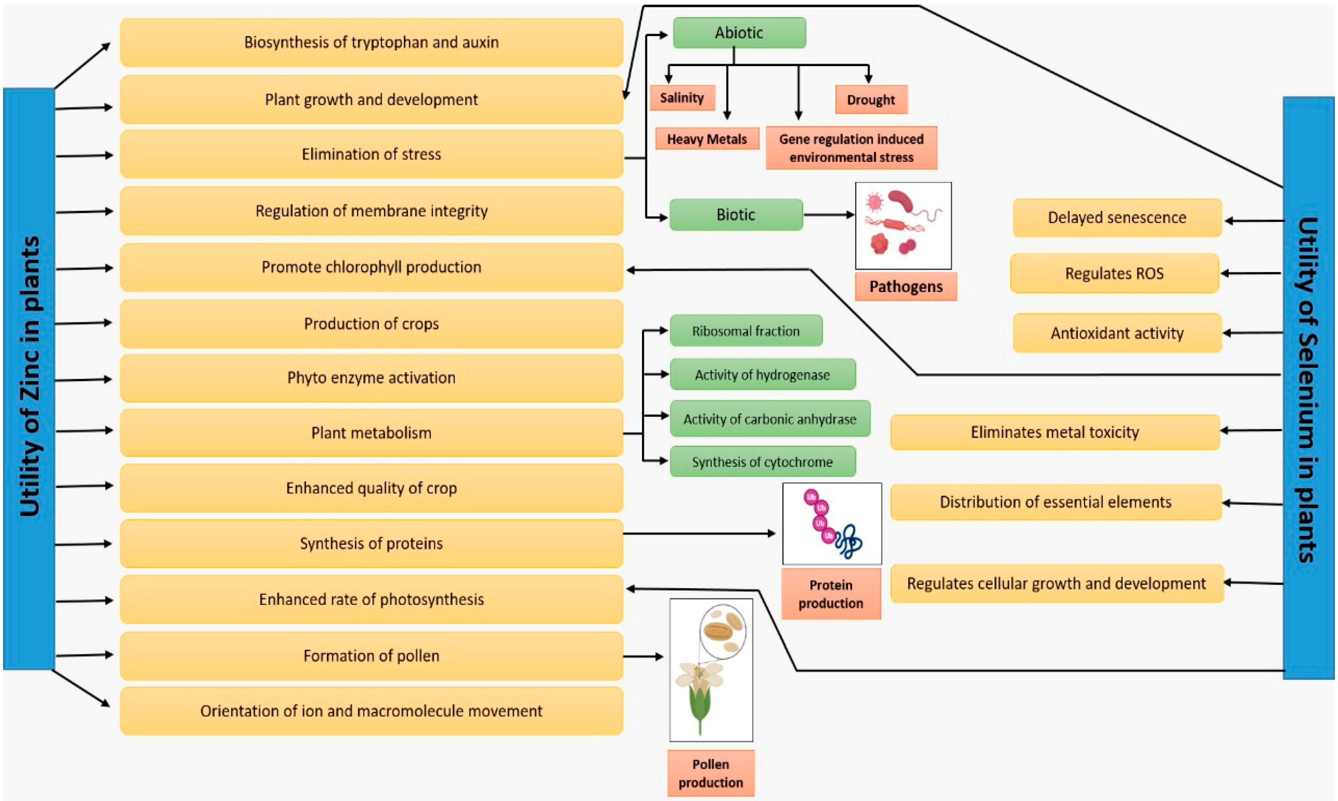

Figure 2. Positive effects of zinc and selenium in plants.

Zn is also useful in contributing to the pigmentation of leaves. However, there are several effects of Zn deficiency observed in different plant parts (**Figure 3**). Discolouration of leaves (i.e., chlorosis) is an indicator of Zn deficiency in the soil. Such discolouration may start at the bottom parts of plants and then gradually spread to the upper parts of plants [1]. At first, after two to four weeks of the sowing of rice seedlings, the initial symptom of chlorosis appears along the midrib region of the leaves, and then gradually, brown spots are observed on the older leaves. Later, these spots elongate, integrate, and provide brown colouration of the leaves. Loss of turgidity is one of the most notable symptoms of Zn deficiency [23]. Zn can regulate the hydrogenase and carbonic anhydrase activity and maintain ribosomal fractions and cytochrome synthesis, which, in turn, play a key role in controlling plant metabolism [24]. Zn activates plant enzymes, helping the conservation of cellular membrane integrity, synthesis of protein, formation of pollen, and balancing the synthesis of auxin [25]. It plays an important role in plants by helping them tolerate several environmental stresses by regulating genes and perpetuating gene expression [24]. Synthesis of a vital plant growth hormone IAA (indole acetic acid) or auxin and its precursor tryptophan is dependent on Zn [26]. Zn is also required for the coherence properties of cellular membranes to conserve the fundamental orientation of macromolecules and ion movement status. It links to the sulfhydryl groups and phospholipids of the transmembrane proteins and ultimately helps regulate the entire membrane [17][24][25][26].

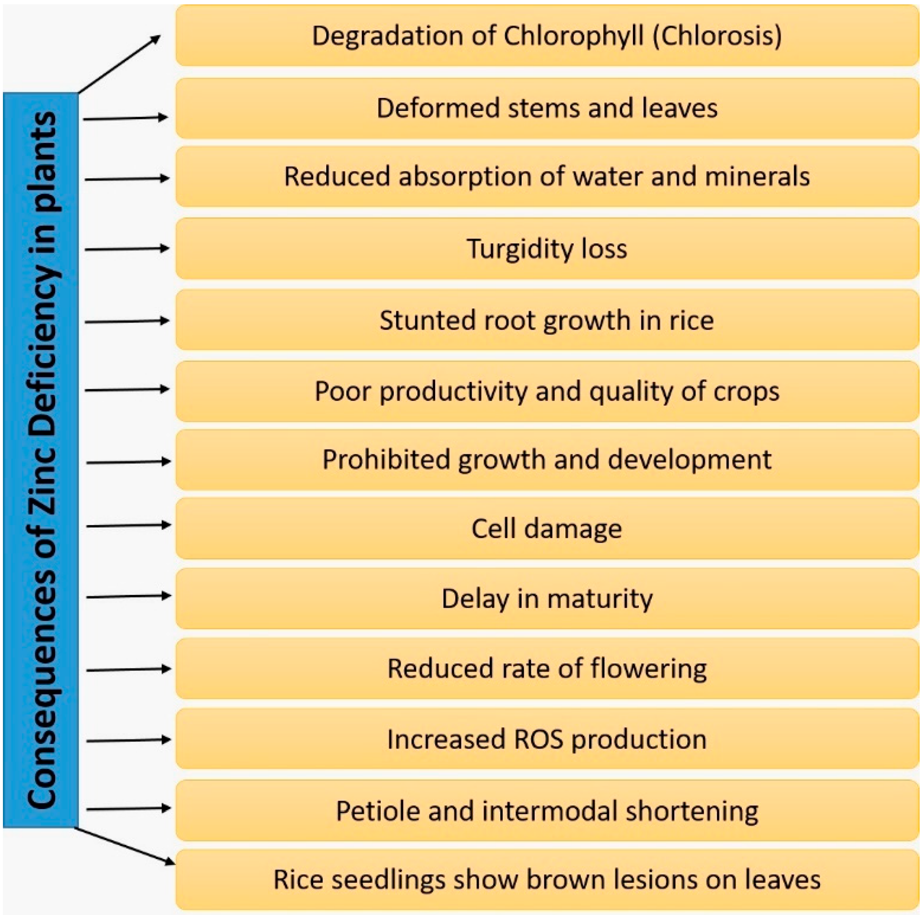

Figure 3. Deficiency effects of zinc in plants.

The quality and productivity of most of the crops are directly proportional to the application of Zn as a mineral nutrient in the soil [27]. There are certain factors responsible for decreased amount of Zn in the soil, such as high $CaCo_3$ content, high pH, phosphate, clay [28], the content of organic matter, type of crop, and the cultivars [23]. Zn deficiency is generally found in some specific types of soils, for example, sandy soils, calcareous soils, soils with a high amount of silicon and phosphorus, and peat soils [26][29]. Numerous visible symptoms of Zn deficiency usually appear up to two to three weeks from the time of the transplantation of the seedlings [30][31]. Such instances have been revealed in some studies with rice seedlings, in which symptoms such as the development of brown-coloured blotches on leaves, stunted growth of the seedlings, a significant delay in maturity, reduced productivity, diminished length of internodes and petioles, and deformed leaves (small in size) and stems have been common. Such distorted-shaped leaves sometimes may appear as ‘rosette’, and stems exhibit fan-shaped structures in the early stages of monocots and dicots, respectively [32]. Moreover, severity may even lead to the death of the rice seedlings [33][34][35]. The correlation between Zn and nitrogen metabolism in plants has been closely observed by many researchers. It is stated that a deficiency of Zn in the soil directly affects root development in lowland rice seedlings [36]. Apart from the root system, a considerable decrease in the absorption of both water and minerals from the soil, reduction in plant growth and crop productivity [29], depletion in the blossoming process [23], high production of ROS, and cell damage [37] have also been noticed in plants as a result of Zn deficiency.

The complex relationships among soil Se concentrations, geology, uptake, and effects in plants, and biofortification in animals were primarily examined in the early stages of research. It has been observed that the varying degree of Se concentration in the soil can produce Se-rich crop plants, which may have toxic effects on livestock. On the other hand, it is also evident that the presence of Se in high doses may also alter the natural growth and development of plants. Plants may suffer because of Se toxicity to various extents. Their growth is generally stunted, and plants may die prior to the normal ones. Mostly the leaves show symptoms in the affected plants and may exhibit chlorosis. Sometimes drying and withering of leaves were observed, caused by the high toxic concentration of Se in the soil. On the other hand, few plants are able to safely accumulate huge amounts of Se into different storage organs, while others cannot. Furthermore, the effects are completely reversed in the absence of Se in soil. As the requirement of Se for regular plant metabolism is minimal, there are no such prominent Se-deficiency effects observed in plants. However, the quality and productivity may be hampered [13].

3. Process of Zn and Se Application, Its Downstream Effects on Plants

There are several methods tested for the safe application of Zn to the soil or the plant. However, the process of absorption of Zn by plants mainly depends on the type and form of the soil [1]. The soil containing a relatively larger amount of sand possesses a lower Zn absorption capacity compared with the soil containing more clay. The Higher Zn absorption capacity of the clayey soil is regulated by its higher CEC value (i.e., an estimation of the soil's absorption and retention of water). So, eventually, the sandy soil (lighter in weight) has a lower CEC value. As the clayey soil has a high CEC value and has the ability to fix more Zn, it results in the unavailability of this mineral nutrient for the plants [23].

Zn and Se can be implemented in various ways (**Figure 4**), for instance, by spraying the leaves in the agricultural field and using Zn powder or solution on the seeds [23]. Sometimes plant leaves are treated with Zn sprinkled upon them, by which Zn can be easily absorbed by plant leaves (most commonly used method). Foliar Zn application (1.5 kg ha^{-1}) is reported as the easiest and most economical way to improve the yield of maize and wheat [38]. According to Leach and Hameleers [39], a remarkable increase has been observed in the starch quantity and crop yield in corn after the foliar application of Zn (140 g Zn L^{-1}). Similar to Zn, foliar and soil applications of Se are very useful for crop plants. According to Boldrin et al. [40], the quantity of Se in the soil increases because of its application directly to the soil. They also showed that foliar application of Se in the form of selenate and that, consequently, selenite enhances the productivity of rice. However, soil application of Se was found to be more effective than its foliar application for the production of shoot dry matter. Impact of Zn and Se application on plants has been summarized in **Table 1**.

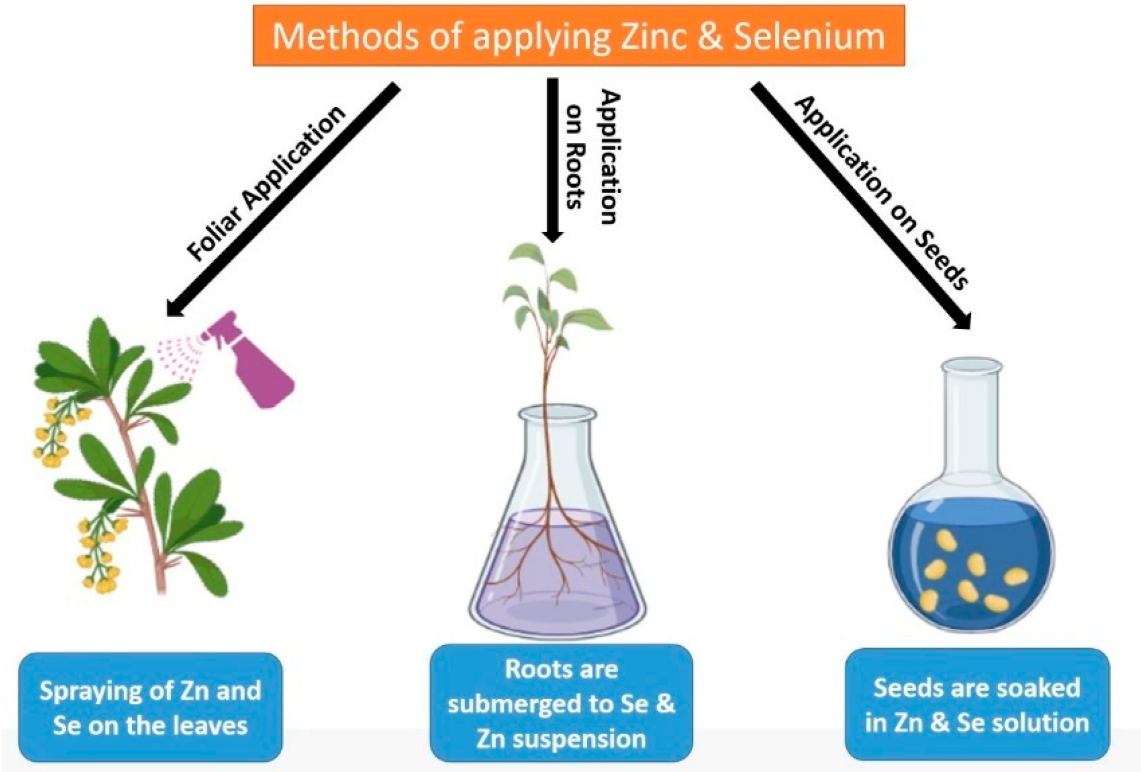

Figure 4. Methods of application of both Zn and Se in plants.

Table 1. Impact of Zinc and Selenium application on plant leaves and soil.

Name of Plant.	The Part on Which Zn Is Applied	Utilities as a Result of Zn Application	References
Maize	Foliar application	Increases starch content Improves crop yield	[35]
Mungbean	Foliar application	Increases the growth and productivity of the crop	[38]
Maize and Wheat	Foliar application	Enhances the yield of both the grains	[34]
French Bean	Foliar application	Improves in the physiological traits Enhances crop quality Improves productivity of grains	[39]
Maize	Soil	Advances crop yield	[41]
Wheat	Soil	Increases in grain productivity	[42]
Wheat	Foliar + soil	remarkable boost in the yield	[9]
Bread wheat	Foliar + soil	Improves the growth rate Enhances crop productivity	[10]

Name of Plant.	The Part on Which Zn Is Applied	Utilities as a Result of Zn Application	References
		Increases Zn content in wheat	
Garden pansy	Foliar application of Se in the form of sodium selenate	Increases fresh weight by 25.10% Increases dry weight by 25.41%	[41]
Rice	Foliar application of Se in the form of selenate and selenite	Enhances the productivity of rice grains	[37]
Rice	Soil application of Se	Produces more shoot dry matter	[37]
Oat	Foliar + soil application of Se in the form of Se fertilizer	Improves Se transport Enhances crop yield	[42]
Atractylodes macrocephala	Foliar application of Se	Increases the growth and survival rate Enhances crop yield	[43]

he growth rate and productivity of mungbean [44]. Improvements in the physiological trait, quality, and productivity have been noted in beans (*Phaseolus vulgaris* L.) as a result of foliar application of Zn with 3 mg L^{-1} [45]. Soil can be fortified with a larger quantity of Zn as a mineral nutrient by direct spray [46]. Soil supplied with Zn (12 kg ha^{-1}) exhibited improvement in the maize yield [47]. This is supported by another study in which it is clearly documented that the application of Zn (15 kg ha^{-1}) to the soil shows a crucial increase in the productivity of wheat grains [48]. Sometimes a combined Zn application to both leaves and the soil enhances the results.

4. Role of Zn and Se in Plants under Salinity Stress

Salinity stress or salt stress in the soil is one of the most common factors well known for its several deleterious effects on a variety of plants. Salinity in the soil makes it really difficult to produce a significant amount of crops [49]. It leads to an increase in sodium and chloride ions in the soil in considerable amounts [50]. Salt stress is one the major reasons for nutrient imbalance both in the soil and crops, which eventually results in the inhibition of enzymatic actions, membrane damage, and may even lead to plant death [51]. Salinity stress enhances the toxicity level of ions in the soil and decreases the accumulation of essential nutrients, as a result of which water availability is reduced in crop seedlings [52].

Among all the essential micronutrients, Zn is known for its ability to alleviate salinity stress in the soil for better growth of crops [53]. Al-Zahrani et al. [18] used *Vigna radiata* (L.) Wilczek seedlings as their experimental plant material. They compared the effects of salt stress in the control set of mung beans (without Zn treatment) to salt-stressed mung bean seedlings with Zn treatment. From this comparative study, they reported less oxidative damage in the Zn-treated mung bean seedlings than in the control set. They also concluded that salt-stressed plants with Zn treatment show more enzymatic activity in comparison with mung beans with Zn application. In this way, Zn improves tolerance against salt stress. Hussein and Abou-Baker [19] studied the contribution of nano Zn in cotton plants under salinity stress. They used nano Zn as soil fertilizer in their study and found some positive responses. At the end of their experiments, they concluded that nano Zn-treated cotton leaves could alleviate the detrimental effects of salt stress by enhancing growth rate and productivity.

Under high salinity stress, the application of nano Zn to the soil enhanced crop productivity in Triticale by 39% compared with the control set without nano Zn addition [54]. Significant improvement in fresh weight and dry weight in rice [55], production of biomass in sunflower [56], and crop yield in wheat [57] have been reported under salt stress as a result of the application of nano Zn at the rates of 25 or 50 mgl^{-1}.

On the other hand, Alharby et al. [58] used soybean to show the effects of salinity stress and also the role of Se in mitigating the damage caused by salt application to soybean plants. As per their study, foliar application of Se exogenously enhanced some antioxidant enzyme activities such as catalase (CAT), peroxidase (POD), and glutathione reductase (GR), together with a few nonenzymatic antioxidants such as glutathione (GSH) and GSH/glutathione disulfide (GSSG). As a result, soybean plants dispose of the adverse effects of oxidative damage by activating an antioxidant defence mechanism. Instead of individual application of Se and Zn, El-badri et al. [59] used Se and Zn together in the form of oxide nanoparticles (SeNPs and ZnONPs) to show their combined role in combating salt stress in *Brassica napus* during the early stage of germination. In this study, SeNPs and ZnONPs exhibited significant elevations in the rate of germination, antioxidant enzyme activity, the microstructure of the seeds, and an overall improvement in plant growth and development under salt stress. Reports have also shown significant promotion in the growth and rate of photosynthesis in tomato seedlings with the application of Se under salt stress by boosting chloroplast antioxidant defence mechanisms [17].

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