Zinc Dynamics and Management for Sustainable Crop Production

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ABSTRACT

Zinc is micronutrient essential for normal growth and development of plants. It is required for the functioning of many different enzymes and proteins involved in various metabolic pathways in plants for instance, in photosynthesis and carbohydrate metabolism, protein as well as auxin metabolism, the maintenance of membrane integrity, pollen formation and resistance to pathogen attack. Zinc deficiency in food crops cause decreased crop yields and nutritional quality. Generally, the regions in the world with Zn-deficient soils are also characterized by widespread Zn deficiency in humans. Zinc deficiency is attributed by large zinc removals due to high crop yields and intensive cropping systems, lesser application of organic manures, increased use of phosphatic fertilizers resulting in P-induced zinc deficiency. Zinc deficiency in crop production can be managed through agronomy and genetic improvement. Fertilization could correct zinc deficiency and ensure optimum yields and increased zinc concentration in grain. Indiscriminate fertilizer use has polluted the soil and water hence the use of biofertilizers (Zn solubilizing bacteria) along with integrated nutrient management is sustainable approach for managing zinc deficiency.

INTRODUCTION

Zinc (Zn) is an essential micronutrient that serves specific functions such as:

- Carbohydrate metabolism, both in photosynthesis and in the conversion of sugars to starch,
- Protein metabolism,
- Auxin (growth regulator) metabolism,
- Pollen formation,
- Maintenance of the integrity of biological membranes,
- Resistance to infection by certain pathogens (Sommer and Lipman 1926).

When the supply of zinc to the plant is inadequate, one or more of the many important physiological functions of zinc is unable to operate normally and plant growth is adversely affected. With the world population continuing to expand and the problems of producing extra food to provide an adequate standard of nutrition for this growing population, it is very important that any losses in production from a cause so easily corrected as zinc deficiency are prevented.

Origin and Behaviour of Zinc in Soils

The sources of zinc in soil are:

1. **Weathering of parent material**: The total zinc content of a soil is largely dependent upon the geochemical composition of the weathering rock parent material on which the soil has developed. The average zinc content of rocks in the Earth's crust is 78 mg Zn kg^{-1}. Zn containing minerals include: sphalerite (ZnS), smithsonite ($ZnCO_3$), zincite (ZnO), zinkosite $ZnSO_4$, franklinite ($ZnFe_2O_4$) and hopeite ($Zn_3(PO_4)_2$ $4H_2O$).
2. **Organic matter**: Organic manures, compost, FYM, vermicompost all have considerable amount of zinc. Sewage sludge and livestock manure also contribute significantly zinc.
3. **Industrial waste**: Food processing wastes, slaughterhouse wastes, sludges from paper manufacture and recycling and metallurgical materials such as foundry sands and steelworks slags.
4. **Fertilizers**: In many areas around the world where zinc deficiency has been identified as a major problem use of zinc fertilisers (such as zinc sulphate) resulted in significant increase in the total and available zinc concentrations of the soils.

Forms of zinc in soil

The total amount of zinc in soils is distributed over 5 fractions (or pools). These comprise:

1. **Water soluble Zn (WS):** Zinc in soil solution may occur as Zn^{2+}, $ZnCl^{+}$ and $ZnOH^{+}$, complexed with organic matter or associated with colloidal particles.
2. **Exchangeable Zn (Ex):** Amount of Zn adsorbed on soil colloids through electrostatic forces is known as exchangeable Zn. This pool influences the soil solution Zn through ion exchange (Panwar et el. 2017). Zn extracted in this form also includes weakly-sorbed Zn species, particularly those retained on the soil surface by relatively weak electrostatic interactions.
3. **Specifically adsorbed Zn (SA):** Zinc is said to be specially adsorbed when it is sorbed by surfaces in opposition to electrostatic forces. Specifically adsorbed Zn can only be replaced by cations with similar affinities or greater for the

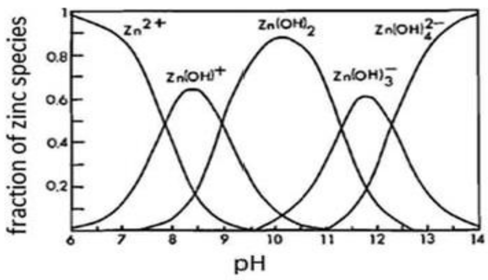
absorption surface or by chemical extraction with chelating agents.

4. **Organically bound Zn (OB):** Zn, a structural component of organic matter, moves to the soil solution through the process of mineralisation. Zn complexed with insoluble humus complexes is a significant component of the specifically adsorbed Zn, while additional Zn is non-specifically adsorbed on exchange sites of organic matter.

Factors Affecting the Availability of Zinc in Soils to Plants

1. Soil pH

Soil pH is the most critical factor influencing Zn availability to crop plants At soil pH below 7.7, Zn^{2+} is the main species, but $ZnOH^{+}$ predominates above pH 7.7, and the neutral species $Zn(OH)_2$ is dominant above pH 9.



2. Soil organic matter

Soil organic matter plays an important role in Zn solubility and its availability to growing plants. The addition of organic matter to such soils enhances Zn bioavailability to plants. Soil organic matter itself can influence Zn adsorption; soils with high organic matter content may exhibit higher Zn adsorption than soils with low organic matter content (Alloy 2008).

3. Soil temperature, moisture, and light intensity

Plants become more sensitive to Zn deficiency under low water availability. Under limited water supply, Zn movement in the soil is limited that restricts the Zn uptake by plants (Prasad et al. 2016). Soil temperature also influences Zn availability as wet and cool seasons result in reduced Zn availability due to the reduced rate of soil mineralization (i.e. the liberation of Zn in organic matter by decomposition).

4. Soil salinity and interaction of Zn with other elements

Zinc deficiency is particularly common in arid and semiarid climates with saline soils. Higher Ca, combined with high pH, decreases Zn availability to plants. Zinc is a cation that interacts with nearly all plant nutrients found in soil, particularly anions. Zn had a beneficial interaction with K because it maintains membrane integrity and minimizes leakage of K and amide. Sulfur treatment increased the Zn concentration in wheat.

5. Zinc interaction with soil biota/mycorrhizal colonization

Soil microorganisms can increase Zn uptake in plants. For instance, mycorrhizal colonization can effectively enhance the absorption of nutrients whose uptake is limited to diffusion from the soil solution to plant roots. Arbuscular mycorrhizal fungi improved Zn uptake in several crops including wheat. Soil bacteria also help to enhance nutrient uptake. Among soil microbes, PGPRs are the most important as they increase nutrient uptake by colonizing the root surface due to signal transduction between the host plant and bacteria. *Bacillus subtilis, Bacillus cereus, Flavobacterium spp. and Pseudomonas aeruginosa* are some of the Zn-tolerant bacteria that help to enhance Zn availability in soil and its uptake by plants.

Mechanisms of Zinc Uptake by Plants

Zinc appears to be absorbed by roots primarily as Zn^{2+}. Nutrients must reach the surface of a root for plant uptake of essential elements to occur. There are three major mechanism of movement of ions from soil to roots. They are:

1. Root interception

Root interception occurs when a nutrient comes into physical contact with the root surface. As a general rule, the occurrence of root interception increases as the root surface area and mass increases, thus enabling the plant to explore a greater amount of soil. Root interception may be enhanced by mycorrhizal fungi, which colonize roots and increases root exploration into the soil.

2. Mass flow

Mass flow occurs when nutrients are transported to the surface of roots by the movement of water in the soil (i.e. percolation, transpiration, or evaporation). The rate of water flow governs the amount of nutrients that are transported to the root surface. Therefore, mass flow decreases are soil water decreases.

3. Diffusion:

Diffusion is the movement of a particular nutrient along a concentration gradient. When there is a difference in concentration of a particular nutrient within the soil solution, the nutrient will move from an area of higher concentration to an area of lower concentration. Diffusion delivers appreciable amounts of zinc to the root surface. Diffusion is a relatively slow process compared to the mass flow of nutrients with water movement toward the root.

Mineral nutrients absorbed from the root has to be carried to the xylem. This transport follows two pathways:

a) Apoplastic pathway

b) Symplastic pathway

In **apoplastic** pathway, mineral nutrients along with water moves from cell to cell through spaces between cell wall by diffusion. The ions, which enter the cell wall of the epidermis move across cell wall of cortex, cytoplasm of endodermis, cell walls of pericycle and finally reach the xylem. In **symplastic** pathway, mineral nutrients entering the cytoplasm of the epidermis move across the cytoplasm of the cortex, endodermis of pericycle through plasmodesmata and finally reach the xylem.

Zinc deficiency symptoms

Visible symptoms of zinc deficiency in various crops include:

- Wilting due to loss of turgidity in the leaves, basal chlorosis of the leaves, delayed development of the plants, "bronzing" of the leaves and, in some cases, death of the rice seedlings occur.

- Light green to white chlorotic and necrotic streaks developed on either side of the leaf mid-rib are characteristic of mild deficiency in wheat. Where the deficiency is more severe, the lower leaves tend to be totally chlorotic and short, but of normal width.

- Maize is highly susceptible to zinc deficiency. Areas of leaf near the stalk may develop a general white to yellow chlorosis (white bud). In cases of severe deficiency, the plants are stunted due to shortened internodes and the lower leaves show a reddish or yellowish streak.

- Zinc deficiency retards development and maturation of the seed heads in sorghum.

- In flaxseed shortened internodes give a rosette appearance. Later the top of the main stem becomes necrotic. Deficient plants are stunted and have yellow (chlorotic) leaves particularly in the lower area.

- Citrus trees are particularly susceptible to zinc deficiency, which appears in the early stages as small blotches of yellow between green veins on the leaf (sometimes called 'mottle-leaf').

Diagnosis of zinc deficiency in soils and crops:

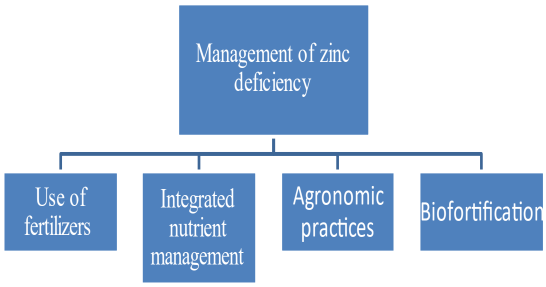
A. **Visual symptoms:** Field observation of visible symptoms can be a quick and convenient diagnostic tool for cases of severe zinc deficiency in many crops. A nutrient deficient plant exhibits specific symptoms as normal plant processes are inhibited.

B. **Soil testing**: Hidden deficiencies of zinc can sometimes cause yield reductions of 20% or more without obvious symptoms. It is advisable to conduct confirmatory soil and/or plant analysis in cases of suspected deficiency. Soil testing provide an index of nutrient availability in soil. Soil testing has the advantage over plant tissue analysis in that it can be carried out at any time.

C. **Plant analysis:** The advantage of plant analysis is that it determines the plant's zinc and other nutritional status at the moment of sample. All of the soil and plant parameters that influence zinc availability to the plant, as well as its uptake and translocation within the plant, will have interacted, and the analysis will show the results. Critical deficiency concentrations (CDCs) are commonly used to interpret plant analytical data. The Critical Deficiency Concentration is defined as the concentration in the given tissue that results in a 10% loss in the plant yield. The lowest critical concentration for zinc is 20 mg Zn kg^{-1}. Young leaves are especially useful for evaluating the zinc status of plants because signs of zinc shortage frequently.

D. **Biochemical tests:** Assays of the activity of several zinc-containing enzymes have been shown to be a relatively reliable indicator of zinc status in certain crops, but they have not been adopted on a wide scale. Three enzymes have been used for these assays: ribonuclease in rice and maize, carbonic anhydrase in citrus and wheat, and aldolase in onions.

Management of zinc deficiency



1. Use of fertilizers:

The most commonly used Zn fertilizer is $ZnSo_4$ with recommended rate of 10-25 $kgha^{-1}$. For foliar application 0.5% solution of $ZnSO_4$ mixed with small amount of lime is used.

Biofertilizers: Biofertilizers, also known as microbial inoculants, are carrier-based live bacterial or fungal formulations that, when applied to plants, soil composting, or pits, assist mobilize various nutrients through biological activity. Zinc-solubilizing bacteria can be employed as biofertilizers. ZSB can help to address Zn shortages by converting insoluble Zn into soluble Zn, increasing its availability and efficiency of uptake by host plants (Singh et al. 2024). Plant growth-promoting bacteria (PGPB) application is a sustainable and greener technique to increasing food quantity without sacrificing quality or production. These PGPBs can promote nutrient usage efficiency and tolerance against biotic and abiotic challenges by contributing to root architecture, boosting soil fertility, and enhancing macro- and micronutrient solubilization.

2. Integrated nutrient management: INM account all factors of soil and crop management including management of all other inputs such as water agrochemicals etc, besides nutrients. The basic concept of integrated nutrient management is maintenance of plant nutrients supply to achieve a given level of crop production by optimizing the benefits from all possible sources of plant nutrients in an integrated manner, appropriate to each cropping system and farming situation.

3. Agronomic practices: Various agronomic practices such as conservation agriculture is helpful in managing soil health and enhancing nutrient availability. Selection of suitable cropping pattern is also helpful for managing soil fertility status.

4. Biofortification:

It is classified into two types: agronomic biofortification and genetic biofortification. The agronomic biofortification foliar spray of nano-Zn fertilizer and 0.5% $ZnSO_4$ is done. Genetic biofortification involves the development of zinc-fortified varieties of various crops.

CONCLUSION

The current agricultural practices heavily depend on chemical fertilizers to boost crop output, prioritizing macronutrients and neglecting micronutrients like zinc. This imbalance leads to zinc deficiencies in plants, ultimately affecting their growth and productivity. Low plant availability of soil zinc is a critical problem for crop production, causing severe reduction in yield and nutritional quality of crops. The sustainable solution to ameliorate zinc deficiency is to adopt integrated nutrient management practices moreover, biofortification is also good approach.

Future thrust

Combining improved tolerance to zinc deficiency and increased zinc concentration and content in seed is high priority research topic. Research is needed on the role of soil biota in zinc accumulation by plants. More experiments should be conducted with different sources of zinc for enhancing zinc use efficiency by crops.

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