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Zinc Nutrition: Functional Roles, Deficiency Impacts, and Evolving Strategies for Optimized Uptake and Utilization

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Abstract: Zinc (Zn) is a vital micronutrient that plays a critical role in supporting the physiological health and proper functioning of both plants and humans. In this sense, it is indispensable in plant biology to activate a multitude of enzymes, synthesize proteins and regulate the hormonal activity. A deficiency in zinc disrupts these fundamental processes, often resulting in stunted growth, delayed crop maturation, chlorosis, and ultimately, diminished agricultural productivity. The prevalence of zinc deficiency is particularly notable in soils characterized by elevated pH levels, excessive phosphorus concentrations, and inadequate zinc bioavailability, which has a direct adverse impact on agricultural productivity. In the context of human health, the consumption of crops deficient in zinc can precipitate severe health issues, including an impaired immune response, cognitive decline, and hindered growth. This review aims to explore the critical roles of zinc in plant and examine the repercussions of its deficiency on plant vitality. Furthermore, it considers various strategies to enhance zinc availability, encompassing traditional practices such as soil and foliar applications, alongside innovative methodologies like the utilization of zinc nano particles and fortified fertilizers. By using these strategies, it’s possible to boost zinc levels in crops, improving both crop yields and human nutrition. The review highlights the importance of combining different fields of research to find effective solutions for improving zinc nutrition and fighting global malnutrition.

Keywords: Micronutrient, Plant nutrition, Zinc deficiency, Zinc fertilizers, Zinc nano particles

Introduction:

Micronutrients are the element that are necessary for all higher plants but whose requirement and accumulation are minimal (Sherefu & Zewide 2021); it is typically expressed in milligrams per kilogram of soil or biomass or in grams per hectare. Essential micronutrients including zinc (Zn), iron (Fe), copper (Cu) molybdenum (Mo), and boron (B), are acknowledged for their fundamental roles in supporting plant growth and developmental processes. Zinc, an indispensable micronutrient, plays a pivotal role in various essential metabolic pathways (Rout & Das 2003;

Aravind & Prasad 2005a, b). The chemical element Zinc is denoted by the symbol Zn; it occupies the first position in group 12 (IIB) of the periodic table and possesses an atomic number of 30. Zn is classified as one of the transition metalsandis solid at room temperature. Major Zn containing ores are Calamine (Zn silicate) and Zn blende (Zn sulfide). China, Australia and Peru are among the main mining regions. In commercial sector, Zn is extracted from its ore by roasting and concentrating the ore followed by electrolysis or heating with carbon to reduce it to Zn. It is essential not only for numerous enzymatic reactions, metabolic activities, and redox processes but also for crop nutrition and the growth of humans, animals, and plants. Various enzymes participating in protein synthesis, energy transfer and nitrogen metabolism also require zinc in the function. In addition to slowing down plant growth and yield, Zn deficiency affects people. More than three billion people globally experience deficiencies in iron and zinc, a condition particularly prevalent in areas where diets are predominantly cereal-based. In these types of diets, a significant portion of both iron and zinc is found in the outer layers of grains, which are commonly eliminated during the processes of milling and polishing.

Biochemical functions of Zn:

Bowen (1979) documented that in plants grown on uncontaminated soils, the metal concentrations usually range from 0.2 to 4 mg/gm dry weight, and in soil the zinc concentration may be less than 125 ppm. While zinc is found in low abundance in plants, it is an essential plant trace element associated with a wide variety of physiological and biochemical processes necessary for the optimum growth and health of plants. Zinc is the major constituent of many metalloenzymes and it also acts in ribosomal structure and is present in the cytoplasm. As a structural component and regulatory cofactor of a generalized spectrum of enzymes and proteins engaged in such basic metabolic processes that are vital to plant growth and development, zinc is also important and this function has proven to be quite complex. These pathways include protein metabolism, auxin regulation, pollen development, maintenance of membrane integrity, carbohydrate metabolism during photosynthesis, starch synthesis from sugars, and the plant's defense mechanisms against pathogens (Alloway2008).

It also provides catalytic action in the oxidation process. Almost all plant enzyme groups are represented by the 59 different types of Zn-containing enzymes. The metabolism of nitrogen and nucleic acids, as well as the glycolate, TCA (Tricarboxylic Acid Cycle), and pentose phosphate pathways, are all facilitated by Zn. Plants require a transition metal like Zn for auxin (Indole 3 Acetic Acid)and protein synthesis, chlorophyll synthesis, carbohydrate metabolism. This is a because actually zinc plays a vital role in supporting plant growth by triggering stem growth elongation, which can provide direct improvement to development and load (Arshewar et al. 2018). Abnormal grain crop progression due to zinc deficiency has been reported in the case of possessing problems in the development and maturation of panicles (Alloway 2004). Low yield, besides, failure to avail maximal nutritional and commercial yield of harvested crops, is caused by insufficient zinc.Furthermore, zinc enhances plant's ability to absorb and transport water efficiently (Disante et al. 2010), and has been shown to buffer plants against short-term environmental stressors such as elevated temperatures (Peck & McDonald2010) and saline conditions.

According to Alloway (2004), zinc is biochemically required for auxin synthesis, as it is essential for the production of tryptophan, a primary precursor in the biosynthetic pathway of this key plant growth-regulating hormone. Zinc has a further structural and regulatory function in stabilization of membrane integral cellular macromolecules, ion transport systems and the integrity of stable cellular membranes. Zinc is further involved in optimizing photosynthetic performance by supporting electron transport in Photo system II, sustaining photochemical activity in thylakoid membranes, and enhancing chlorophyll synthesis, thereby improving the photosynthetic capacity of plants (Roach & Liszkay 2014). As stated by Qiao et al. (2014), applying zinc to the rice leaves topically increased the activity of zinc dependent enzyme carbonic anhydrase that functions in photosynthesis. Cherif et al. (2011) reported that the application of zinc in Solanum lycopersicum led to increased activity of crucial antioxidant enzymes, including ascorbate peroxidase (APX), Catalase (CAT), and Superoxide Dismutase (SOD). This suggests that zinc may contribute significantly to the plant's defense against oxidative stress by enhancing its ability to neutralize reactive oxygen species (ROS). Application of Zn (seed priming) enhances maize, wheat, and chickpea germination and yield in a variety of environmental circumstances and interlinkage of zinc with sulphydryl groups and phospholipid of membrane proteins contributes to membrane stability.

Impact of Zn on Plant Morphology and Physiology

a. **Root and shoot length:**

Due to decreased nutrient remobilization from reserves to the embryo, drought stress shortens plumules and decreases their dry weight. Zn application enhances the production of Gibberellic acid (GA3) and IAA during shortage of water, and the production of these phytohormones increases embryonic shoot weight and length during stress caused due to water scarcity. Increase in Zn in soil in more than optimum concentration result in decreasing the length of cluster bean plants' roots and shoots. It was seen that cluster bean roots and shoots were longer at 50 and 100 mg/kg (Vijayarengan P 2013), whereas higher concentrations inhibited root and shoot length. Sharma and Sharma (1993) recorded similar decline in plant height in wheat under different metals, while Kalyanaraman and Sivagurnathan (1993) observed the same in blackgram and Moustakas et al. (1994) exhibited in Avena sativa. Direct root growth restriction can occur due to excessive Zn levels which can block cell division, elongation or both. This diminishes the soil area accessible for nutrient and water absorption and transport, resulting in mineral deficiencies. (Foy1988). According to Kalaikandhan et al. (2014), the plants of S. portulacastrum treated with Zn (100, 200 and 300 mg/kg of soil) showed higher root lengths. However, the shortest root length occurred on all sampling days at the 600 mg/ kg of Zn level. On every sampling day, plants of S. portulacastrum treated with Zn at 100, 200 and 300 mg/kg of soil exhibited increased shoot length. Increasing Zn concentrations above this threshold had negative impacts on root length. Zn toxicity can have a variety of direct and indirect effects on almost every physiological metabolism process in the plants (Shen et al. 1998). Modification of enzyme catalytic function, cell membrane damage and growth inhibition of root are shown to be the main mechanism of heavy metal toxicity. The suppressive imapct of excess copper and Zn on cell division and other photosynthesis, respiration, and protein synthesis may be responsible for the suppressive imapct on root and shoot elonation. Clearly these had a role in postponing normal growth.The Machano et al. (2002) and Hagemayer & Breckle (2002) also suggested that metal toxicity in plants causes morphological and structural consequences such as reduced root elongation, tip root damage, collapse of root hairs, a reduced rate of root formation, an increased suberification and lignification, a smaller root vessel diameter, increased structural change in the hypodermis and endodermis. According to Lombardi & Sebastiani (2005), who previously reported on the phenomenon, plant height was significantly reduced compared to a corresponding decrease in root growth in Prunus cerasifera.

b. Relative water content (RWC):

Typically, plant physiological responses to drought stress are studied using the relative water content, which is crucial parameter to assess plant water status (Silva et al. 2010).

Zn is an important macronutrient controlling the amount of water in plants, as Zn is responsible for physiological functions such as photosynthesis, enzyme activity and stress response. While a Zn deficiency can result in a lower relative water content (RWC) because of compromised root function and elevated transpiration rates, adequate Zn levels aid in maintaining cell turgor and minimizing water loss. Kader et al. (2017) reported that their own study demonstrated that when stressed plants were supplemented with Zn, it significantly increased their RWC which indicates that Zn enhances plant capabilities to retain water under drought conditions. Zn application increases the antioxidant activity and decreases the electrolyte leakage that increases the stability of membrane and enhances the RWC in drought stress. Zinc supplementation, under water scarcity conditions has been found to enhance the activity of antioxidant enzymes (Hassan et al.2020), increase stomatal conductance and RWC while reducing electrolyte leakage.

Kapur & Singh (2023) reported that Zn supplementation increased RLWC in soybean plants under Cd stress. Applying Zn improves the growth of the root system and increases the number of root tips, which facilitates water uptake (Zaman et al. 2018). Zn enhanced the formation of vascular tissue and, consequently, RLWC, preventing its destruction under adverse conditions (Gadallah & Ramadan 1997) Zn supplementation was associated with improved water content, leaf pigment level, photosynthetic rate, and decreased electrolyte leakage in mustard plants under Cd stress (Ahmad et al. 2017).

c. Cell Membrane Stability/ Electrolyte leakage:

More than half of zinc's role in plant function can be attributed to its strong chemical interactions with sulfhydryl (–SH) groups, which helps maintain the construction and correct biological functioning of biological membranes (Rengel, 1995a, b; Sadeghzadeh & Rengel 2011). In addition to this, this micronutrient is an essential element of the Cu/Zn-SOD enzyme, acting as a first line of defense against oxidative stress through catalyzing breakdown of ROS and other possible damaging oxidants (Cakmak & Marschner 1998). Through these roles, zinc contributes not only to cellular stability but also to the broader resilience of plant systems under environmental stress. Additionally, it safeguards membrane lipids and sulfhydryl-containing compounds in plants against oxidative stress (Cakmak 2000a, b). Secondly, Zn deficiency different from Ca deficiency in the sense that Zn deficiency impairs membrane function and cannot be reversed (Welch et al. 1982).

Zn is unique, because although it is divalent also, it is stable in biological media since it cannot undergo redox cycling. Based on these characteristics, Zn allows for ROS to be protected from the membrane lipids while stopping ions from leaking out of ion channels. In conclusion, drought stress has been shown to suppress antioxidant activity, while simultaneously increasing malondialdehyde (MDA) levels and ion leakage (Ghanepour et al. 2015). The environmental stress has been reduced and as a result, the oxidative damage has been decreased, which, in turn, has resulted in decreased MDA content and loss of electrolytes by applying zinc. It additionally induces action of a few critical important antioxidant enzymes, similar to SOD and Peroxidase (POD). Additionally, research by Kapur &Singh (2023) demonstrated that zinc application in soybean effectively reduces the heightened electrolyte leakage caused by cadmium-induced stress. Zn supplementation prevented ion leakage with a higher Membrane stability index (MSI) and induced an increase in RWC for counteracting adverse effects caused by water availability deficit due to Cd.

d. Photosynthesis:

In the chloroplasts of C3 plants, Carbonic Anhydrase is one of the most prevalent metalloenzymes that contain Zn. Rubisco (Ribulose-1, 5-bisphosphate carboxylase/oxygenase), a key enzyme involved in photosynthesis, requires zinc for its function and facilitates the diffusion of carbon dioxide into chloroplasts (Hatch & Slack 1970). A lack of enough zinc in plants frequently is marked by leaf chlorophyll content sharply reduced and with a decreased chlorophyll a:b ratio, both of which are indicative of disruption in Photosystem II (PSII) efficiency at quantum level (Chen et al. 2008a). Also, the activity of antioxidant enzymes declines due to zinc deficiency thus inducing elevated oxidative stress especially at tips of chloroplasts of leaves. This increased stress is largely attributed to impaired energy transfer between PSII and Photosystem I (PSI), disrupting the normal flow of excitation energy essential for optimal photosynthetic function (Chen et al. 2009). As a consequence of reduced PSII density per unit leaf area, the photosynthetic centers become compromised, leading to decreased photosynthetic capacity and increased susceptibility to photodamage (Chen et al. 2008b).Zn supplementation improves photosynthesis under drought stress by repairing PSII processes and integrating the Rubisco structure. Additionally, supplementing with Zn during periods of water deficit enhances photosynthetic rates and chlorophyll content, mitigating the effects of drought.

e. Photosynthetic pigments (Chlorophyll and carotenoid):

Zn levels in the soil had a significant impact on carotenoid and chlorophyll biosynthesis, as evidenced by the wide variations in leaf chlorophyll content. It is clear that improved growth was the cause of the higher chlorophyll content at lower Zn levels.

According to observations by Kapur &Singh (2023), Zn plays a counteractive role in restoring leaf pigments like carotenoids and chlorophyll that have been depleted by Cd. Cd toxicity causes inhibition of chlorophyll biosynthesis and lowers production of the first common precursor of tetrapyrrole rings, δ aminolevulinic acid (ALA), by interference with sulfhydryl groups (-SH) of ALA dehydratase and proto-chlorophyllide reductase (Gadallah 1995; Prasad & Strzalka 1999). Another reason is that Cd causes pigments loss because it favors the overproduction of the ROS, which inhibits the formation of chlorophyll precursor, disrupts the thylakoid membrane, PS I and II mediated electron transport system and the chlorophyll lamellae (Laspina et al. 2005). The enzyme ALA dehydratase uses Zn or magnesium (Mg) ions to change ALA into porphobilinogen. They are also shielded from thiol oxidation by Zn's binding to the protein moiety's -SH group (Cakmak 2000). As the first line of defense, Zn is crucial because it detoxifies ROS as a co-factor of the SOD enzyme. In many crop species, including rice (Adil et al. 2020), tomatoes (Cherif et al. 2011) and mustard (Ahmad et al. 2017)the ability of Zn to preserve the amount of leaf pigments under stress has been demonstrated. Zn stimulates electron transport via PSII, photosynthetic rate, photochemical reaction, and chlorophyll synthesis. Zinc application, both through foliar sprays and soil amendments, has been shown to enhance carotenoid accumulation in wheat. Hasan et al. (2012) reported that Chenopodium album exhibited the highest levels of chlorophyll a, chlorophyll b, and total chlorophyll when grown in soil containing 300.7 mg/kg of zinc. Generally, chlorophyll accumulation is suppressed by plant exposure to heavy metal stress. They are such decreased mainly due to two mechanisms: They diminished the key enzymes during synthesis of chlorophyll such as ALA dehydratase and protochlorophyllide reductase (Van Assche& Clijsters 1990) and second, they are competing for an uptake and availability of vital micronutrients like magnesium (Mg) and iron (Fe) which is an essential cofactor in the chlorophyll biosynthetic pathway (Kupper et al.1996).

f. Antioxidative enzymes:

The best markers of stress are increases in cluster bean catalase, peroxidase, and polyphenol oxidase activity; measuring these enzymes' activity may help identify invisible damage that plants under metal stress sustain.

The overproduction of ROS during drought stress leads to cell membrane damages and accumulates MDA that will result to cell death. However, application of Zn under drought stress decreases MDA content, indicating that Zn is quite helpful in protecting the cell membrane against ROS during drought stress (Wu et.al. 2015). To withstand the oxidative damage triggered by drought, plants activate a complex enzymatic defense system designed to neutralize ROS (Reddy et al. 2004). Central to this system are different forms of SOD specifically, Cu/Zn-SOD, Mn-SOD, and Fe-SODwhich function by converting harmful superoxide radicals ($O_2^{\bullet -}$) into less reactive molecules such as H_2O_2 and oxygen (Gratao et al. 2008). Zinc is a vital element in Cu/Zn-SOD enzyme, where it helps regulate ROS levels by stabilizing the enzyme's structure through its interaction with histidine and cysteine residues (Tsonev et al. 2012).

It has been shown through research that application of zinc has considerably increased both expression and activity of enzymatic antioxidants and decreased MDA content, an indicator of oxidative stress (Kapur &Singh2019). It is known that zinc treatment significantly enhances the activity of SOD, CAT, and APX in crops like rice and cotton under drought conditions (Thounaojam et al. 2014; Wu et al. 2015). These results suggest that zinc is involved in enhancing plant antioxidative defense system and preventing cellular damage under water stress conditions. Additionally, Prasad et al. (1999) and Chen et al. (2000) also reported similar earlier results that higher levels of zinc in the soil positively influenced the activity of catalase, peroxidase and polyphenol oxidase.

g. Starch and reducing sugars:

Zn supplementation depleted the starch and reducing sugars in the soybean crop accumulated under Cd stress (Kapur &Singh 2023). Rosa et al. (2009) found that, stress causes a negative impact on sugar translocation through the source sink mechanism and carbon assimilation. To maintain osmotic homeostasis, water potential and base metabolism, plants tend to secrete high soluble sugars in their laminas (Zoufan et al. 2020). Besides osmo-protection function, sugars are also involved in many other important processes such as signaling, energy production, turgor pressure, and membrane integrity. Under the above-mentioned conditions, Cd affects not only the antioxidative metabolism, but also disrupts the enzymes participating in Calvin cycle and carbohydrates metabolism. In stressed soybean cultivars the level of soluble sugars which serve as important osmolytes, were reduced and Zn treatment helped in elevating the level of these osmolytes (Karami et al. 2016).

Zn deficiency:

Zinc deficiency in soils is a widespread issue across extensive agricultural regions in countries such as Brazil, China, India, Bangladesh, and Australia. It is considered the most prevalent micronutrient deficiency affecting crop production globally (Broadley et al.2007; Cakmak 2008) Several contributing factors have led to this widespread deficiency in cultivated soils. In particular, zinc deficiency in major staple crops like rice is often associated with specific soil characteristics, including low total zinc content, elevated levels of calcite, high concentrations of bicarbonate ions and salts, as well as excessive availability of phosphorus (Alloway 2008). The physiological strain triggered by Zn deficiency leads to abnormal plant development.

Symptoms of Zn deficiency:

Zn deficiency in crops can be signaled by various plant species with a wide range of symptoms combinations of different degrees of seriousness. In soils with mild Zn deficiency, yields may decrease, and quality may suffer without visible symptoms, a condition known as 'hidden' (or 'latent') deficiency. Severe Zn deficiency can manifest through a range of distinct visual symptoms, including interveinal or patchy chlorosis, necrotic spots on the leaves, bronzing or reddish-brown discoloration, and abnormal leaf clustering. Additional signs include reduced leaf expansion, distorted foliage, inward curling of the leaf blade, and inhibited stem elongation, ultimately resulting in overall plant stunting (Broadley et al. 2007; Alloway 2008). In plants, Zn inadequacy leads to biochemical and tissue related alterations. This incorporate deposition of free amino acids, a decline in auxin levels, an elevation in activity of peroxidase, and impaired protein synthesis. Additionally, plants lacking Zn exhibit expanded tips underdeveloped meristematic cells, and spherical-bodied nucleus.

In addition to impacting agricultural productivity, the deficiency has negative consequences on human nutrition, since many crops cultivated on Zn deficient soils do not contain sufficient complement of Zn, and are a risk factor for micronutrient malnutrition in the populations depending on it. Addressing soil Zn deficiency typically involves soil testing, proper fertilization with Zn-containing fertilizers, and the implementation of agronomic practices aimed at enhancing Zn bioavailability, thereby improving plant health and crop productivity.

Zn nanoparticle

Advantages of creating Zinc oxide nanoparticles (ZnONPs) with eco-friendly ingredients rather than hazardous chemicals are sustainability and suitability for pharmaceutical and medical applications. These substances include biopolymers, natural materials, plant leaf extract, bacteria, fungi, and algae. Green ZnO NPs have been made from a variety of plant extracts, such as Trifolium pratenese, Laurus nobilis, Pyrus pyrrifolia, Ocimumbasilicum, Cassia fistula, and Artocarpus gomezianus. Basit et al. (2022) recently studied the possibility of using ZnO NPs to overcome chromiumtoxicity in rice plants. They discovered that while exposure to chromium was very toxic to seed sprouting and early seedling growth, the addition of ZnO NPs effectively mitigated this toxic effect. There was a marked improvement in several germination related indices such as germination percentage, energy, index and over all seedling vigour for the treated plants.

Moreover, ZnO NP application also caused enhanced activity of antioxidant key enzymes, including CAT, SOD, and POD, to enhance stress tolerance. The treatment also caused biomass accumulation and elevated the absorption of vital micronutrients such as zinc and iron. Notable is that it decreased oxidative damage expressed by reduced lipid peroxidation and electrolyte leakage and similarly restricted chromium uptake in addition to its accumulation in plant tissues. These results suggest that ZnO NPs may be of utility in improving plant resilience in heavy metals polluted environment. A decline in endogenous abscisic acid (ABA) levels, alongside increased levels of growth-promoting hormones such as brassinosteroids, likely contributed to improved plant height under ZnO NP treatment.

Ramzan et al. (2023) investigated the effects of ZnO NPs synthesized using Fagonia extract (referred to as Fagonia-ZnO NPs) on Zea mays exposed to chromium (Cr) stress. Their findings revealed that the external application of these nano particles effectively alleviated the toxic impacts of chromium, which typically infiltrates plants through contaminated soil. Significant decrease in root and shoot length and fresh weights, total soluble sugars, chlorophyll, and proline contents and activities of CAT, POD and APX was observed on exposure to chromium stress. Similarly, the negative effects of pesticide were countered by the use of zinc oxide nanoparticles from Fagonia. The increased biomass accumulation, shoot and root growth, amount of chlorophyll and antioxidant enzyme activity (as a very large protective response to chromium toxicity) in turn in plants treated with exopolysaccharide.

Zn fertilizers

Zinc deficiency significantly undermines crop yield and quality, prompting widespread use of zinc-enriched fertilizers in modern agriculture. Although soil application remains a common practice, foliar spraying is often favored for high-value crops like grapevines, fruit trees, &certain annual species due to its rapid effectiveness. Beyond these conventional methods, additional strategies like seed priming and root dipping specially in transplanted crops such as riceare also employed to minimize yield reduction and enhance plant performance under zinc-limited conditions.

Zinc is usually applied to soil at rates between 4.5 and 34 kilograms per hectare, with zinc sulfate being the most commonly used source. This compound is often applied either as a liquid spray or incorporated into the seedbed to ensure effective nutrient delivery. Banded soil applications may be more effective than broadcasting for certain crops, such as maize, enabling the use of less zinc fertilizer. During banding, the fertilizer is positioned 5 cm below and 5 cm to the side of row planted seeds. The water solubility of inorganic zinc fertilizers has a significant impact on their efficacy. Effective zinc uptake by plants requires a water solubility of at least 40–50%, according to studies. Zinc sulfate is high in solubility, least expensive, and readily available which is why it is one of the reasons zinc sulfate is often used to treat zinc deficiency. Extensive research has been conducted in India to find out the most efficient methods for zinc fertilizer application, particularly given that approximately half of the country's agricultural soils exhibit zinc deficiency. Zinc sulfate remains the most widely used compound for both soil and foliar applications. Among the various methods, incorporating zinc directly into the topsoil through broadcasting and mixing has proven more effective than alternatives such as drip application, side dressing, band placement, or foliar spraying with 0.5–2% $ZnSO_4$ solutions.

Foliar sprays are typically employed as a remedial measure during the crop growth cycle, especially when zinc deficiency becomes pronounced, and are commonly used in high-value horticultural and plantation crops. For larger-seeded crops like maize, soybean, wheat, groundnut, potato, and gram, seed priming or coating with a zinc oxide slurry offers a more economical alternative. In rice production, treating seedling roots with a 2–4% zinc oxide (ZnO) suspension prior to transplanting has proven to be nearly as effective as the application of 11 kg Zn per hectare in the form of zinc sulfate heptahydrate ($ZnSO_4 \cdot 7H_2O$). However, this root dipping method has shown limited effectiveness in other crops, such as sugarcane.

For potatoes, seed treatments with zinc sulfate have demonstrated performance comparable to that of traditional soil or foliar zinc applications. Moreover, the efficiency of zinc fertilizers can be significantly enhanced when used in conjunction with organic materials like farmyard manure. For example, combining 2.5 kg Zn per hectare with 200–500 kg of fresh cow dung and allowing the mixture to incubate for about a month has been found to be just as effective as applying 5 kg Zn per hectare through conventional inorganic zinc sources (Singh 2008).

Conclusion:

Zinc being an important micronutrient, plays roles in number of physiological processes of plants and can also help plants to reach satisfactory crop productivity. Zinc deficiency is an important problem that persists on agricultural soils and in human diets and is especially chronic in areas where cereal grains are the main item of the diet. In addition to insufficient availability of the zinc in the soil (high pH, organic matter interactions and unfavorable soil textures), plants do not translocate absorbed zinc efficiently resulting in its accumulation in non-edible parts of the plants, especially grain. Bridging this gap requires an integrated approach combining precise agronomic interventions like soil and foliar Zn fertilization with advanced breeding strategies aimed at enhancing Zn uptake, translocation, and accumulation in edible plant parts. Such efforts not only ensure healthier crop yields but also contribute to alleviating micronutrient malnutrition, particularly in resource-limited populations reliant on cereals as dietary staples.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Adil, M. F., Sehar, S., Han, Z., Lwalaba, J. L. W., Jilani, G., Zeng, F., Chen, Z. H. and Shamsi, I. H. (2020). Zn alleviates cadmium toxicity by modulating photosynthesis, ROS homeostasis, and cation flux kinetics in Oryza sativa. Environ. Pollut.**265**: 114979.
2. Ahmad, P., Ahanger, M. A., Alyemeni, M. N., Wijaya, L., Egamberdieva, D., Bhardwaj, R. and Ashraf, M. (2017). Zn application mitigates the adverse effects of NaCl stress on mustard (Brassica juncea L. Czern & Coss) through modulating compatible organic solutes, antioxidant enzymes, and flavonoid content. J. Plant Interact.**12** (1): 429–437.
3. Aravind, P. and Prasad, M. N. V. (2005a). Modulation of cadmium-induced oxidative stress in Ceratophyllum demersum by Zn involves ascorbate-glutathione cycle and glutathione metabolism. Plant Physiol. Biochem.**43**: 107–116.
4. Aravind, P. and Prasad, M. N. V. (2005b). Cadmium-Zn interactions in hydroponic system using Ceratophyllum demersum: Adaptive plant ecophysiology, biochemistry and molecular toxicology. Braz. J. Plant Physiol. **17**(1): 3–20.

5. Arshewar, S. P., Karanjikar, P. N., Takankhar, V. G. and Waghmare, Y. M. (2018). Effect of nitrogen and zinc on growth, yield and economics of pearl millet (Pennisetum glaucum L.). Int. J. Curr. Microbiol. Appl. Sci.**6**: 2246–2253.
6. Basit, F., Nazir, M. M., Shahid, M., Abbas, S., Javed, M. T., Naqqash, T., Liu, Y. and Yajing, G. (2022). Application of zinc oxide nano particles immobilizes the chromium uptake in rice plants by regulating the physiological, biochemical and cellular attributes. Physiol. Mol. Biol. Plants. **28**(6): 1175–1190.
7. Bowen, H. J. M. (1979). Environmental chemistry of the elements. Academic Press, London: 333.
8. Broadley, M. R., White, P. J., Hammond, J. P., Zelko, I. and Lux, A. (2007). Zinc in plants. New Phytol.**173**(4): 677–702.
9. Cakmak, I. (2000). Possible roles of zinc in protecting plant cells from damage by reactive oxygen species. New Phytol.**146**(2): 185–205.
10. Cakmak, I. (2000a). Role of Zn in protecting plant cells from reactive oxygen species. New Phytol.**146**: 185–205.
11. Cakmak, I. (2000b). Possible roles of Zn in protecting plant cells from damage by reactive oxygen species. New Phytol.**146**: 185–205.
12. Cakmak, I. (2008). Enrichment of cereal grains with Zn: Agronomic or genetic biofortification? Plant Soil.**302**: 1–17.
13. Cakmak, I. and Marschner, H. (1998). Enhanced superoxide radical production in roots of Zn-deficient plants. J. Exp. Bot.**39**: 1449–1460.
14. Chen, L. M., Lin, C. C. and Kao, C. H. (2000). Copper toxicity in Oryza sativa seedlings: Changes in antioxidative enzyme activities, H_2O_2 level, and cell wall peroxidase activity in roots. Bot. Bull. Acad. Sin.**41**: 99–103.
15. Chen, W. R., Feng, Y. and Chao, Y. E. (2008b). Genomic analysis and expression pattern of OsZIP1, OsZIP3 and OsZIP4 in two Oryza sativa genotypes with different Zn efficiency. Russ. J. Plant Physiol.**55**: 400–409.
16. Chen, W., He, Z. L., Yang, X. and Feng, Y. (2009). Zn efficiency is correlated with root morphology, ultrastructure, and antioxidative enzymes in Oryza sativa. J. Plant Nutr.**32**: 287–305.
17. Chen, W., Yang, X., He, Z., Feng, Y. and Hu, F. (2008a). Differential changes in photosynthetic capacity, 77 K chlorophyll fluorescence and chloroplast ultrastructure between Zn-efficient and Zn-inefficient rice genotypes (Oryza sativa) under low Zn stress. Physiol. Plant.**132**: 89–101.
18. Cherif, J., Mediouni, C., Ammar, W. B. and Jemal, F. (2011). Interactions of Zn and cadmium toxicity in their effects on growth and in antioxidative systems in tomato plants (Solanum lycopersicum). J. Environ. Sci.**23**(6): 837–844.
19. Disante, K. B., Fuentes, D. and Cortina, J. (2010). Response to drought of zinc-stressed Quercus suber L. seedlings. Environ. Exp. Bot.**70**(1): 96–103.
20. Foy, C. D. (1988). Plant adaptation to acid, aluminum soils. Commun. Soil Sci. Plant Anal.**19**: 959–987.

21. Gadallah, M. A. A. (1995). Effects of cadmium and kinetin on chlorophyll content, saccharides and dry matter accumulation in sunflower plants. Biol. Plant.**37**: 233–240.
22. Gadallah, M. and Ramadan, T. (1997). Effects of Zn and salinity on growth and anatomical structure of Carthamus tinctorius L. Biol. Plant.**39**: 411–418.
23. Ghanepour, S., Shakiba, M. R., Toorchi, M. and Oustan, S. (2015). Role of Zn nutrition in membrane stability, leaf hydration status, and growth of common bean grown under soil moisture stress. J. Biodivers. Environ. Sci.**6**: 9–20.
24. Gratao, P. L., Monteiro, C. C., Antunes, A. M., Peres, L. and Azevedo, R. A. (2008). Acquired tolerance of tomato (Lycopersicon esculentum cv. Micro-Tom) plants to cadmium-induced stress. Ann. Appl. Biol.**153**: 321–333.
25. Hagemayer, J. and Breckle, S. W. (2002). Trace element stress in roots. In: Waisel, Y., Eshel, A. and Kafkafi, U. (Eds.), Plant Roots: The Hidden Half (3rd ed.). Dekker, New York:763–785.
26. Hasan, S. A., Fariduddin, Q., Ali, B. and Hayat, S. (2012). Zinc-induced modulation of antioxidative enzymes, proline, and malondialdehyde contents in Brassica juncea L. Plant Soil Environ.**58**(3): 85–91.
27. Hassan, M. U., Aamer, M., Chattha, M. U., Haiying, T., Shahzad, B., Barbanti, L., Nawaz, M., et al. (2020). The critical role of Zn in plants facing the drought stress. Agriculture (Switzerland), **10**(9): 1–20.
28. Hatch, M. D. and Slack, C. R. (1970). Photosynthetic CO_2 fixation pathways. Annu. Rev. Plant Physiol.**21**: 141–162.
29. Kader, M. A., et al. (2017). Zn alleviates the adverse effects of drought stress in rice seedlings. Plant Physiol. Biochem.**117**: 198–206.
30. Kalaikandhan, R., Alagu Lakshmanan, G. M., Rajendran, K. and Jayanthi, P. (2014). Effect of zinc on growth and antioxidant potential of Sesuviumportulacastrum L. under coastal soil. Int. J. Curr. Microbiol. Appl. Sci.**3**(9): 321–329.
31. Kalyanaraman, S. B. and Sivagurunathan, P. (1993). Effect of cadmium, copper and Zn on growth of blackgram. J. Plant Nutr.**16**: 2029–2042.
32. Kapur, D. and Singh, K. J. (2023). The effect of exogenous Zn application on photosynthetic pigments, electrolyte leakage and carbohydrate metabolism in soybean plants subjected to Cd stress. Scope**13(**4): 1070-1083.
33. Kapur, D. and Singh, K.J. (2019). Zinc alleviates cadmium induced heavy metal stress by stimulating antioxidative defense in soybean [Glycine max (L.) Merr.] crop.J. Appl. Nat. Sci., **11**(2): 338- 345.
34. Karami, S., Modarres Sanavy, S. A. M., Ghanehpoor, S. and Keshavarz, H. (2016). Effect of foliar Zn application on yield, physiological traits, and seed vigor of two soybean cultivars under water deficit. Notulae Sci. Biol. **8**(2): 181–191.

35. Kupper, K. and Spiller, M. (1996). Environmental relevance of heavy metal-substituted chlorophylls using the example of water plants. J. Exp. Bot.**47**: 259–266.
36. Laspina, N. V., Groppa, M. D., Tomaro, M. L. and Benavides, M. P. (2005). Nitric oxide protects sunflower leaves against Cd-induced oxidative stress. Plant Sci.**169**(2): 323–330.
37. Lombardi, L. and Sebastiani, L. (2005). Copper toxicity in Prunus cerasifera: Growth and antioxidant enzymes responses of in vitro grown plants. Plant Sci.**168**: 797–802.
38. Machano, L., Carruyo, A., Delcampo, C. and Monteil, X. (2002). Effect of cadmium on the nucleoli of meristematic cells of onion (Allium cepa L.): An ultrastructural study. Environ. Res.**88**: 30–35.
39. Moustakas, M., Lanaras, T., Symeonidis, L. and Karataglis, S. (1994). Growth and some photosynthetic characteristics of field grown Avena sativa under copper and lead stress. Photosynthetica.**30**(3): 389–396.
40. Peck, A. W. and McDonald, G. K. (2010). Adequate Zn nutrition alleviates the adverse effects of heat stress in bread wheat. Plant Soil.**337**: 355–374.
41. Prasad, K. V. S. K., Saradhi, P. P. and Sharmila, P. (1999). Concerted action of antioxidant enzymes and curtailed growth under Zn toxicity in Brassica juncea. Environ. Exp. Bot.**42**: 1–10.
42. Qiao, X., He, Y., Wang, Z., Li, X., Zhang, K. and Zeng, H. (2014). Effect of foliar spray on β carbonic anhydrase expression and enzyme activity in rice (Oryza sativa L.) leaves. Acta Physiol. Plant.**36**: 263–272.
43. Ramzan, M., Naz, G., Parveen, M., Jamil, M., Gill, S. and Sharif, H. M. A. (2023). Synthesis of phytostabilized zinc oxide nanoparticles and their effects on physiological and antioxidative responses of Zea mays (L.) under chromium stress. Plant Physiol. Biochem.**196**: 130–138.
44. Reddy, A. R., Chaitanya, K. V., &Vivekanandan, M. (2004). Drought-induced responses of photosynthesis and antioxidant metabolism in higher plants. J. Plant Physiol.**161**, 1189–1202.
45. Rengel, Z. (1995a). Carbonic anhydrase activity in leaves of wheat genotypes differing in Zn efficiency. J. Plant Physiol.**147**, 251–256.
46. Rengel, Z. (1995b). Sulfhydryl groups in root-cell plasma membranes of wheat genotypes differing in Zn efficiency. Physiol. Plant.**95**, 604–612.
47. Roach, T. and Liszkay, A. K. (2014). Regulation of photosynthetic electron transport and photoinhibition. Curr. Protein Pept. Sci.**15**: 351–362.
48. Rosa, M., Prado, C., Podazza, G., Interdonato, R., González, J. A., Hilal, M. and Prado, F. E. (2009). Soluble sugars: Metabolism, sensing, and abiotic stress: A complex network in the life of plants. Plant Signal.Behav.**4**, 388–393.
49. Rout, G. R. and Das, P. (2003). Effect of metal toxicity on plant growth and metabolism. Agronomie.**23**, 3–11.

50. Sadeghzadeh, B. and Rengel, Z. (2011). Zn in soils and crop nutrition. In: Hawkesford, M. J. and Barraclough, P. (Eds.), the molecular basis of nutrient use efficiency in crops. Wiley: 335–376.
51. Sharma, D. C. and Sharma, C. P. (1993). Chromium uptake and its effects on growth and biological yield of wheat. Cereal Res. Commun.**21**(4): 317–322.
52. Shen, Z., Fenqin, Z. and Fusuo, Z. (1998). Toxicity of copper and Zn in seedling of mung bean and inducing accumulation of polyamine. J. Plant Nutr.**21**: 1153–1162.
53. Sherefu, A. and Zewide, I. (2021). Review paper on effect of micronutrients for crop production. J. Agric. Environ. Sci.**10**(4): 63–75.
54. Silva, E. C., Silva, M. F. A., Nogueira, R. J. M. C. and Albuquerque, M. B. (2010). Growth evaluation and water relations of Erythrina velutina seedlings in response to drought stress. Braz. J. Plant Physiol.**22**: 225–233.
55. Singh, M. V. (2008). Micronutrient deficiencies in crops in India. In: Alloway, B. J. (Ed.), Micronutrient deficiencies in global crop production. Springer, Dordrecht: 93–126.
56. Thounaojam, T. C., Panda, P., Choudhury, S., Patra, H. K. and Panda, S. K. (2014). Zinc ameliorates copper-induced oxidative stress in developing rice (Oryza sativa L.) seedlings. Protoplasma.**251**: 61–69.
57. Tsonev, T. and Lidon, F. J. C. (2012). Zn in plants – an overview. Emir. J. Food Agric.**24**: 322–333.
58. Van Assche, F. and Clijsters, H. (1990). Effects of metals on enzyme activity in plants. Plant Cell Environ.**13**: 195–206.
59. Vijayarengan, P. (2013). Changes in growth, biochemical constituents and antioxidant potentials in cluster bean (Cyamopsis tetragonoloba L. Taub) under zinc stress. Int. J. Curr. Sci.**5**: 37–49.
60. Welch, R. M., Webb, M. J. and Loneragan, J. F. (1982). Zn in membrane function and its role in phosphorus toxicity. In: Scaife, A. (Ed.), Plant Nutrition. Proceedings of the 9th International Plant Nutrition Colloquium, Warwick University, England: 710–715.
61. Wu, S., Hu, C., Tan, Q., Li, L., Shi, K., Zheng, Y. and Sun, X. (2015). Drought stress tolerance mediated by Zn-induced antioxidative defense and osmotic adjustment in cotton (Gossypium hirsutum). Acta Physiol. Plant.**37**: 167.
62. Zaman, Q. U., Aslam, Z., Rashid, M., Khaliq, A. and Yaseen, M. (2018). Influence of Zn fertilization on morpho-physiological attributes, growth, productivity and hematological appraisal of paddy rice. J. Anim. Plant Sci.**28**(3): 778–790.
63. Zoufan, P., Azad, Z., Ghahfarokhie, A. R. and Kolahi, M. (2020). Modification of oxidative stress through changes in some indicators related to phenolic metabolism in Malva parviflora exposed to cadmium. Ecotoxicol. Environ. Saf.**187**: 109811.