Role of Zinc Solubilizing Bacteria in Improving Zinc Bioavailability

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ABSTRACT

Zinc (Zn) deficiency is a major constraint to crop productivity and human nutrition due to the low bioavailability of zinc in soils. Conventional zinc fertilizers often show limited efficiency because of rapid zinc immobilization. Zinc-solubilizing bacteria (ZSB) offer a sustainable approach to improve zinc availability in soil–plant systems. These beneficial microorganisms mobilize insoluble zinc through organic acid production, chelation, and rhizospheric pH modification, enhancing Zn uptake by plants. In addition, ZSB improve soil health, root development, and crop productivity while supporting microbial-assisted zinc biofortification. This article highlights the mechanisms and agricultural potential of zinc-solubilizing bacteria as eco-friendly tools for sustainable zinc nutrition management.

INTRODUCTION

Zinc (Zn) is an essential micronutrient involved in key physiological and biochemical processes regulating plant growth and development, including enzyme activation, protein synthesis, carbohydrate and lipid metabolism, auxin biosynthesis, gene expression, and reproductive development. Adequate zinc nutrition is therefore critical for optimal crop productivity. However, zinc deficiency is widespread in agricultural soils and remains one of the most serious micronutrient constraints to global crop production. Nearly half of the world's arable soils are zinc deficient, leading to symptoms such as chlorosis, stunted growth, poor root development, and yield reduction.

Zinc deficiency in crops also poses serious risks to human health, as zinc is essential for immune function, growth, and cognitive development. Populations relying predominantly on plant-based diets are particularly vulnerable due to low zinc bioavailability, highlighting the urgent need to improve zinc nutrition in food crops.A zinc shortage can significantly reduce agricultural productivity and quality, which is a significant barrier to global food production systems. "Hidden hunger" refers to a lack of zinc and other micronutrients, including iron and selenium (De Valenca et al., 2017). Insufficient zinc intake can lead to impaired immune response, growth retardation, and neurological disorders, underscoring the urgent need to improve zinc concentration and bioavailability in food crops.

Widespread zinc deficiency in crops is largely attributed to low zinc solubility and poor bioavailability rather than low total soil zinc. In India, nearly 50% of agricultural soils are zinc deficient due to factors such as high soil pH, elevated bicarbonate and organic matter content, imbalanced Mg:Ca ratios, and excessive phosphorus and iron availability, which cause rapid zinc immobilization and low fertilizer efficiency.

Zinc-solubilizing bacteria (ZSB) have therefore emerged as a sustainable strategy to enhance zinc bioavailability by converting insoluble zinc compounds into plant-available forms through organic acid production, chelation, and proton extrusion in the rhizosphere. This article highlights the role of ZSB in zinc mobilization, soil–plant interactions, and their potential application in sustainable agriculture.

Mechanism of Zinc Solubilisation

Zinc Chelation: Due to its reactive nature and low persistence, the bioavailable fraction of zinc in soil is often limited. Microbial chelators and metabolites, including siderophores, interact with zinc ions, reducing their fixation and enhancing mobility in soil. These Zn–chelate complexes can move toward the plant root zone, where Zn^{2+} is released and becomes available for uptake. Chelation is therefore a primary microbial mechanism for improving zinc bioavailability.

Although siderophores are mainly involved in iron acquisition, they also chelate zinc. Bacterial species such as *Pseudomonas monteilii*, *Microbacterium saperdae*, and *Enterobacter cancerogenesis* produce Zn-chelating metallophores that enhance Zn^{2+} availability in soil. Other microorganisms, including *Pseudomonas*, *Azospirillum lipoferum*, *Agrobacterium* spp., and *Penicillium bilaji*, also solubilize fixed zinc forms through chelation, thereby prolonging zinc availability in the rhizosphere.

Acidification (via Organic Acids Production): Zinc is soluble through the most important process of organic acid generation. Through secreting Organic Acids these bacterial strains lower the pH of the surrounding soil (Kamran et al., 2017; Upadhayay et al., 2022). Gluconic acid and its derivatives play a major role in converting insoluble zinc compounds, such as zinc oxide, carbonate, and phosphate, into plant-available forms. Several microbial genera, including *Gluconacetobacter*, *Pseudomonas*, and *Acinetobacter*, are known to produce substantial amounts of gluconic acid associated with zinc solubilization. In contrast, *Burkholderia cepacia* solubilizes zinc primarily through the production of other organic acids, such as oxalic, formic, tartaric, and acetic acids.

Cell membrane proton system: Bacteria facilitate zinc (Zn^{2+}) mobilization in soil through proton (H^+) extrusion, which displaces zinc ions from soil binding sites due to charge interactions. The released Zn^{2+} becomes more

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mobile in the soil solution and readily available for plant uptake. These protons originate either from bacterial membrane transport systems that maintain cellular homeostasis or from the dissociation of organic acids secreted by bacteria. Collectively, proton-mediated desorption enhances zinc solubility in the rhizosphere and improves its uptake by plants.

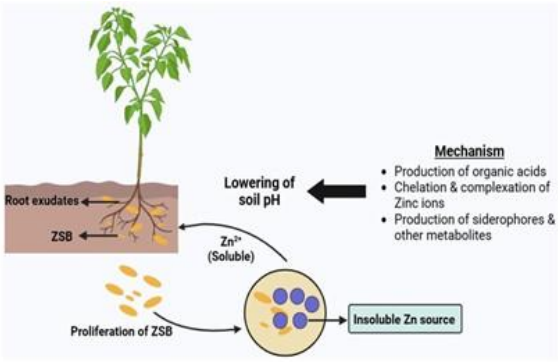

Fig.1 General overview of the mechanism of Zn solubilization

Changes in root architecture: In the rhizosphere, zinc availability is often limited due to low external inputs or poor native bioavailability, resulting in reduced mobility. For efficient plant uptake, zinc must be present in a soluble form. Increased root surface area and root system development enhance zinc acquisition through diffusion, even from greater distances. Mycorrhizal fungi, which colonize root surfaces, significantly modify root architecture and facilitate zinc uptake from beyond the immediate rhizosphere. The inoculation of Zn-soluble bacteria and mycorrhizal fungi has been shown to improve Zn biofortification and enhance root length (Subramanian et al., 2009), weight, and volume.

Influence of Zn-SB on soil health and crop productivity

ZSB not only make zinc available to plants, but also contribute to the overall soil health.

Symbiotic relationships with plants: Zinc-solubilizing bacteria (ZSB) form mutualistic associations with plants by mobilizing zinc and other nutrients, thereby promoting plant growth, while plants supply root exudates such as sugars, amino acids, and organic acids that support bacterial activity. ZSB also interact synergistically with other beneficial microorganisms, including nitrogen-fixing bacteria, phosphate-solubilizing bacteria, and mycorrhizal fungi, resulting in enhanced nutrient uptake. For instance, *Rhizobium* in legumes contributes both nitrogen fixation and zinc solubilization, improving soil fertility and reducing dependence on chemical fertilizers.

Soil structure and Organic Matter: Soil structure and organic matter are key to soil health and fertility. Zinc-solubilizing bacteria (ZSB) produce extracellular polysaccharides (EPS) and biofilms that help binding soil particles into stable aggregates thereby promote soil structure. ZSB also releases enzyme that helps in breaking down of complex organic compounds into simpler(plant-available) forms.

Soil enzyme activity: Important biochemical activities in the soil such as the breakdown of complex organic compounds, organic matter decomposition, and the cycling of nutrients are facilitated by Soil enzymes. By increasing the activity of important soil enzymes such phosphatase, dehydrogenase, urease, protease, cellulase, and amylase, zinc-solubilizing bacteria improve soil fertility and nutrient availability.

CONCLUSION

Zinc-solubilizing bacteria (ZSB) play a vital role in enhancing zinc bioavailability and improving soil health and crop productivity through mechanisms such as organic acid production and chelation. By addressing zinc deficiency in soils, these beneficial microorganisms contribute to sustainable nutrient management, promote microbial diversity, and support nutrient cycling.

In the face of declining soil fertility, rising fertilizer costs, and environmental concerns, ZSB offer an eco-friendly alternative to conventional fertilizers by reducing chemical inputs, nutrient losses, and environmental degradation. Future research should focus on optimizing bioinoculant formulations, understanding interactions with diverse cropping systems, and elucidating the genetic and metabolic basis of zinc solubilization. The integration of ZSB into agricultural practices holds strong potential for enhancing soil health, crop productivity, and long-term agricultural sustainability.

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