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ZINC DYNAMICS IN SOIL-PLANT SYSTEM AND ITS IMPLICATION FOR CROP NUTRITION- A REVIEW

Neeraj Bhadu, Akhil Bharti*, Aaina Sharma and Mohit Kamboj
Faculty of Agriculture, Maharishi Markandeshwar (Deemed to be University),
Mullana, Ambala 133207, Haryana, India
*Corresponding author E-mail: abharti.bharti@gmail.com
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ABSTRACT

Zinc is an essential micronutrient required for optimum plant growth, metabolic functioning and human nutrition. Zinc deficiency has become widespread in soils particularly in intensively cultivated areas, due to imbalanced fertilizers use, low organic matter, and soil degradation. Role of zinc in plants and its interactions with other nutrients, factors affecting and its availability in soils or its importance for human health. Zinc plays a key role in enzyme activation, protein synthesis, auxin metabolism, membrane integrity, and stress tolerance in plants. Its availability in soil is influenced by factors such as soil pH, texture, organic matter, parent material, and climatic conditions. Nutrient interactions significantly affect zinc dynamics, where it shows synergistic effects with nitrogen and potassium, but antagonistic relationships with phosphorus, calcium, copper, and boron. Zinc deficiency in crops leads to reduced yield and nutritional quality, contributing to human malnutrition, commonly to as hidden hunger. Agronomic biofortification, balanced fertilization, and microbial approaches are effective strategies to enhance zinc availability and uptake. Zinc management through integrated nutrient practices for improving crop productivity, soil health, and nutritional security under changing climatic conditions.
***Keywords*:** Zinc Dynamics, Soil-Plant System, Crop Nutrition.

Introduction

Plants require various nutrients for their growth and development. These are imperative for both agricultural productivity and maintenance soil system for long-term viability which helps to maintain the ecosystem sustainability (Shrivastav *et al*., 2020). They are important for appropriate biochemical procedures, for improving crop protection against pests and diseases (Yadav *et al.,* 2024). For completing the plant life cycle *Arnon and Stout* proposed the criteria of essentiality in 1939 to determine whether elements were essential for plant growth and development. An element is considered essential if it satisfies three criteria *viz*. necessary for life cycle completion, direct role in metabolism and nonreplicable (Sharma *et al.,* 2025 A). In agriculture, it has been identified that there are 17 essential nutrients that are necessary for completion of life cycle in plants (Pandey, 2018). Out of these, 3 are non-mineral nutrients (C, H and O) which are taken up from air and water, 6 are macro nutrients (N, P, K, Ca, Mg and S) which are required in large quantities while 8 are micronutrients (Fe, B, Zn, Ni, Cl, Cu, Mo, Mn) which are required in minute quantities (Kumar *et al,*. 2021). Although, very less amount of micronutrients is required by the plants but they are crucial for optimum growth and development (Gupta *et al*., 2008). Different elements have different functions in the plant body (Khare *et al.,* 2025). Each nutrient acts as an individual worker that maintains everything functioning properly in plants, which are like individual factories (Bashir *et al*., 2025). One of the most important components is nitrogen, which helps in the synthesis of proteins, coenzymes, chlorophyll, and even nucleic acids, which are the genetic material of plants (Yang *et al*., 2025). As the plant's energy manager, phosphorus promotes rapid root development, blooming, and fruiting by promoting energy transmission through ATP (Rather *et al*., 2025). Potassium functions as a supervisor, controlling vital processes including protein synthesis and flow of carbohydrates (Mugisha, 2025). By protecting cell membranes and controlling what goes into and out of each cell, calcium helps in maintaining the structural integrity of plants (Adekiya *et al*., 2025). While micronutrients directly or indirectly affect the vital processes in plants such as respiration, photosynthesis, transpiration lateral growth and reproduction phase (Johnson and Mirza. 2020). Iron supports the creation of chlorophyll and facilitates the transmission of electrons through enzymes, which are necessary for photosynthesis (Jomova *et al*., 2025). Boron ensures that the plant has energy where it needs it by managing the transfer of sugars and supervising the metabolism of carbohydrates (Álvarez-Herrera *et al*., 2025). While magnesium functions as an enzyme activator and is a component of the chlorophyll molecule itself, sulfur helps in the construction of plant proteins (Sun *et al.,* 2025).

Zinc also belongs to the category of micronutrients and plays vital role in plant growth and development (Channab *et al*., 2024). Zinc maintains proper functioning of multiple metabolic processes and supports different kinds of enzyme systems by acting as regulator for them (Tufail *et al.,* 2018). It also helps in synthesis of several growth hormones like indole acetic acid (IAA), cytokinin and gibberellins in plants (Minello *et al,*. 2025). Zinc also promotes starch formation, seed maturation and production (Chen *et al.,* 2025 A). It is important and specific physiological roles in all living membrane to maintaining the structural and functional integrity as well as facilitating gene expression (Kaur *et al*., 2025). Zinc value is depending on chemical composition of raw materials in the soil. Zinc value of earth's crust is 80 mg/kg approximately and value in soil is usually 10 to 300 mg/kg with an average of 50 mg/kg (Lukaszek-Chmielewska *et al.,* 2025). It is present in different forms in earth's crust, like sulfate, silica and carbonate minerals. Zinc deficiency in plants is frequently observed because low availability of the mineral (Pandey and Gautam 2025). Before Green Revolution soils were naturally fertile as organic manures were used for supplementing depleted soil nutrients however, after green revolution, soil fertility drastically depleted owing to higher cropping intensity and use of synthetic fertilizers which only supplied macro nutrients to the soil resulting in deficieny of micronutrients in the soil (Bashi *et al*., 2025). On that particular time soils were losing vital nutrients over time that leads to nutrient imbalance and soils were generally nutrient deficient with low nitrogen, phosphorus and depleting in potassium thus resulting in micronutrient deficiencies in plants and ultimately in humans as well as (Das *et al*., 2022). After Green Revolution with high-yielding varieties, chemical fertilizers and irrigation initially improved soil nutrient status (Meetei *et al*., 2025) but long term impacts included nutrient imbalance (high N, high P, low K), widespread micronutrient deficiencies (Zn, Fe, S), declining organic matter, and increasing soil degradation due to input intensive farming (Dimkpa *et al*., 2023). Micronutrient deficiency occurs when essential plant nutrients required in small amounts are not present in sufficient levels in the soil and that are unavailable for plant uptake (Saleem *et al.,* 2023). This induced the poor plant growth, reduced yield, and characteristic deficiency symptoms. Main causes of micronutrient deficiencies are imbalanced fertilizer use (high N and P, low micronutrients), low organic matter in soil, continuous cropping without replenishment that transform the pH of soil (Radulov and Berbecea, 2024). High soil pH reduces Zn, Fe, Mn availability, soil erosion and leaching (Regasa *et al*., 2024). Micronutrient deficiency in plants occurs when soil does not provide sufficient amount of essential micronutrients required for normal plant growth and metabolism (Lilay *et al*., 2024). Even plants need micronutrients in very small quantities, their deficiency causes physiological disorders in plants like stunted growth, curling of leaves, lower flowering and fruit setting, etc (Morya *et al.,* 2023). The most sensitive plants to zinc deficiency include beans, maize, onions, sorghum, and rice; barley, potatoes, soybeans, sugar beet, and tomatoes are moderately sensitive, and forage plants are resistant (Jattan *et al*., 2023).

According to WHO report 2024-25 micronutrient deficiency also known as hidden hunger and remains a major global health problem. Over 2 billion people worldwide are estimated to be deficient in one or more key micronutrients (Koshyb 2024). Deficiencies of iron, iodine, vitamin A, zinc and other vitamins, minerals are very common. Most of populations especially children and women are affected (Kiani *et al.,* 2022). According to WHO estimate 30.7% of women aged under 15–49 are anemic and among of them 35.5% are pregnant women (Vijayakumar *et al.,* 2025). Zinc deficiency in humans estimated that 15–17 % of the global population (1.1 billion people) is at risk of zinc undernourishment that causes a wide range of human problem like hair losses, weak immune system, impaired wound healing, hypogonadism in males, neurological issues and much more (Hussain *et al.,* 2022). Zinc deficiency is considered as public-health problem in developing countries, especially in South Asia and sub-Saharan Africa (Gupta *et al.,* 2020). In India around 17–18% children of 1–9 years age and about 31% teenager of 10–19 years age have zinc deficiency according to the National Nutrition Survey

(Venkatesh *et al.,* 2021). National nutrition data suggest that overall 25% of population may have inadequate dietary zinc intake in India (Kumar *et al*., 2025).

To overcome this limitation agronomic biofortification can be a very effective strategy (Matumba *et al.,* 2025). This strategy is particularly important to overcome problems caused by hidden hunger that affects primarily women and young children, often due to an insufficient intake of micronutrients specially zinc (Yilmaz and Yilmaz 2025). This technique aims to increase the bioavailability of nutrient content in parts of plants such as roots, leaves, and grains to improve the dietary quality and public health (Singh *et al*., 2016). Zinc also exhibits antagonistic interactions with copper and phosphorus which significantly influences the uptake bioavailability and quantitative status of nutrients. Due to this reason the interaction between Zinc, phosphorus and copper supplying of zinc as foliar spray is of great importance (Gong *et al*., 2020). Deficiency of zinc is increasing day by day and if proper management techniques are not implemented then security is at uptake especially in developing and underdeveloped countries (Singh and Maurya 2025).

Role of zinc

Role of zinc in plants

Zinc is a crucial micronutrient for crop growth. It plays a part in the synthesis of tryptophan, a precursor to indole acetic acid (IAA), and the hydrogenation of carbonic anhydrates (Kaur *et al*., 2025). Plant enzymes involved in protein synthesis, auxin synthesis, pollen development, cellular membrane integrity, and carbohydrate metabolism have been stimulated by zinc (Shao *et al*., 2023). It also regulates cytochrome synthesis and ribosomal fragments. Aldolase, particularly assists in the cellular breakdown of carbon, gets boosted by zinc (Kaur *et al*., 2025). Applying zinc has enhanced crop quality and productivity (Ashikuzzaman *et al*., 2024). Higher zinc concentrations can be noxious to plants, inhibiting cell division and elongation and reducing biomass production (Qian *et al*., 2023). An adequate quantity of zinc may minimize the damaging effects of temporary heat and salt stress and also enhance drought tolerance in several kinds of crops, such as wheat, sunflower, tomato, and red cabbage (Ahmed *el al.,* 2023). The gene expression necessary for plants to withstand stressful conditions is regulated and maintained by zinc (Moulick *et al.,* 2023). Plants that have been deficient in zinc suffer from abnormalities which display deficiency symptoms such as stunted growth, chlorosis, smaller leaves, and plants may become susceptible to damage from intense light, extreme temperatures, and fungal diseases (Ghimirey *et al*., 2024). Zinc affects a plant's ability to absorb and transport water (Singh *et al.,* 2023).

Table 1: Role of Zinc in Plants

S. No	Role of zinc	Mechanism	References
1	Development of pollen tube	Help full in fertilization of pollen grain	Huang *et al*., 2026
2	Resistance to diseases	Adequate zinc improves plant tolerance to disease and environment strees	Wang *et al*., 2026
3	Ribosomal fraction stabilizes	Key factor in structural integrity	Tsonev and Cebola, 2012
4	Tranlocation and transport	Zinc enhance the development of vascular tissues (Xylum and Phloem)	Hellmann *et al*., 2018
5	Auxin metabolism	Crucial plant harmone regulates growth and development	Hamzah *et al*., 2022
6	Protein synthesis	Formation of proteins which are essential for plant growth and development (Dehydrogenase Enzymes, Peptidases, aminoacyl-tRNA synthetase)	Sharma *et al.,* 2018
7	Synthesis of Cytocrome-C	Important role in respiration and energy production (ATP)	Sen *et al.,* 2026
8	Nitrogen metabolism	It helps in nitrogen absorption and its conversion into amino acids in plants.	Ashwini *et al.,* 2026
9	Membrane integrity	Maintain cell membrane stability and protect cells from damage	Tufail *et al*., 2018
10	Carbohydrates metabolism	It helps in starch formation and regulates sugar conversion and energy supply.	Suganya et al., 2020

Role of zinc in humans

Even humans and animals are susceptible to zinc deficiency (Kaur *et al.,* 2025). Zinc deficiency affects 30% of the world's population (Borpatra *et al*., 2025). In the process of helping to strengthen the human immune system, zinc plays essential roles in cellular processes in living beings (Jomova *et al.,* 2025). Adult humans should consume 8-11 milligrams of zinc per day. In several bodily enzymes, zinc serves as a structural or catalytic component (Temnik *et al*., 2025). Zinc insufficient levels may result from improper zinc absorption in the body. Human beings will suffer from memory loss, hair loss, problems with the skin, and muscle weakness as a result of a zinc shortage (Patil *et al*., 2025). A fetus's brain development may be affected by inadequate zinc consumption during pregnancy. Men who are deficient in zinc may experience infertility (Berger *et al*., 2025). The average daily need for zinc is 11 mg for men and 9 mg for women. Women require 13–14 mg of zinc per day throughout pregnancy and lactation (Zegeye *et al*., 2025). Children need 3 mg of zinc per day between the ages of 7 months and 3-5 mg between the ages of 4-8, and 8 mg between the ages of 9 and 13. Pig, poultry, breakfast cereals, nuts including roasted peanuts, almonds, walnuts, and oats, and dairy products like yogurt, cheese, and milk are among the foods high in zinc (Monroy *et al*., 2025).

Zinc deficiencies in Indian soils

Zinc levels in India vary depending on the kind and quality of the soil (Ramalakshmi *et al*., 2025). Variations in parent material types, soil formation processes, climate, and many other factors contribute to the variation (Haensel 2025). Zinc is abundant in soils formed from igneous rocks and replaces similar-sized ions in silicates, such as Mg^{+2} and Fe^{+2}. Compared to limestone, shale, and igneous rocks, sandstone-derived soils have a lower zinc content (Ghosh *et al*., 2025). Granite derived soils were found to contain more available zinc than gneiss and basalt (Akingboye *et al*., 2025). Laterite soils in Tamil Nadu have the highest accessible zinc content, followed by red, alluvial, and black soils (Sarkar and Das 2025). Low total zinc content, high pH, high calcite and organic matter content, and high concentrations of sodium, calcium, magnesium, bicarbonate, and phosphate in the soil solution or labile forms are the primary soil variables that influence zinc availability to plants (Cyprichová *et al.,* 2025). Intensively farmed soils, improperly drained soils, and peat soils frequently have zinc deficiencies (Kadyan and Kumari 2025). Course texture soils have negative interaction with zinc because it has leaching losses, low cation exchange capacity, low organic matter and poor nutrients retentions while heavily weathered acid soils have high zinc availability due to low pH, but zinc availability reduced by fixing with iron and aluminum oxides present in soils and high accessible phosphorus and silicon has negative interaction with zinc because of nutrient antagonism it makes zinc insoluble and inmobible, with all these reasons zinc availability reduce to plants. (Kahsu *et al.,* 2025). Coarse texture soils with low to medium organic carbon content in area like Rajasthan are generally deficient in zinc (Rana and Sharma, 2025). After phosphorus and nitrogen, zinc is regarded as the third major nutrient that limits crop production in India (Makdoh *et al.,* 2025). Due to ongoing soil fertility depletion, zinc deficiency in Indian soils has risen from 42% in 1970 to 63% in 2025 (Behera *et al*., 2025).

Calcareous soils (pH>7) with high bicarbonate (HCO_3^-) in the soil solution and moderate to high organic matter content (>1.5% organic C) are probably zinc deficient (Sharma *et al.,* 2025 B). Zinc deficiency may also be indicated by a soil exchangeable Mg:Ca ratio greater than 1 (Hosseiny and Maftoun 2025). Due to the production of insoluble zinc hydroxide and related carbonates, 50% of India's soils are mostly zinc deficient (Mued *et al*., 2025). Zinc is quickly precipitated after being absorbed into the soil colloids and producing chelates. As a result, plants access to zinc rapidly declines (Zhang *et al*., 2025 A). The crop's ability to absorb zinc may be impacted by high phosphorus application in calcareous soil (Morsy *et al.,* 2025). Seven distinct pools of zinc can be found in soils: carbonate and amorphous oxide bound zinc, organically bound zinc, complexed zinc, water soluble + exchangeable zinc, and zinc pool and zinc bonded by crystalline oxide (Korai *et al.,* 2025). The percentage and concentration of each zinc fraction to total zinc in soil changes the behavior of zinc in soils and its availability of zinc to plants (Umair *et al*., 2020).

Factors affecting availability of zinc in soil

Numerous factors, including parent material, soil pH, organic matter, texture, calcium carbonate content, phosphate fertilizer application, soil flooding, interaction with other nutrients, temperature etc affect the availability of zinc in the soil (Kumari *et al*,. 2025).

Parent material

Parent material is the primary factor influencing the zinc concentration in the soils (Mu *et al*., 2025). Zinc content varies among rocks and sediments. Mafic igneous rocks, basalt, and shale have comparatively high zinc contents (Beaudry *et al*., 2025). Zinc content is often low in quartz-rich materials, granite, and sandstone. Total and accessible zinc levels are generally higher in soils generated from parent materials rich in zinc (Kumar *et al*., 2025 A). Zinc is more easily released into the soil solution by parent materials that weather quickly, such as basalt or volcanic ash (Sharma *et al.,* 2025 C). Zinc is released very slowly from slow-weathering rocks (such as quartz or sandstones), which lowers its availability (Hilgard 2025). Compared to illite or bentonite, kaolonite fixes less zinc. As a result, clays with greater CECs, such bentonite and illite, help fix zinc more firmly, preventing plants from using it (Sayahi *et al.,* 2025).

Soil texture

Sand and other lighter-textured soils have low zinc content (Markoski *et al*., 2025). Because they have higher CEC values, soils with finer textures like clay have more reactive sites and can hold into more zinc than soils with lighter textures (Yousuf *et al*., 2025). Zinc adsorption capability is higher in heavier textured soils with greater CEC than in lighter textured soils (Ghosh *et al*., 2025). Consequently, sandy soils are more prone to zinc shortage than clayey soils. Zinc is adsorbed by clay soils, and pH and CEC regulate this process (Isaboke *et al*., 2025).

Soil pH

Zinc availability rises when the pH of the soil decreases. The majority of zinc-deficient soils are calcareous and neutral (Athar *et al.,* 2025). Zinc forms the insoluble amorphous $ZnFe_2O_4$ and $ZnSiO_4$ precipitates at high pH levels (Muensita *et al*., 2025). Zn^{2+} uptake decrease in acidic soils that are particularly deficient in zinc due to pH impact (Wang *et al*., 2025). Dolomite absorbs zinc less readily than magnesite (Leybourne *et al.,* 2025). In calcareous soils, zinc is absorbed by $CaCO_3$, which is partially responsible for Zn^{2+} availability (Wali *et al* 2025); however, when soil calcium carbonate levels rise, zinc availability falls (Sharma *et al.,* 2025 C). The zinc solution in the soil is additionally reduced by iron and aluminum oxides, and this reduction increases as pH rises (Regasa *et al*., 2025).

Climatic conditions

Zinc availability rises in warm, dry climates, while zinc insufficiency is more prevalent in chilly, rainy seasons (Nayak *et al*., 2025). Low temperatures, high moisture content, and low light levels can all lead to a zinc deficit (Poudel et al., 2025). Conversely, higher soil temperatures improve zinc availability by increasing Zn^{2+} solubility and diffusion (Ahmed *et al.,* 2025). Flooded soils are more frequently linked to zinc deficiency than dry soils. Flooding-related zinc shortage was caused by a zinc interaction with free sulfide (Jadhav *et al.,* 2025). Zinc transforms into amorphous sesquioxide under submerged circumstances, precipitating $ZnFe_2O_4$ decrease the rate of zinc absorption by plant roots (Dhaliwala *et al*., 2025).

Soil organic matter

Zinc forms both soluble and insoluble complexes with high molecular weight organic compounds, such as fulvic and humic acids (Boguta and Sokołowska, 2020). When humic soils and insoluble peats are combined, zinc availability decreases (Yasir *et al.,* 2025). Zinc forms a chelated zinc complex in the mineral soil, increasing the soil's zinc solution. Zinc in soil can be chelated by recently applied organic material (Sethi *et al*., 2025).

Interaction with nutrients

Nitrogen and zinc shows positive response with each other. Nitrogen deficient soils which contain all other essential nutrients do not response to zinc application and plants became zinc deficient (Bazie *et al.,* 2025).

The zinc shortage prevalent in soils is caused by high phosphorus availability (Rehman *et al.,* 2025). Zinc concentration in shoots of plants decreases by effect of growth (dilution effect) which signifies that zinc concentration in plant decrease by increasing plant growth and its concentration decreases in plant tissues. Plants with low zinc increase the phosphorus concentration, which results in hazardous symptoms that resemble zinc deficiencies (Singh *et al.,* 2025). Whereas mycorrhizae can have increased phosphorus intake and result in zinc shortage (Bhardwaj *et al*., 2025).

High Calcium content inhibits the absorption of zinc by plants from soil. Zinc concentrations positively decreased with increasing Calcium concentrations in soil solutions (Chatzissavvidis *et al.,* 2025). They found that increasing of calcium from 0 mM to 40 mM inhibited the rate of zinc absorption. However higher calcium (100 mM) had no additional effect on zinc absorption (Orth *et al*., 2025).

Sulphate and chloride are water soluble and it cannot create any problem in the availability of zinc to plants and while borate and molybdate are present in very small amounts so it is not a problem to the zinc availability to plants (Meyvisch *et al.,* 2025).

Nutrients dynamics and their interaction with zinc

Plant growth and development are largely determined by macronutrients and micronutrient availability. To ensure beter productivity of crops plants, it is essential to understand the plants nutrients uptake, transport, assimilation and their biological interactions (Kumar *et al.*, 2021). An influence or reciprocal action of one element upon another in relation to plant growth is one definition of interaction (Stein *et al.*, 2025). The way plants react differently to one ingredient combined with varied concentrations of a second element applied concurrently is another factor (Hashempur *et al.,* 2025). These kinds of interactions can occur both inside the plant and in the soil. When giving plants a sufficient quantity of micronutrients, these interactions should be considered (Richards *et al.,* 2025). Zinc's availability from soils and its status in the plant during the growth process particularly its absorption, distribution, or utilization can be influenced by nutrients (Usmani *et al.*, 2025).

Zinc interaction with macronutrient

Zinc-nitrogen interaction

Nitrogen fertilizers can help plants that are deficient in zinc. Since the administration of nitrogen encourages plant growth, it is possible to provide favorable interactions between growing levels of zinc and nitrogen fertilizers (Virkhare *et al.,* 2025). The outcome of nitrogen application serves to promote plant growth and, to a lesser extent, changes the pH of the root environment (Das *et al.,* 2025). Excessive application of nitrogen fertilizers in the zinc deficient soils do not improve zinc uptake in root, shoot and grain (Xue *et al.,* 2021). Because ammonium ions have an acidifying impact on soil, application of zinc sulphate ($ZnSO_4$) in conjunction with nitrogen fertilizers effectively control zinc shortage, whereas $ZnSO_4$ alone had little effect (Almendros *et al.*, 2025).

Zinc-phosphorus interaction

Since 1936, research on the relationship between zinc and phosphorus has been conducted. Research on this significant plant growth problem is ongoing (Kumar *et al.,* 2025 B). Phosphorus induced zinc deficiency is the common term used to describe the interaction (Zhang *et al*., 2025 A). Phosphorus application to the soil or high levels of accessible phosphorus is linked to this problem in plant growth (Jahan *et al.,* 2025). The use of zinc fertilizers helps stop the symptoms of zinc insufficiency (Sethi *et al.,* 2025). Phosphorus-induced zinc shortage has been linked to four general causes (Miruna *et al.*, 2025). These include

i. The interaction between phosphorus and zinc in the soil
ii. A slower rate of zinc translocation from the roots to the shoots
iii. A straight forward dilution effect on zinc concentration in plant tops as a result of growth responses to phosphorus
iv. A metabolic disorder within plant cells associated with an imbalance between phosphorus and zinc

Lowering of zinc concentration to inadequate levels in soil due to the production of an insoluble zinc phosphate [$Zn_3(PO_4)_2$] (Sazanova *et al.,* 2025). Applied phosphorus has been shown by numerous researchers to elicit signs of zinc shortage in plants (Khan *et al* 2023). Both the total zinc contents and the zinc concentrations in the plant tops were lowered by the increased phosphorus levels in the soil (Abbas *et al.*, 2025). Zinc and phosphorus have an antagonistic effect on plant roots. The antagonistic effect of phosphorus on zinc can be lessened by a balanced fertilizer ratio, and the total zinc content can either rise or stay the same (Shahzad *et al.*, 2025). Phosphorus interferes with the absorption, transport, and use of zinc, which is the primary cause of phosphorus-induced zinc insufficiency (Samal *et al* 2025).

Zinc-potassium Interaction

Zinc and potassium interaction in the soil plant system is generally synergistic in nature (Pavithra *et al*., 2025). Adequate potassium nutrition improves root growth, enzyme activation, and membrane permeability which enhances the uptake and translocation of zinc within the plant (Karthika *et al.,* 2018). Potassium also helps in efficient utilization of absorbed zinc by reducing the zinc deficiency symptoms (Hacisalihoglu 2020). Zinc support better potassium uptake by maintaining membrane integrity and normal metabolic activity (Wang *et al.,* 2013). There is no direct chemical antagonism between zinc and potassium in soil and also they not form any insoluble complexes (Bashir *et al.,* 2025). However excessive potassium application under certain conditions may indirectly reduce zinc availability by slightly increasing soil pH especially in calcareous soils (Demirkaya and Gulser, 2025). In general, balanced application of zinc and potassium fertilizers promotes better nutrient use efficiency and crop productivity (Sebhatleab *et al.,* 2025).

Zinc-calcium Interaction

Plants cannot readily access calcium zincate [$CaZn_2(OH)_6.2H_2O$], which is formed when calcium carbonate reacts with zinc in soil solution (Nadim and Khitab, 2023). Ksp = 43.9 is the solubility product for calcium zincate which is a large value that indicate compound dissolve in alkaline condition (Chaudhary, 2023). Calcium zincate after dissolve in alkaline condition [$CaZn_2(OH)_6 \rightleftharpoons C\alpha a^{2+} + 2Zn^{2+} + 6OH$] releases

Ca^{2+} and Zn^{2+} ions and act as temporary zinc source that is available to plants (Feng *et al.,* 2023). Calcium zincates ionic strength is 0.1 M in a pH range between 11.4 to 12.7 (Rashid, 2020). The availability of calcium decreases by high zinc application. Zinc and calcium have long been known to have antagonistic effects (Haleema *et al.,* 2024). Zinc absorption and translocation in roots was both reduced when calcium content in soil solution increased (Chahal *et al*., 2023). In certain instances, zinc fertilization reduced the amount of calcium in leaves (Pimentel *et al*., 2023). The application of calcium helps in mitigating zinc toxicity. Under conditions of zinc toxicity, calcium stabilizes the plasma membrane and plays a significant role in cell permeability (Costa *et al*., 2023).The crops cultivated in limestone soils had lower zinc concentrations in plant biomass than those grown in acidic soils and metal-contaminated soils (Lahori *et al*., 2020).

Zinc-magnesium interaction

There is positive interaction between zinc and magnesium (Hamedifard *et al.,* 2020). The concentration of zinc in crop biomass increased on magnesium application and vice-versa (Sadeghi *et al.,* 2021). By choosing the lime materials like $CaCO_3$, $CaMg(CO_3)_2$, CaO, $CaOH_2$ based on their magnesium content present in the soil, zinc availability reduced to plants uptake (Minato *et al*., 2023). Using $CaCO_3$ and $MgCO_3$ in a 1:1 or 2:1 ratio produced the best plant development, while using a 5:1 ratio resulted in less growth (Umer *et al*., 2020).

Zinc-sulphur interaction

Zinc and sulphur have both antagonistic and complementary effects (Hemasree *et al*., 2025). Sulphur application reduced the zinc concentration in shoots and inhibited the production of dry matter production (Vidal *et al*., 2025). An application of 100 kg S/ha resulted in a modest decrease in the content of zinc in *kharif* crop plants (Magodia *et al*., 2025). However, the concentration of zinc in *rabi* crop plants increased significantly when sulphur was applied (Rais, *et al*., 2025). Zinc and sulphur application are positive correlated with growth characteristics, yield attributes, and yield of various crop plants with their synergistic effect and sulphur helps in zinc uptake, protein synthesis, enzyme activation etc (Ghanem *et al*., 2025).

Zinc interaction with micronutrient

Zinc-copper interaction

Zinc significantly reduces the absorption of copper. Copper alters the distribution of zinc in plants by preventing zinc absorption (Rolic *et al*., 2025). Crops grown on copper and zinc-deficient soils have been shown to have a very strong copper-zinc antagonistic relationship (Gao *et al*., 2025). Zinc significantly reduces copper uptake in plants, due to competitive suppression of zinc on copper absorption (Ouyang *et al*., 2025). Further it has also been proven that copper ions competitively impede zinc absorption (Chen *et al*., 2025 (A) Ullah *et al*., 2025). Copper and zinc ions act different in soil and soil solution owing to adsorption, precipitation and buffering processes in soil that are absent in soil solution (Solymos *et al*., 2025). Zinc and copper existed as divalent ions in solution, but in majority of soils, they are mostly found in complex forms, with a significantly higher percentage of complexed copper than zinc (Rocco *et al*., 2025). Zn^{2+} activity would therefore be significantly higher than Cu^{2+} activity at the absorbing sites, making it an efficient competitor against absorption of copper (Gautam *et al*., 2025).

Zinc-iron interaction

Similar to the connection between zinc and phosphorus, the interaction between zinc and iron is equally complex (Sethi *et al.,* 2025). The content of zinc in plant tissues decreases with increasing iron levels (Ozkutlu and Korkmaz, 2025). It has been demonstrated that an increase in soil iron concentration slows down the pace at which plant roots absorb zinc (Kumar *et al*., 2025 C). However, the rate at which the crops absorbed zinc remain unaffected by iron at low concentration (10 μM) (Suganya *et al*., 2020). Higher concentration of iron (100 μM Fe^{2+}) found in flooded soils totally inhibited crops' ability to absorb zinc (Deng *et al*., 2009). Zinc concentrations in plant shoots and the rate of zinc absorption in grasses and dicotyledonous plants were both elevated by iron deprivation (Mateos Naranjo *et al*., 2008). Zinc absorption in dicotyledonous plants can be enhanced by the acidification of the rhizosphere in iron deficiency soils (Molnar, *et al*., 2023), while in grasses, the release of phytosiderophores causes higher rate of zinc absorption also to improved mobilization of zinc from calcareous soils (Kumar *et al*., 2025 D). Similarly, acidification of the rhizosphere and the release of reductants and phytosiderophores may be the cause of iron accumulation in the shoots of zinc-deficient plants (Leskova *et al*., 2022).

Zinc-boron interaction

There is an antagonistic link between the buildup of zinc and boron in plants (Long and Peng, 2023). Under zinc deficiency, plants will accumulate more boron, but applying zinc fertilizers will reduce it

(Shahgholi *et al*., 2023). Zinc fertilizers can successfully reduce boron toxicity to crops in soil with excessive boron concentrations (Zhao *et al*., 2024). However, applying boron fertilizers to crops has not been successful in lowering zinc buildup (Okasha *et al*., 2024). Zinc and boron can show synergistic interaction under extreme conditions of boron deficiency or excess boron. Excess boron can enhance zinc uptake and translocation which may result in zinc toxicity symptoms (Gulut, 2024).

Zinc toxicity

Excessive zinc concentrations can be hazardous to plants. Zinc poisoning reduced the growth and development of leaves and roots (Wei *et al.*, 2022). As zinc concentration rises, plant chloroplasts produce less NADPH, and RUBP carboxylase enzyme (Chen *et al*., 2022). Zinc toxicity lowers ATP synthesis, which in turn decreases chloroplast activity and photosynthesis (Sperdouli *et al*., 2022). Iron and phosphorus uptake is decreased by high zinc levels. Zinc toxicity is caused at more than 300 ppm of zinc in plants tissue (Angon *et al*., 2024).

Future prospects

Due to increased incidence of macronutrients and micronutrients deficiencies in humans there is a need to improve the nutritional value in humans diet (Avnee *et al*., 2023). There are several bio-fortification strategies introduced like traditional breeding, transgenic, agronomic, and modernized agriculture practices which are employed to biofortify crops that fulfill the nutritional needs (Jaiswal *et al*., 2022). However, these strategies are also lacking sustainability due to the specific crop species and micronutrients provision of long-term monitoring and assistance (Jaiswal *et al*., 2022). High cost of special chemical fertilizers induced alteration in soil metabolism, environment flow and agriculture sustainability (Saikanth *et al*., 2023) remain major challenge for nutrient management. Therefore, microbial biofortification is imperative and should be emphasized for exploring the plant microbe interaction within specific soil system and climatic condition. Plant uptake of micronutrient (Fe, Zn, Mg, Ca, Se, and S) and there availability in the soil system can be effeciently enhanced through such microbe based approaches (Chung *et al*., 2022). At present microbial biofortification provides a sustainable strategy for inproving macro and micro nutrients of crops through balanced soil system, ultimately contributing to climate resilent agriculture (Jaiswal *et al*., 2022).

Conclusion

Zinc is a vital micronutrient that plays a central role in plant growth, metabolism, stress tolerance, and human nutrition. Intensive agriculture, imbalanced fertilizer use and soil degradation have lead to widespread zinc deficiency in soils, crops and ultimately human diets particularly in developing countries. Although at the regional level, a thorough 4R (right site, right time, right source, and right dose) strategy to zinc application can be created for various crops, and the ideal combination can be discovered to achieve high grain zinc concentration and also studded nutrient interactions, especially with nitrogen, phosphorus, calcium, copper, iron, and boron, strongly influence zinc availability and uptake in soil plant systems. Understanding these interactions is essential for improving zinc use efficiency and crop productivity. Continuous zinc administration at the basal dose may be able to resolve the conflict with zinc deficiency in soil conditions. However, under stressful situations, agronomic biofortification might be an alternative, and its impacts must be assessed. More weather variations are anticipated as a result of climate change, necessitating the development of a stress-resistant biofortification strategy. When compared to other application techniques, foliar spraying yields the highest bioavailability of zinc.

References

Abbas, M., Murtaza, G., Owens, G., Khursheed, M. M. and Hussain, T. (2025). Interactive effects of zinc oxide nanoparticles and phosphorus on wheat (*Triticum aestivum* L.) grown under salt‐affected soil conditions. *Journal of Plant Nutrition and Soil Science*, **188**(1), 139–150.

Adekiya, A. O., Ogunbode, T. O., Esan, V. I., Adedokun, O., Olatubi, I. V. and Ayegboyin, M. H. (2025). Impact of calcium sources on soil chemical properties, tomato growth, yield, and quality. *The Scientific World Journal*, **2025**(1), 6653874.

Ahmed, A. F., Fawzy, M., Al-Zahrani, M. and Abdelkader, M. (2025). Enhancing metabolic processes and water deficit stress tolerance of maize plants through biochar addition and foliar application of zinc nanoparticles. *Russian Journal of Plant Physiology*, **72**(1), 10.

Ahmed, N., Zhang, B., Bozdar, B., Chachar, S., Rai, M., Li, J. and Tu, P. (2023). The power of magnesium: Unlocking the potential for increased yield, quality, and stress tolerance of horticultural crops. *Frontiers in Plant Science*, **14**, 1285512.

Akingboye, A. S., Bery, A. A., Ogunyele, A. C., Dick, M. D., Ale, T. O. and Titus, E. A. (2025). Magnetic-assisted radiometric, speciation, and environmental studies of an orogenic gold terrain: Okpella, Igarra Schist belt, SW Nigeria. *Earth Systems and Environment*, **9**(3), 2277–2306.

Almendros, P., Mendez, A. M., Gascó, G. and Sanchez-Martin, L. (2025). Zinc-glycine complex as an alternative zinc source in acid and calcareous soils: Nutritional efficiency in lettuce and N_2O emissions. *Journal of Soil Science and Plant Nutrition*, **1–15**.

Álvarez-Herrera, J. G., Jaime-Guerrero, M. and Fischer, G. (2025). The effect of boron on fruit quality: A review. *Horticulturae*, **11**(8), 992.

Angon, P. B., Islam, M. S., Das, A., Anjum, N., Poudel, A. and Suchi, S. A. (2024). Sources, effects and present perspectives of heavy metals contamination: Soil, plants and human food chain. *Heliyon*, **10**(7).

Ashikuzzaman, P. S., Ahmed, T., Upama, S. A., Uddin, R. and Sarker, U. K. (2024). Soil applied zinc fertilizer enhanced yield and yield components of wheat. *Journal of Agroforestry and Environment*, **17**(1), 50–56.

Ashwini, M. N., Gajera, H. P., Hirpara, D. G. and Parakhia, M. V. (2026). Nanoscale zinc for sustainable groundnut growth: An eco-conscious molecular approach. *Scientific Reports*, **16**(1), 4887.

Athar, M., Fatima, S., Zahra, A., Shah, M. A., Bashir, S., Seleiman, M. F. and Ali, N. (2025). Optimizing wheat growth and zinc uptake with compost and rice husk in alkaline conditions. *BMC Plant Biology*, **25**(1), 502.

Avnee, Sood, S., Chaudhary, D. R., Jhorar, P. and Rana, R. S. (2023). Biofortification: An approach to eradicate micronutrient deficiency. *Frontiers in Nutrition*, **10**, 1233070.

Bashi, Z., Rashi, B., Qadir, G. and Nisa, M. (2025). Green manuring, vermicomposting, and composting: A green technology for soil health. In *Organic Farming* (pp. 241–281). CRC Press.

Bashir, Z., Wani, P. A., Majeed, S., Ganai, B. A., Jan, T., Hamid, B. and Mohiddin, F. A. (2025). Biological peptides, metabolites and nanoparticles from potassium-solubilizing bacteria: A recent horizon in antimicrobial and anti-biofilm strategies. *Current Microbiology*, **82**(12), 579.

Bazie, Z., Amare, T., Alemu, E., Kerebh, B., Tenagn, A., Awoke, A. and Agumas, B. (2025). Response of tef (*Eragrostis tef* (Zucc.) Trotter) yield to nutrient management under rainy and irrigation production systems in northwestern Amhara, Ethiopia. *PLoS One*, **20**(1), e0315730.

Beaudry, P., Jagoutz, O., Bauer, A. M., Rezeau, H., Reimink, J. R., Grove, T. L. and Ono, S. (2025). Major-element, trace-element and sulfur-isotope evidence for arc-like magmatism in the 4.0–2.9 Ga Acasta Gneiss Complex. *Contributions to Mineralogy and Petrology*, **180**(9), 61.

Behera, S. K., Srivastava, S., Jha, P., Mishra, R., Meena, B. P. and Shukla, A. K. (2025). Soil fertility status of Indian soils. *Indian Journal of Fertilisers*, **21**(11), 1052–1066.

Berger, P. K., Bansal, R., Sawardekar, S., Monk, C. and Peterson, B. S. (2025). Associations of maternal prenatal zinc consumption with infant brain tissue organization and neurodevelopmental outcomes. *Nutrients*, **17**(2), 303.

Bhardwaj, G., Brar, P. S., Sharma, U. and Kaushal, R. (2025). Management of phosphorus–zinc antagonism through mycorrhizae to improve plant growth and soil metrics in capsicum. *Communications in Soil Science and Plant Analysis*, **1–16**.

Boguta, P. and Sokołowska, Z. (2020). Zinc binding to fulvic acids: Assessing the impact of pH, metal concentrations and chemical properties of fulvic acids on the mechanism and stability of formed soluble complexes. *Molecules*, **25**(6), 1297.

Borpatra, P. J. and Saikia, B. S. (2025). Zinc supplementation as a preventive measure for zinc deficiency. In *Strategies to Alleviate Human Zinc Deficiency* (pp. 159–192). IGI Global Scientific Publishing.

Chahal, S. K., Hettiarachchi, G. M., Nelson, N. O. and Guttieri, M. J. (2023). Fate and plant uptake of different zinc fertilizer sources upon their application to an alkaline calcareous soil. *ACS Agricultural Science & Technology*, **3**(9), 725–737.

Channab, B. E., Idrissi, A. E., Ammar, A., Dardari, O., Marrane, S. E., El Gharrak, A. and Zahouily, M. (2024). Recent advances in nano-fertilizers: Synthesis, crop yield impact, and economic analysis. *Nanoscale*, **16**(9), 4484–4513.

Chatzissavvidis, C., Devetzi, N., Antonopoulou, C., Papadakis, I. E., Therios, I. and Koundouras, S. (2025). Salinity stress and calcium in pomegranate: Impacts on growth, ion homeostasis, and photosynthesis. *Horticulturae*, **11**(7), 786.

Chaudhary, S. (2023). *Effect of zinc applications on the productivity of kiwifruit (Actinidia deliciosa Chev.)* (Doctoral dissertation, Dr. Yashwant Singh Parmar University of Horticulture and Forestry).

Chen, H., Li, D., Zhang, H., Zhang, M., Lin, Y., He, H. and Han, Z. (2025). Mechanisms of copper metabolism and cuproptosis: Implications for liver diseases. *Frontiers in Immunology*, **16**, 1633711.

Chen, H., Song, L., Zhang, H., Wang, J., Wang, Y. and Zhang, H. (2022). Cu and Zn stress affect the photosynthetic and antioxidative systems of alfalfa (*Medicago sativa*). *Journal of Plant Interactions*, **17**(1), 695–704.

Chen, Y., Deng, Z., Chen, X., Li, B., Xing, Y., Gu, W. and Zhou, Y. (2025). Foliar zinc fertilization: Enhancing sorghum productivity and starch quality under zinc deficiency. *European Journal of Agronomy*, **169**, 127671.

Chugh, G., Siddique, K. H. and Solaiman, Z. M. (2022). Iron fortification of food crops through nanofertilisation. *Crop and Pasture Science*.

Costa, M. I., Sarmento-Ribeiro, A. B. and Gonçalves, A. C. (2023). Zinc: From biological functions to therapeutic potential. *International Journal of Molecular Sciences*, **24**(5), 4822.

Cyprichová, V., Gelsomino, A., Miglierini, M. B., Bujdoš, M., Petrovičová, B. and Urík, M. (2025). Redistribution of major mineral-forming elements (Fe, Al, Si, Mn) and nutrient-associated trace elements (Cu, Zn, P) following rice-to-pomegranate land-use conversion in Southern Italy. *Plant and Soil*, **1–19**.

Das, D., Ingti, B., Paul, P., Jamatia, J. P., Ete, T., Khan, T. and Kalita, J. (2025). Soil microbial dynamics in response to the impact of nanoparticles on agricultural implications. *Discover Soil*, **2**(1), 58.

Das, D., Sahoo, J., Raza, M. B., Barman, M. and Das, R. (2022). Ongoing soil potassium depletion under intensive cropping in India and probable mitigation strategies: A review. *Agronomy for Sustainable Development*, **42**(1), 4.

Demirkaya, S. and Gülser, C. (2025). Biochar innovations for sustainable agriculture: Acidification and zinc enrichment strategies to improve calcareous soil fertility and wheat yield. *Soil and Water Research*.

Deng, H., Ye, Z. H. and Wong, M. H. (2009). Lead, zinc and iron (Fe^{2+}) tolerances in wetland plants and relation to root anatomy and spatial pattern of ROL. *Environmental and Experimental Botany*, **65**(2–3), 353–362.

Dhaliwala, S. S., Shuklab, A. K., Behera, S. K., Sharma, V. and Vermaa, V. (2025). Geochemistry of potentially and readily available nutrients under. *Advances in Agronomy*, **192**, 69.

Dimkpa, C., Adzawla, W., Pandey, R., Atakora, W. K., Kouame, A. K., Jemo, M. and Bindraban, P. S. (2023). Fertilizers for food and nutrition security in sub-Saharan Africa: An overview of soil health implications. *Frontiers in Soil Science*, **3**, 1123931.

Feng, Y. S., Zhou, S. J., Xia, W. Y. and Du, Y. J. (2023). Solidify/stabilise a heavy metal-contaminated soil using a novel steel slag-based binder. *Environmental Geotechnics*, **10**(5), 303–318.

Gao, F., Qiang, C., Tao, P., Cao, D. and Feng, W. (2025). Effect of zinc oxide nanoparticles (nZnO) on antioxidant defense, lignin metabolism and cadmium subcellular distribution in lettuce (*Lactuca sativa* L.) under low-dose cadmium stress (hormesis). *PLoS One*, **20**(12), e0337953.

Gautam, S., Singh, N. K., Gupta, N. and Hoque, M. N. (2025). Exclusive detection of Ni^{2+}, Cu^{2+}, Zn^{2+}, and CO_3^{2-} ions using a novel Schiff base. *Journal of Fluorescence*, **1–18**.

Ghanem, H. E., Hamza, D. A., Zain El-Abdeen, A. A., Elbatrawy, W. S. and El-Habashy, H. M. (2025). Influence of zinc foliar spray on growth, some important physiological processes, yield and yield attributes of bread wheat under water stress. *Scientific Reports*, **15**(1), 14943.

Ghimirey, V., Chaurasia, J. and Marahatta, S. (2024). Plant nutrition disorders: Insights from clinic analyses and their impact on plant health. *Agriculture Extension in Developing Countries*, **2**(1), 09–17.

Ghosh, S., Chowdhuri, A., Rakshit, S. and Rao, P. M. (2025). *Boosting crop yields with zinc: The ultimate guide to micronutrient management, soil fertility, and plant health.*

Gong, B., He, E., Qiu, H., Van Gestel, C. A., Romero-Freire, A., Zhao, L. and Cao, X. (2020). Interactions of arsenic, copper, and zinc in soil-plant system: Partition, uptake and phytotoxicity. *Science of the Total Environment*, **745**, 140926.

Gulut, K. Y. (2024). A comprehensive review on exploring the mechanisms of boron toxicity in plants. *MAS Journal of Applied Sciences*, **9**(2), 279–289.

Gupta, S., Brazier, A. K. M. and Lowe, N. M. (2020). Zinc deficiency in low‐ and middle‐income countries: Prevalence and approaches for mitigation. *Journal of Human Nutrition and Dietetics*, **33**(5), 624–643.

Gupta, U. C., Kening, W. U. and Liang, S. (2008). Micronutrients in soils, crops, and livestock. *Earth Science Frontiers*, **15**(5), 110–125.

Hacisalihoglu, G. (2020). Zinc (Zn): The last nutrient in the alphabet and shedding light on Zn efficiency for the future of crop production under suboptimal Zn. *Plants*, **9**(11), 1471.

Haensel, T. P. (2025). *Pedogenesis, soil fertility, and indigenous adaptation: The formation of Hawaiian volcanic soils across climate, time, and parent material* (Doctoral dissertation, University of Hawaiʻi at Manoa).

Haleema, B., Shah, S. T., Basit, A., Hikal, W. M., Arif, M., Khan, W. and Fhatuwani, M. (2024). Comparative effects of calcium, boron, and zinc inhibiting physiological disorders, improving yield and quality of *Solanum lycopersicum*. *Biology*, **13**(10), 766.

Hamedifard, Z., Farrokhian, A., Reiner, Ž., Bahmani, F., Asemi, Z., Ghotbi, M. and Taghizadeh, M. (2020). The effects of combined magnesium and zinc supplementation on metabolic status in patients with type 2 diabetes mellitus and coronary heart disease. *Lipids in Health and Disease*, **19**(1), 112.

Hamzah Saleem, M., Usman, K., Rizwan, M., Al Jabri, H. and Alsafran, M. (2022). Functions and strategies for enhancing zinc availability in plants for sustainable agriculture. *Frontiers in Plant Science*, **13**, 1033092.

Hashempur, M. H., Ghorat, F., Karami, F., Jahanbin, A., Nouraei, H., Abbasi, M. and Zareshahrabadi, Z. (2025). Topical delivery systems for plant‐derived antimicrobial agents: A review of current advances. *International Journal of Biomaterials*, **2025**(1), 4251091.

Hellmann, E., Ko, D., Ruonala, R. and Helariutta, Y. (2018). Plant vascular tissues connecting tissue comes in all shapes. *Plants*, **7**(4), 109.

Hemasree, K. R., Sairam, M., Maitra, S., Ray, S., Maheswari, N., Gaikwad, D. J. and DT, S. (2025). Effects of sulphur and zinc on growth and productivity of summer cowpea under conditions of southern Odisha. *Crop Research*, **60**.

Hilgard, E. W. (2025). *Soils: Their formation, properties, composition, and relations to climate and plant growth in the humid and arid regions.* Good Press.

Hosseiny, Y. and Maftoun, M. (2025). Effects of nitrogen levels, nitrogen sources and zinc rates on the growth and mineral composition of lowland rice. *Journal of Agricultural Science and Technology*, **10**(4), 307–316.

Huang, A., Wang, S., Yang, S., Lu, X., Zhang, N., Yang, C. and Ding, Q. (2026). Regulatory effects of micronutrient fertilizers on endogenous hormones and pollen quality in *Camellia oleifera* Abel (Theaceae). *Scientia Horticulturae*, **355**, 114537.

Hussain, A., Jiang, W., Wang, X., Shahid, S., Saba, N., Ahmad, M. and Mustafa, A. (2022). Mechanistic impact of zinc deficiency in human development. *Frontiers in Nutrition*, **9**, 717064.

Isaboke, J., Osano, O., Humphrey, O. S., Dowell, S. M., Njoroge, R. and Watts, M. J. (2025). Influence of agricultural land use management on soil particle size distribution and nutrient adsorption in Western Kenya. *Chemistry Africa*, **8**(4), 1599–1610.

Jadhav, P. B. (2025). Induced hazards. In *Urban Geology: A Machine-Generated Literature Overview* (pp. 339–525). Springer Nature Singapore.

Jahan, N., Mahmud, U. and Khan, M. Z. (2025). Sustainable plant-soil phosphorus management in agricultural systems: Challenges, environmental impacts and innovative solutions. *Discover Soil*, **2**(1), 1–8.

Jaiswal, D. K., Krishna, R., Chouhan, G. K., de Araujo Pereira, A. P., Ade, A. B., Prakash, S. and Verma, J. P. (2022). Bio-fortification of minerals in crops: Current scenario and future prospects for sustainable agriculture and human health. *Plant Growth Regulation*, **98**(1), 5–22.

Jattan, M., Kumari, N., Rani, B., Phogat, D. S., Kumari, S., Ravika and Chawla, R. (2023). Conventional breeding and advance approaches to mitigate drought and salt stress in crop plants. In *Salinity and drought tolerance in plants:*

Physiological perspectives (pp. 121–135). Springer Nature Singapore.

Johnson, V. J. and Mirza, A. (2020). Role of macro and micronutrients in the growth and development of plants. *International Journal of Current Microbiology and Applied Sciences*, **9**, 576–587.

Jomova, K., Alomar, S. Y., Valko, R., Nepovimova, E., Kuca, K. and Valko, M. (2025). The role of redox-active iron, copper, manganese, and redox-inactive zinc in toxicity, oxidative stress, and human diseases. *EXCLI Journal*, **24**, 880.

Kadyan, M. and Kumari, M. (2025). Integrated approaches to soil health and fertility for sustainable agriculture. *Role of Organic Farming for Sustainability in Agriculture*, **1**(1), 1–12.

Kahsu, G., Teka, K. and Zenebe, A. (2025). Soil characterization and classification in granite‐dominated rock formations of Beles Watershed in Tigray, Northern Ethiopia. *Applied and Environmental Soil Science*, **2025**(1), 1103048.

Karthika, K. S., Rashmi, I. and Parvathi, M. S. (2018). Biological functions, uptake and transport of essential nutrients in relation to plant growth. In *Plant Nutrients and Abiotic Stress Tolerance* (pp. 1–49). Springer Singapore.

Kaur, H., Devi, K. S. and Yadav, R. (2025). Physiological significance of zinc for plants, animals, and humans. In *Zinc in Soil-Plant Continuum* (pp. 33–62). Springer Nature Singapore.

Khan, F., Siddique, A. B., Shabala, S., Zhou, M. and Zhao, C. (2023). Phosphorus plays key roles in regulating plants' physiological responses to abiotic stresses. *Plants*, **12**(15), 2861.

Khare, N., Khare, P. and Singh, S. (2025). Molecular and physiological concepts: Macronutrients in crop plant growth and development. In *Agricultural Crop Improvement* (pp. 148–164).

Kiani, A. K., Dhuli, K., Donato, K., Aquilanti, B., Velluti, V., Matera, G. and Bertelli, M. (2022). Main nutritional deficiencies. *Journal of Preventive Medicine and Hygiene*, **63**(2 Suppl 3), E93.

Korai, S. K., Korai, P. K., Jaffar, M. A., Qasim, M., Younas, M. U., Shabaan, M. and Artyszak, A. (2025). Leveraging biochar amendments to enhance food security and plant resilience under climate change. *Plants*, **14**(13), 1984.

Koshyb, G. J. E. G. (2024). Micronutrient hunger or hidden hunger among infants and young children on healthy diets. *Shaping the Future with Nutrition*, **111**.

Kumar, J., Singh, O., Gaurav, S. S. and Mishra, S. (2025). Shaping nutritional sustainability in wheat: The crucial role of agronomic biofortification in zinc enhancement. *Journal of Scientific Research and Reports*, **31**(11), 985–1000.

Kumar, M., Narwal, E., Rakshit, S., Bishi, S. K., Bhadana, V. P., Kumar, M. and Layek, J. (2025). Zinc homeostasis and biofortification in crop plants: Towards efficient zinc utilization. *Journal of Plant Growth Regulation*, **44**(10), 5926–5945.

Kumar, P., Khandelwal, D., Kanwar, V. and Mukherjee, S. (2025). Geochemical and mineralogical analysis of ophiolitic and sedimentary formations in middle Andaman. *Discover Geoscience*, **3**(1), 97.

Kumar, S. C., Kumar, M., Singh, R. and Saxena, A. K. (2025). Selection of competitive and effective rhizobial strain for enhanced chickpea production under Indo-Gangetic plains of India. *Brazilian Journal of Microbiology*, **56**(4), 2811–2825.

Kumar, S., Kumar, S. and Mohapatra, T. (2021). Interaction between macro‐ and micro-nutrients in plants. *Frontiers in Plant Science*, **12**, 665583.

Kumari, M., Kumar, R., Padbhushan, R., Singh, Y. K., Vimal, B. K., Kumari, R. and Parmar, B. (2025). Investigating the spatial variability of soil parameters and mineralogical characterization in the tea growing area of Kishanganj district Bihar India. *Scientific Reports*, **15**(1), 29372.

Lahori, A. H., Mierzwa-Hersztek, M., Demiraj, E., Idir, R., Bui, T. T. X., Vu, D. D. and Zhang, Z. (2020). Clays, limestone and biochar affect the bioavailability and geochemical fractions of cadmium and zinc from Zn-smelter polluted soils. *Sustainability*, **12**(20), 8606.

Leskova, A., Javot, H. and Giehl, R. F. (2022). Metal crossroads in plants: Modulation of nutrient acquisition and root development by essential trace metals. *Journal of Experimental Botany*, **73**(6), 1751–1765.

Leybourne, M. I., Simandl, G. J., Petrus, J. A., Paradis, S., Akam, C., Voinot, A. and McDonald, A. M. (2025). U-Pb geochronology of fersmite: Potential time constraints on magnesite formation, sparry dolomitisation, and MVT Pb-Zn mineralisation in SE British Columbia, Canada. *Minerals*, **15**(2), 128.

Lilay, G. H., Thiébaut, N., du Mee, D., Assunção, A. G., Schjoerring, J. K., Husted, S. and Persson, D. P. (2024). Linking the key physiological functions of essential micronutrients to their deficiency symptoms in plants. *New Phytologist*, **242**(3), 881–902.

Long, Y. and Peng, J. (2023). Interaction between boron and other elements in plants. *Genes*, **14**(1), 130.

Lukaszek-Chmielewska, A., Rachwał, M., Rakowska, J., Piec, R., Podleśna, A., Piotrowska, B. and Kosturkiewicz, B. (2025). Heavy metals and natural radioactive isotopes in phosphate and compound fertilisers and their impact on human health. *Scientific Reports*, **15**(1), 33701.

Magodia, H. A., Jagasia, P. V. and Kale, A. P. (2025). Synergistic effect of elemental sulfur doses and micronutrient foliar application on growth and yield of *Glycine max* L. (soybean). *Environment and Ecology*, **43**(1A), 349–354.

Makdoh, B., Singh, A. P., Zhiipao, R. R., Biswakarma, N., Nayak, S., Sangma, C. B. and Newmai, Z. K. (2025). Zinc-based agronomic bio-fortification strategies for soybean in the North Eastern Himalayas of India. *Scientific Reports*, **15**(1), 36152.

Markoski, M., Mitkova, T., Minchev, I., Todorovska, M., Petek, M. and Angelova, I. (2025). Spatial distribution of copper (Cu) in apple orchards in the Resen region. *Poljoprivreda i Sumarstvo*, **71**(4), 37–56.

Mateos‐Naranjo, E., Redondo‐Gómez, S., Cambrollé, J., Luque, T. and Figueroa, M. E. (2008). Growth and photosynthetic responses to zinc stress of an invasive cordgrass, *Spartina densiflora*. *Plant Biology*, **10**(6), 754–762.

Matumba, A., Nalivata, P. C., Bailey, E. H., Lark, M. R., Broadley, M. R., Ander, L. E. and Chimungu, J. G. (2025). Biofortification of common bean: Critical analysis of genetic and agronomic strategies as viable alternatives to tackling zinc deficiency in developing countries. *Sustainability*, **17**(18), 8510.

Meetei, T. T., Singh, S. K. and Devi, Y. B. (2025). Linking of the past, present, and future scenarios of soil. In *Modern Technology for Sustainable Agriculture* (pp. 3–18). Springer Nature Switzerland.

Meyvisch, T., Willems, E. and Everaert, M. (2025). Micronutrient seed coatings of layered double hydroxides overcome seedling toxicity and improve micronutrient uptake in comparison with soluble micronutrient coatings. *Journal of Agricultural and Food Chemistry*, **73**(2), 1131–1144.

Minato, E. A., Brignoli, F. M., Neto, M. E., Besen, M. R., Cassim, B. M. A. R., Lima, R. S. and Batista, M. A. (2023). Lime and gypsum application to low-acidity soils: Changes in soil chemical properties, residual lime content and crop agronomic performance. *Soil and Tillage Research*, **234**, 105860.

Minello, L. V. P., Kuntzler, S. G., Berghahn, E., Dorneles, L. T., Ricachenevsky, F. K. and Sperotto, R. A. (2025). Nanotechnology-driven biofortification of Fe, Zn, and Se in edible plants. *Journal of Nanobiotechnology*, **23**(1), 669.

Miruna, M., Immanuel, R. and Baradhan, G. (2025). Enhancing rice (*Oryza sativa* L.) productivity in coastal environments through real-time nitrogen management and zinc fertilisation. *Research on Crops*, **26**(3).

Molnar, Z., Solomon, W., Mutum, L. and Janda, T. (2023). Understanding the mechanisms of Fe deficiency in the rhizosphere to promote plant resilience. *Plants*, **12**(10), 1945.

Monroy Valle, M., Estrada, M. R., del Carmen Caamaño, M., Cordón-Arrivillaga, K., Lane, G. and Vatanparast, H. (2025). Preschoolers in severely food insecure Guatemalan Mayan households consume a monotonous grain-based diet. *BMC Public Health*, **25**(1), 2836.

Morsy, H. Y., El-Etr, W., Zein, E. A. and Hanaa, A. (2025). Impact of nanoparticles on phosphorus availability and plant productivity in calcareous soil. *Menoufia Journal of Soil Science*, **10**(11), 256–278.

Morya, R., Morya, R., Mittoliya, V. K. and Chhirouliya, J. K. (2023). Functions and deficiency symptoms of micro nutrients. *Dr. Nareshkumar B. Desai*, **35**.

Moulick, D., Bhutia, K. L., Sarkar, S., Roy, A., Mishra, U. N., Pramanick, B. and Hossain, A. (2023). The intertwining of Zn-finger motifs and abiotic stress tolerance in plants: Current status and future prospects. *Frontiers in Plant Science*, **13**, 1083960.

Mu, T., Cao, B., Yang, M., Gan, X., Chen, L., Wang, X. and Xu, J. (2025). Heavy metals distribution and source identification in contaminated agricultural soils: Isotopic and multi-model analysis. *Agronomy*, **15**(4), 812.

Mued, M. M., Yadav, A. S., Siddiqui, S., Rao, P. S., Khan, N. and Pratap, D. (2025). Zinc in wheat cultivation: Physiological roles, agronomic impact, and management strategies—A comprehensive review. *International Journal of Plant and Environment*, **11**(03), 428–436.

Muensita, P., Asavapisit, S. and Piyaphanuwat, R. (2025). Performance and heavy metal leaching behavior of bituminous fly ash-based geopolymer in aggressive environments. *Environment and Natural Resources Journal*, **23**(2), 165–175.

Mugisha, G. (2025). *Phytochemical screening and mineral composition analysis of Solanum melongena plant (eggplant) grown in Muhoporo sector in Ngororero district* (Doctoral dissertation, University of Rwanda).

Nadim, M. A. and Khitab, U. (2023). Improving zinc biofortification in plants. In *Mineral Biofortification in Crop Plants for Ensuring Food Security* (p. 95).

Nayak, S., Singh Shivay, Y., Mandi, S., Nayak, P., Biswakarma, N., Gawdiya, S. and Borate, R. B. (2025). Zinc accumulation, translocation and remobilization in biofortified wheat variety as influenced by Zn fertilization strategies. *Journal of Soil Science and Plant Nutrition*, **25**(3), 8121–8134.

Okasha, A. M., Abbelhameed, M. M., Aamer, S. M. and Abdelfatah, A. G. (2024). Comprehensive effect of zinc boron with NPK and salicylic acid foliar application treatments on rice yield and grain quality under salty soil conditions. *Journal of Plant Production*, **15**(9), 531–539.

Orth, H. N., Pirkwieser, P., Benthin, J., Koehler, M., Sterneder, S., Parlar, E. and Somoza, V. (2025). Bitter taste receptor TAS2R43 co-regulates mechanisms of gastric acid secretion and zinc homeostasis. *International Journal of Molecular Sciences*, **26**(13), 6017.

Ouyang, Y., Jiang, W., Long, X., Mao, P., He, P. and Ouyang, X. (2025). The role of micronutrients in atherosclerosis: Mechanisms and clinical application. *Journal of Cellular and Molecular Medicine*, **29**(21), e70920.

Ozkutlu, F. and Korkmaz, K. (2025). Impact of Fe-EDTA, EDTA, and Zn applications on Fe and Zn levels and biomass production in bread wheat. *Turkish Journal of Agricultural and Natural Sciences*, **12**(4), 1109–1119.

Pandey, A. K. and Gautam, A. (2025). Zinc deficiency and toxicity in soil and plants: Causes and remediation. In *Zinc in Plants* (pp. 59–76). Academic Press.

Pandey, N. (2018). Role of plant nutrients in plant growth and physiology. In *Plant Nutrients and Abiotic Stress Tolerance* (pp. 51–93). Springer Singapore.

Patil, S. A., Udachan, I. S., Lokhande, S. M., Ranveer, R. C., Mote, G. V. and Khandekar, S. P. (2025). Effect of inhibitors on flour fortification: A nutritional approach. *Journal of the Science of Food and Agriculture*.

Pavithra, S. I., Leninraja, D., Dhevagi, P., Bama, K. S., Beaulah, A. and Kavitha, M. P. (2025). Removal of lead: The synergistic power of clinoptilolite and nano-composite materials—A comprehensive review. *Discover Applied Sciences*, **7**(6), 608.

Pimentel, C., Pina, C. M., Müller, N., Lara, L. A., Melo Rodriguez, G., Orlando, F. and Fernández, V. (2023). Mineral particles in foliar fertilizer formulations can improve the rate of foliar uptake. *Plants*, **13**(1), 71.

Poudel, P., Jeffries, K. A., Bai, J., Dorado, C., Rosskopf, E. and Di Gioia, F. (2025). Radish microgreen metabolomic profile in response to zinc biofortification and light intensity. *Journal of Agricultural and Food Chemistry*, **73**(27), 16996–17013.

Qian, L., Dawar, K., Ullah, I., Irfan, M., Zhang, Z., Mian, I. A. and Alarfaj, A. A. (2023). Zinc foliar application mitigates cadmium-induced growth inhibition and enhances wheat growth, chlorophyll contents, and yield. *ACS Omega*, **8**(36), 32372–32381.

Radulov, I. and Berbecea, A. (2024). *Nutrient management for sustainable soil fertility.*

Rais, N., Qureshi, S. A., Deho, N. A., Katyar, N. K., Memon, F. N. and Yaseer, M. (2025). Sulphur-bentonite improves wheat growth, yield, and postharvest nutrient status in alkaline-calcareous soils. *Pakistan Journal of Agriculture*, **2**(2), 70–74.

Ramalakshmi, C. S., Prasad, T. N. V. K. V., Sireesha, A., Sreelatha, T. and Bharathalakshmi, M. (2025). Synthesized zinc and iron nanoparticles on nutrient fortification and crop productivity in sugarcane plant-ratoon sequences. *Sugar Tech*, **1–9**.

Rana, A. and Sharma, R. (2025). Evaluating and mapping soil quality in a limestone mining landscape using GIS: Insights from Ramganjmandi, Rajasthan. *Environment and Ecology*, **43**(2), 441–461.

Rashid, I. (2020). *Evaluation of effectiveness of phosphate and zinc as scale inhibitor in delaying precipitation of* $CaCO_3$.

Rather, G. A., Manhas, A. and Sharma, N. (2025). Mobility of nutrients and their metabolism in agriculture crops. In *Agricultural Biotechnology* (pp. 75–93). Apple Academic Press.

Regasa, A., Haile, W. and Abera, G. (2024). Soil acidity and fertility status of surface soils under different land uses in Sayo district of Oromia, western Ethiopia. *PLoS One*, **19**(12), e0316009.

Regasa, A., Haile, W. and Abera, G. (2025). Effects of lime and vermicompost application on soil physicochemical properties and phosphorus availability in acidic soils. *Scientific Reports*, **15**(1), 25544.

Rehman, B., Zulfiqar, A., Saleem, M. Z., Hussan, M. U., Siddiqui, M. H. and Hussain, S. (2025). Role of ZnSO4 in modulating physiochemical traits and bZIP genes expression in rice varieties grown in zinc-deficient soil. *Journal of Soil Science and Plant Nutrition*, **1–16**.

Richards, J. D., Cori, H., Rahn, M., Finn, K., Barcena Echegollen, J. E., Kanellopoulos, A. K. and Spooren, A. (2025). Micronutrient bioavailability: Concepts, influencing factors, and strategies for improvement. *Frontiers in Nutrition*, **12**, 1646750.

Rocco, C., Suzuki, M., Vilar, R., Garcia-España, E., Blasco, S., Larrouy-Maumus, G. and Weiss, D. (2025). Enhancing zinc bioavailability in rice using the novel synthetic siderophore ligand proline-2′-deoxymugineic acid (PDMA): Critical insights from metal binding studies and geochemical speciation modeling. *Journal of Agricultural and Food Chemistry*, **73**(14), 8243–8253.

Rolić, T., Yazdani, M., Mandić, S. and Distante, S. (2025). Iron metabolism, calcium, magnesium and trace elements: A review. *Biological Trace Element Research*, **203**(4), 2216–2225.

Sadeghi, F., Rezeizad, A. and Rahimi, M. (2021). Effect of zinc and magnesium fertilizers on the yield and some characteristics of wheat (*Triticum aestivum* L.) seeds in two years. *International Journal of Agronomy*, **2021**(1), 8857222.

Saikanth, D., Kesarwani, A., Nain, M., Pandey, S. K., Singh, B. V. and Maurya, C. (2023). Bio-fortification and its impact on global health. *Journal of Experimental Agriculture International*, **45**(10), 106–115.

Saleem, S., Mushtaq, N. U., Rasool, A., Shah, W. H., Tahir, I. and Rehman, R. U. (2023). Plant nutrition and soil fertility: Physiological and molecular avenues for crop improvement. In *Sustainable Plant Nutrition* (pp. 23–49). Academic Press.

Samal, D. K., Sukla, L. B. and Bishoyi, A. K. (2025). Biosynthesis of phosphorus nanoparticles for sustainable agroecosystems: Next generation nanotechnology application for improved plant growth. *ACS Omega*, **10**(15), 14555–14565.

Sarkar, D. and Das, R. (2025). Regional soil health assessments: Eastern. In *Soil Health and Sustainability in India* (p. 128).

Sayahi, N., Othmani, B., Mnif, W., Algarni, Z., Khadhraoui, M. and Ben Rebah, F. (2025). Clay minerals as enzyme carriers for pollutant removal from wastewater: A comprehensive review. *Minerals*, **15**(9), 969.

Sazanova, K. V., Zelenskaya, M. S., Korneev, A. V., Bakhvalova, E. V., Vlasov, D. Y. and Frank-Kamenetskaya, O. V. (2025). Effect of fungal metabolism on Zn minerals formation: The case of *Aspergillus niger* and *Penicillium chrysogenum*. *Crystals*, **15**(2), 118.

Sebhatleab, M., Gebresamuel, G., Girmay, G., Tsehaye, Y. and Haile, M. (2025). Effect of phosphorus and zinc fertilization on yield and nutrient use efficiency of wheat (*Triticum aestivum* L.) in Tigray Highlands of Northern Ethiopia. *Crops*, **5**(3), 32.

Sen, S., Patil, P. M., Parihar, N., Das, S. S., Saha, A. D. and Pemmaraju, D. B. (2026). Photobiomodulation therapy with zinc oxide/pheophorbide-a nanoflakes enhances neurovascular repair in spinal cord injury evidenced using photoacoustic imaging. *ACS Applied Bio Materials*.

Sethi, G., Behera, K. K., Sayyed, R., Adarsh, V., Sipra, B. S., Singh, L. and Behera, M. (2025). Enhancing soil health and crop productivity: The role of zinc-solubilizing bacteria in sustainable agriculture. *Plant Growth Regulation*, **1–17**.

Shahgholi, S., Sayfzadeh, S., Hadidi Masouleh, E., Shahsavari, N. and Zakerin, H. (2023). Assessment of zinc, boron, and iron foliar application on wheat yield and yield components under drought stress. *Communications in Soil Science and Plant Analysis*, **54**(9), 1283–1292.

Shahzad, M., Bibi, A., Khan, A., Shahzad, A., Xu, Z., Maruza, T. M. and Zhang, G. (2025). Utilization of antagonistic interactions between micronutrients and cadmium (Cd) to alleviate Cd toxicity and accumulation in crops. *Plants*, **14**(5), 707.

Shao, J., Tang, W., Huang, K., Ding, C., Wang, H., Zhang, W. and Qari, S. H. (2023). How does zinc improve salinity tolerance? Mechanisms and future prospects. *Plants*, **12**(18), 3207.

Sharma, A., Sharma, D. and Verma, S. K. (2018). *In silico* study of iron, zinc and copper binding proteins of *Pseudomonas syringae* pv. *lapsa*: Emphasis on secreted metalloproteins. *Frontiers in Microbiology*, **9**, 1838.

Sharma, A., Sharma, R., Awasthi, A., Awasthi, K. K. and Awasthi, G. (2025). Zinc in soils and the regulatory roles of soil properties. In *Zinc in Soil-Plant Continuum* (pp. 3–32). Springer Nature Singapore.

Sharma, N., Manhas, A., VijaiSelvaraj, K. S., Bajpai, A. B., Rather, G. A. and Kumar, M. (2025). Regulation of essential plant nutrients and beneficial elements for growth and development of vegetable crops. In *Growth Regulation and Quality Improvement of Vegetable Crops: Physiological and Molecular Features* (pp. 71–95). Springer Nature Singapore.

Sharma, U. C., Datta, M. and Sharma, V. (2025). Chemistry, microbiology, and behaviour of acid soils. In *Soil Acidity:*

Management Options for Higher Crop Productivity (pp. 121–322). Springer Nature Switzerland.

Shrivastav, P., Prasad, M., Singh, T. B., Yadav, A., Goyal, D., Ali, A. and Dantu, P. K. (2020). Role of nutrients in plant growth and development. In *Contaminants in Agriculture: Sources, Impacts and Management* (pp. 43–59). Springer International Publishing.

Singh, A. and Maurya, A. (2025). Confronting zinc deficiency: A public health challenge in the developing world. In *Strategies to Alleviate Human Zinc Deficiency* (pp. 91–124). IGI Global Scientific Publishing.

Singh, A., Rajput, V. D., Pandey, D., Sharma, R., Ghazaryan, K. and Minkina, T. (2023). Nano zinc-enabled strategies in crops for combatting zinc malnutrition in human health. *Frontiers in Bioscience-Landmark*, **28**(8), 158.

Singh, T., Kothari, M., Saini, P., Singh, A. V., Verma, A. K., Singh, B. R. and Shankhdhar, S. C. (2025). Exploring diverse strategies for zinc biofortification: Insights into enhancing crop zinc content. *Journal of Soil Science and Plant Nutrition*, **1–17**.

Singh, U., Praharaj, C. S., Chaturvedi, S. K. and Bohra, A. (2016). Biofortification: Introduction, approaches, limitations, and challenges. In *Biofortification of Food Crops* (pp. 3–18). Springer India.

Solymos, K., Kanász, E., Ágoston, Á., Gyulavári, T., Pálffy, B., Szamosvölgyi, Á. and Pap, Z. (2025). Impact of different soil solutions on the stability and photocatalytic activity of commercial zinc oxide nanoparticles. *Environmental Science: Nano*, **12**(2), 1328–1339.

Sperdouli, I., Adamakis, I. D. S., Dobrikova, A., Apostolova, E., Hanć, A. and Moustakas, M. (2022). Excess zinc supply reduces cadmium uptake and mitigates cadmium toxicity effects on chloroplast structure, oxidative stress, and photosystem II photochemical efficiency in *Salvia sclarea* plants. *Toxics*, **10**(1), 36.

Stein, M., Weiss, M., Kühner, C. and Zacher, H. (2025). Environmentally‐specific transformational leadership and environmental voice: A five‐wave study of reciprocal within‐person relations. *Corporate Social Responsibility and Environmental Management*, **32**(6), 7956–7968.

Suganya, A., Saravanan, A. and Manivannan, N. (2020). Role of zinc nutrition for increasing zinc availability, uptake, yield, and quality of maize (*Zea mays* L.) grains: An overview. *Communications in Soil Science and Plant Analysis*, **51**(15), 2001–2021.

Sun, X., Zhang, L., Gu, Y., Wang, P., Liu, H., Qiang, L. and Huang, Q. (2025). Nutrient-element-mediated alleviation of cadmium stress in plants: Mechanistic insights and practical implications. *Plants*, **14**(19), 3081.

Temnik, M., Gurin, S., Magidenko, L., Balakin, A., Byshovets, R., Kalmukova, O. and Savchuk, O. (2025). Zn64 aspartate modulates inflammation, tryptophan metabolism, and pancreatic function in diet-induced obesity. *Scientific Reports*, **15**(1), 43080.

Tsonev, T. and Cebola Lidon, F. J. (2012). Zinc in plants—An overview. *Emirates Journal of Food & Agriculture*, **24**(4).

Tufail, A., Li, H., Naeem, A. and Li, T. X. (2018). Leaf cell membrane stability‐based mechanisms of zinc nutrition in mitigating salinity stress in rice. *Plant Biology*, **20**(2), 338–345.

Ullah, S., Naeem, A., Praspaliauskas, M., Vaskeviciene, I., Hosney, A. and Barcauskaite, K. (2025). Comparative toxicity of copper and zinc contaminated wastewater irrigation on growth, physiology, and mineral absorption of wheat. *Water Environment Research*, **97**(1), e70001.

Umair Hassan, M., Aamer, M., Umer Chattha, M., Haiying, T., Shahzad, B., Barbanti, L. and Guoqin, H. (2020). The critical role of zinc in plants facing drought stress. *Agriculture*, **10**(9), 396.

Umer, M. I., Rajab, S. M. and Ismail, H. K. (2020, August). Effect of CaCO3 form on soil inherent quality properties of calcareous soils. In *Materials Science Forum* (**1002**, pp. 459–467). Trans Tech Publications Ltd.

Usmani, L., Shakil, A., Khan, I., Alvi, T., Singh, S. and Das, D. (2025). Brassinosteroids in micronutrient homeostasis: Mechanisms and implications for plant nutrition and stress resilience. *Plants*, **14**(4), 598.

Venkatesh, U., Sharma, A., Ananthan, V. A., Subbiah, P. and Durga, R. (2021). Micronutrient deficiency in India: A systematic review and meta-analysis. *Journal of Nutritional Science*, **10**, e110.

Vidal, A., Nguyen, C., Brunel-Muguet, S., Avice, J. C., Ameline, A. F. and Cornu, J. Y. (2025). Sulfur deficiency affects the accumulation and allocation to shoots of cadmium and some macro- (P, K, Ca, Mg) and micro-nutrients (Cu, Mn, Mo, Zn) in durum wheat at heading. *Environmental Science and Pollution Research*, **1–13**.

VijayaKumar, A., Syed, I., Dhulipalla, H., Ghosh, P., Srinivasan, L. V., Ahmad, F. and Singh, V. (2025). Biofortification as a sustainable strategy to address micronutrient malnutrition in South Asia. *Journal of Health, Population and Nutrition*, **44**(1), 425.

Virkhare, U., Gupta, G., Tewari, S., Nimbulkar, P., Dutta, A. and Kher, D. (2025). Pioneering biofertilization: Advanced zinc solubilizing bacteria use as biostimulants for transforming mustard yields: A review. *Journal of Pure and Applied Microbiology*, **19**(3), 1662–1677.

Wali, S. U., Alias, N. B., Muhammad, N., Kaoje, I. U., Abubakar, A. U., Umar, A. and Lada, H. M. (2025). Geochemical and regression analyses of shallow groundwater evolution in a semi-arid basin. *SSRN Electronic Journal*, 5264086.

Wang, M., Zheng, Q., Shen, Q. and Guo, S. (2013). The critical role of potassium in plant stress response. *International Journal of Molecular Sciences*, **14**(4), 7370–7390.

Wang, S., Guo, J., Wu, Z., Shang, J., Shen, C., Tang, H. and Liu, Y. (2025). Zn2+ adsorption in ferric-silicates microstructures in sulfidic tailings mediated through mineral weathering by *Acidithiobacillus* species. *Chemosphere*, **370**, 144032.

Wang, Y., Li, Y., Wu, J., Shen, M., Zhan, A., Wang, Y. and Liu, B. (2026). Regulatory mechanisms of zinc on bacterial antibiotic resistance and virulence in a One Health context. *Microbiology Research*, **17**(1), 22.

Wei, C., Jiao, Q., Agathokleous, E., Liu, H., Li, G., Zhang, J. and Jiang, Y. (2022). Hormetic effects of zinc on growth and antioxidant defense system of wheat plants. *Science of the Total Environment*, **807**, 150992.

Xue, Y., Yan, W., Gao, Y., Zhang, H., Jiang, L., Qian, X. and Liu, K. (2021). Interaction effects of nitrogen rates and forms combined with and without zinc supply on plant growth and nutrient uptake in maize seedlings. *Frontiers in Plant Science*, **12**, 722752.

Yadav, V., Meena, A. K., Kumar, D. and Verma, N. (2024). Criteria of essentiality, forms of nutrients in soil. In *Manure, Fertilizers and Soil Fertility Management* (p. 107).

Yang, H., Wu, Y., Zhang, C., Lyu, L., Wu, W., Huang,Z. and Li, W. (2025). Growth and physiological traits of blueberry seedlings in response to different nitrogen forms. *Plants*, **14**(10), 1444.

Yasir, M., Hossain, A. and Pratap Singh, A. (2025). Pesticide degradation: Impacts on soil fertility and nutrient cycling. *Environments*, **12**(8), 272.

Yilmaz, H. and Yilmaz, A. (2025). Hidden hunger in the age of abundance: The nutritional pitfalls of modern staple crops. *Food Science & Nutrition*, **13**(2), e4610.

Yousuf, M., Tian, Z. Y., Mansy, A. E. and Naseer, M. U. H. (2025). Soil chemistry. In *Environmental Chemistry: Advanced Concepts and Applications* (pp. 217–261). Springer Nature Singapore.

Zegeye, A. B., Ayelign, A., Gezmu, A. H., Tadesse, C., Tesfaye, K., Andualem, M. and Sime, Z. A. (2025). Evaluation of the iron, zinc, and folic acid stability in fortified wheat flour storage and its impact on quality indicators. *BMC Nutrition*.

Zhang, H., Zou, Q., Li, W., Liao, F., Wang, J., Zhang, H. and Yang, Y. (2025). Changes in soil phosphorus forms affect soil zinc availability in distinct paddy rice soil textures under long-term phosphate fertilization. *European Journal of Agronomy*, **168**, 127615.

Zhang, S. R., Yang, J. Q., Wang, D. M., Gao, X. S., Liu, J. H., Zhang, J. and Yang, L. Z. (2025). Mechanisms behind zinc transport in a calcareous soil-wheat system and their impacts on human health. *China Geology*, **8**(3), 573–585.

Zhao, S., Huq, M. E., Fahad, S., Kamran, M. and Riaz, M. (2024). Boron toxicity in plants: Understanding mechanisms and developing coping strategies: A review. *Plant Cell Reports*, **43**(10), 238.