Research and Reviews in Plant Science

ISBN: 978-81-970663-4-4| Year: 2024 | pp: 155 - 158 |

Zinc as an Essential Micronutrient in Plant Growth and Stress Management

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Article DOI Link: https://zenodo.org/uploads/20305802

DOI: 10.5281/zenodo.20305802

Abstract

Zinc (Zn) is an essential micronutrient required for the normal growth and development of plants, playing a crucial role in enzymatic activity, protein synthesis, and stress tolerance. Despite its requirement in trace amounts, zinc deficiency is widespread in agricultural soils, particularly in saline and alkaline environments, leading to reduced crop productivity. This chapter provides a comprehensive account of zinc chemistry, soil availability, uptake and translocation, physiological roles, involvement in salt stress mitigation, deficiency and toxicity symptoms, and its broader applications. The discussion integrates classical knowledge with recent research findings to provide a useful resource for researchers and academicians

Introduction

Plants require a continuous supply of mineral nutrients for completing their life cycle. According to Emanuel Epstein (1972), an element is considered essential if its absence prevents the completion of the life cycle and if it plays a direct role in plant metabolism. Among essential nutrients, zinc is categorized as a micronutrient because it is required in very small quantities, generally less than 100 μg g^{-1} dry matter. However, its role in plant metabolism is disproportionately large compared to its concentration. Zinc is the second most abundant transition metal in biological systems after iron and is indispensable for numerous biochemical processes. In recent years, zinc deficiency has become a major constraint in agriculture, particularly in developing countries, significantly affecting crop yield and nutritional quality (Cakmak, 2008).

Chemistry and Sources of Zinc:

1. Occurrence and Forms in Soil

Zinc is widely distributed in the Earth's crust and occurs naturally in mineral forms such as zinc sulfides, carbonates, and silicates. The primary source of zinc in soil is the weathering of parent rocks. In soils, zinc exists in different forms including mineral-bound, adsorbed, soil solution (Zn^{2+}), and organically complexed forms. Among these, the Zn^{2+} ion in soil solution is the form readily available for plant uptake.

2. Factors Affecting Zinc Availability

The availability of zinc to plants is strongly influenced by soil physicochemical properties such as pH, organic matter, clay content, and ionic interactions. High soil pH, especially in calcareous soils, significantly reduces zinc availability, while organic matter enhances it by forming soluble complexes. In Indian soils, zinc concentration ranges between 20–89 mg kg^{-1} depending on climatic conditions (Aref, 2011; Broadley et al., 2007). Salinity and excess calcium ions also reduce zinc uptake, making deficiency more common in arid and semi-arid regions.

Uptake and Translocation of Zinc in Plants

Zinc is absorbed by plant roots primarily as Zn^{2+} ions through active transport mechanisms mediated by specific transporter proteins such as the ZIP family (Hall & Williams, 2003). After absorption, zinc is transported through the xylem from roots to aerial parts and redistributed via the phloem. Its mobility within plants is considered intermediate, allowing limited redistribution under deficiency conditions (Haslett et al., 2001). Molecular studies, particularly in Arabidopsis thaliana, have identified several genes responsible for zinc transport and homeostasis, highlighting the complexity of its regulation in plant systems.

Physiological Roles of Zinc in Plants:

1. Enzymatic and Metabolic Functions

Zinc is a structural and catalytic component of more than 300 enzymes, including carbonic anhydrase, alcohol dehydrogenase, and superoxide dismutase. These enzymes are essential for processes such as photosynthesis, respiration, and antioxidant defense (Broadley et al., 2007).

2. Role in Protein Synthesis and Gene Regulation

Zinc plays a critical role in protein synthesis and gene expression by stabilizing ribosomal RNA and forming zinc-finger proteins that regulate transcription (Andreini et al., 2006).

3. Photosynthesis and Growth Regulation

Zinc contributes to chlorophyll synthesis and carbon metabolism and is involved in the synthesis of tryptophan, a precursor of the plant hormone auxin, which regulates plant growth and development (Marschner, 1995).

4. Membrane Stability and Antioxidant Defense

Zinc helps maintain membrane integrity and protects cells from oxidative damage by regulating reactive oxygen species (ROS), thereby enhancing stress tolerance (Cakmak, 2000).

Role of Zinc in Mitigation of Salt Stress:

1. Antioxidant Defense Mechanism

Zinc enhances the activity of antioxidant enzymes such as superoxide dismutase, reducing oxidative stress caused by salinity (Gunes et al., 2000).

2. Osmoregulation and Water Balance
It promotes the accumulation of osmolytes, helping plants maintain cellular water balance under saline conditions.

3. Ion Homeostasis
Zinc reduces sodium toxicity and improves potassium retention, thereby maintaining ionic balance within plant cells.

4. Improvement of Growth under Salinity
Application of zinc improves plant growth, chlorophyll content, and biomass under salt stress conditions (Tavallali, 2016). Thus, zinc plays a vital role in enhancing plant tolerance to salinity.

Availability of Zinc in Soil
Zinc availability is influenced by several soil factors, including pH, organic matter, salinity, and nutrient interactions. High pH and calcareous conditions reduce zinc solubility, whereas organic matter enhances its availability. Zinc deficiency is widespread in saline, sodic, and intensively cultivated soils. Globally, zinc deficiency is a major agricultural and nutritional concern (White & Zasoski, 1999), and its prevalence is expected to increase with ongoing soil degradation.

Zinc Deficiency in Plants

1. Causes of Deficiency
Zinc deficiency arises due to low soil zinc content, high soil pH, excessive phosphorus fertilization, and salinity stress.

2. Deficiency Symptoms
Deficiency symptoms include interveinal chlorosis in young leaves, reduced leaf size, shortened internodes, and stunted growth. Severe deficiency leads to poor seed formation, premature leaf fall, and reduced yield. Specific disorders include Khaira disease in rice, white bud in maize, and little leaf in cotton. Zinc deficiency is typically observed when plant tissue concentration falls below 10–20 ppm.

Zinc Toxicity in Plants

1. Causes of Toxicity
Zinc toxicity results from excessive accumulation due to industrial pollution, mining, and overuse of fertilizers and sewage sludge.

2. Toxicity Symptoms and Mechanisms
Toxicity symptoms include chlorosis, inhibited growth, and disruption of enzymatic activities. Toxic effects are generally observed when zinc concentrations exceed 300–400 mg kg^{-1} in plant tissues (Mulligan et al., 2001). Plants tolerate excess zinc through mechanisms such as sequestration in vacuoles, binding to cell walls, and synthesis of metal-binding proteins.

Potential Uses of Zinc

1. Agricultural Applications
Zinc is widely used as a micronutrient fertilizer in the form of zinc sulfate and chelated compounds to improve crop yield and quality. It also plays an important role in biofortification, enhancing the nutritional value of crops.

2. Environmental Applications
Zinc is used in phytoremediation to remove heavy metals from contaminated soils and to mitigate environmental pollution.

3. Industrial and Biological Uses
Zinc is used in alloy production, particularly brass, and is essential for

enzyme function and metabolic processes in both plants and humans.

Conclusion

Zinc is a crucial micronutrient that plays diverse roles in plant growth, metabolism, and stress tolerance. Its importance extends beyond basic nutrition to include protection against abiotic stresses such as salinity. Despite its significance, zinc deficiency remains a widespread issue limiting agricultural productivity. Effective zinc management through fertilization and improved agronomic practices is essential for sustainable agriculture. Future research should focus on enhancing zinc use efficiency, developing zinc-efficient crop varieties, and integrating zinc nutrition into climate-resilient agricultural systems.

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