International Journal of Research in Agronomy 2025; SP-8(8): 517-522

E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2025): 5.20
www.agronomyjournals.com
2025; SP-8(8): 517-522
Received: 17-06-2025
Accepted: 19-07-2025

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Zinc solubilizing bacteria: A promising cost-saving solution for Indian farmers: A review

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DOI: https://www.doi.org/10.33545/2618060X.2025.v8.i8Sg.3657

Abstract
Zinc (Zn) is a critical micronutrient for plants, animals, and humans, yet nearly 50% of Indian soils are Zn-deficient, significantly affecting crop productivity and human nutrition, especially in cereal-based diets. Conventional Zn fertilizers like zinc sulphide and zinc oxide, though widely used via soil application, result in up to 90% Zn fixation—leading to substantial economic losses for farmers. This review emphasizes the cost-effective potential of zinc-solubilizing bacteria (ZSB), which enhance Zn bioavailability through mechanisms like organic acid production and chelation. ZSB application, either alone or in combination with Zn sources, improves Zn uptake, yield, and grain nutrition in rice and other crops, while also supporting soil health. As an environmentally sustainable and economically viable solution, integrating ZSB into nutrient management strategies can reduce reliance on chemical fertilizers, lower input costs, and contribute to mitigating Zn malnutrition. Future research should focus on field validation and biofortification approaches.

Keywords: Zinc solubilizing bacteria, zinc sulphide, cost-effective, soil health, and zinc malnutrition

Introduction

Zinc (Zn) is an essential micronutrient vital for the growth and development of plants, animals, and humans. In plants, zinc plays a key role in enzymatic activities, metabolic processes, protein synthesis, and the regulation of growth hormones (Cakmak, 2002) [2]. Despite its significance, zinc deficiency is widespread, particularly in cereal-based diets and in Indian soils, where nearly 50% of cultivated land is reported to be deficient (Kapoor *et al*., 2002) [11]. This deficiency adversely affects both crop productivity and human nutrition.

Globally, over 3 billion people suffer from zinc and iron deficiencies, often due to consumption of polished cereal grains that have lost their micronutrient-rich husk during processing (Cakmak, 2002) [2]. Zinc deficiency in humans is recognized as a major public health concern, contributing to impaired immune function and increased mortality (Stein, 2010) [27].

In agricultural soils, zinc exists in various forms, ranging from soluble ionic and organically bound forms to forms occluded within oxides or trapped in silicate minerals. However, the mobility and availability of zinc in soils are often restricted, particularly in alkaline, calcareous, or phosphate-rich soils where zinc becomes immobilized. This leads to inefficient uptake by plants and poor translocation to edible parts.

Traditional agronomic strategies to address zinc deficiency involve applying zinc fertilizers (e.g., zinc sulphate or zinc oxide - Multiplex Zinc param and Chelated Zinc in EDTA Form ex: Multiplex Swarna Zn), either through soil or foliar application. However, soil applications are often inefficient, as up to 90% of the applied zinc becomes fixed and unavailable to plants, leading to significant economic losses for farmers. Therefore, sustainable alternatives are needed to improve zinc availability while minimizing environmental and financial costs.

One such approach involves the use of zinc-solubilizing bacteria (ZSB)—a group of beneficial rhizosphere microorganisms capable of converting insoluble zinc compounds into plant-available forms via mechanisms such as organic acid production, acidification, and chelation (Sarathambale *et al*., 2010) [20]. Genera like *Bacillus*, *Pseudomonas*, *Acinetobacter*, and *Gluconacetobacter* have shown promise in this regard *(Fasim et al., 2002)* [6]. For example, Multiplex Zinc B.

Among these, *Bacillus* spp. is especially valued due to their endospore-forming ability, environmental resilience, ease of m0ass production, and broad-spectrum compatibility with host plants. Leveraging such microbial bioinoculants offers a low-input, eco-friendly solution that enhances zinc phytoavailability, crop yield, and ultimately, dietary zinc content, contributing to both agricultural sustainability and human health.

Importance of Zn in Humans

Zinc deficiency is a widespread issue affecting humans, animals, and plants, with over 30% of the global population estimated to be deficient in zinc (Welch, 2002) [35]. Zinc is vital for numerous cellular functions across all living organisms and plays a key role in strengthening the human immune system. The recommended dietary intake for adult humans is approximately 15 mg of zinc per day. Zinc acts as both a catalytic and structural component in various enzymes within the body. Deficiency can arise from inadequate dietary intake or impaired absorption.

The effects of zinc deficiency in humans include hair loss, memory problems, skin conditions, and muscle weakness. During pregnancy, inadequate zinc intake can impair fetal brain development, while in men, zinc deficiency has been associated with infertility. Severe deficiency may also cause congenital disorders such as Acrodermatitis enteropathica.

Zinc is primarily concentrated in the husks and grains of cereals like rice and other cereals; hence, their consumption can help mitigate zinc deficiency. Other dietary sources of zinc include beef, pork, poultry, fish, fortified breakfast cereals, nuts (e.g., roasted peanuts, almonds, walnuts), oats, and dairy products such as yogurt, cheese, and milk (Cakmak, 2002) [2].

The recommended dietary allowance (RDA) for zinc varies by age and condition: 3-5 mg/day for infants, 10 mg/day for children (1-10 years), 15 mg/day for adult men, 12 mg/day for adult women, and 16-19 mg/day for lactating women. In cattle, deficiency symptoms arise when pasture or fodder contains less than 18-42 mg of zinc per kilogram of dry matter (Legg & Sears, 1980) [14].

Role of Zinc in Plants

Zinc (Zn) plays a vital role in plant metabolism by regulating the activity of various enzymes, including hydrogenase and carbonic anhydrase. It contributes to the stabilization of ribosomal structures and is involved in the synthesis of cytochrome (Tisdale *et al*., 1984) [30]. Zinc-activated enzymes are crucial for carbohydrate metabolism, protein synthesis, maintenance of cellular membrane integrity, auxin synthesis regulation, and pollen formation. Moreover, zinc is essential for the regulation and maintenance of gene expression, which enables plants to tolerate various environmental stresses (Cakmak, 2002) [2].

Zinc deficiency in plants can lead to a range of physiological abnormalities, such as stunted growth, chlorosis (leaf yellowing), reduced leaf size, and spikelet sterility. It can also negatively affect the quality of harvested produce, increase plant susceptibility to high light and temperature stress, and enhance vulnerability to fungal infections. Zinc plays a role in water uptake and transport, and it helps mitigate the adverse effects of short-term heat and salt stress (Tavallali *et al*., 2010) [29].

Additionally, since zinc is required for the synthesis of tryptophan—a precursor of indole-3-acetic acid (IAA)—it plays a key role in the production of the essential plant growth hormone auxin, which also takes part in fruit setting. Zinc is also critical for maintaining the integrity of cellular membranes and the proper orientation of macromolecules and ion transport systems. Its interaction with phospholipids and sulfhydryl groups of membrane proteins supports membrane stability (Dang *et al*., 2010) [3].

Zinc-finger transcription factors further underscore zinc's importance in plant reproductive development. These proteins are involved in the formation and functioning of floral tissues such as anthers, tapetum, and secretory structures in the pollen and pistil. Moreover, zinc is essential for nectar production, which is crucial for attracting pollinators.

Conditions Indicating Zinc Deficiency

Zinc deficiency is commonly observed under the following conditions:

Calcareous soils, with a pH over 7 and more than 1.5% organic carbon, may show zinc deficiency due to high bicarbonate (HCO_3^-) levels in the soil.

Ratio of Exchangeable Magnesium to Calcium:

A ratio greater than 1 for exchangeable magnesium (Mg) to calcium (Ca) in the soil may also suggest the presence of zinc deficiency.

Soil pH

Zinc availability is notably affected by pH levels. In alkaline soils (pH above 7), Zn solubility decreases, leading to a higher risk of deficiency compared to acidic soils. Liming acidic soils raises pH, which can enhance Zn fixation and hinder Zn mobility, resulting in lower crop absorption and potential deficiency.

Soil Organic Matter

In India, soil organic matter (OM) content is under 0.5%, resulting in widespread zinc (Zn) deficiency. Increased organic matter from decomposed plant and animal materials enhances Zn availability, particularly through humic substances that chelate Zn, improving its solubility across different pH levels. Simple organic compounds like amino acids and phosphoric acids also aid in Zn availability. However, excessively high organic matter, as found in peat and muck soils, can lead to Zn deficiency by binding Zn to humic substances.

Soil texture

Sandy soils generally have lower zinc (Zn) levels compared to clay soils, which have higher cation exchange capacity (CEC) and can retain more Zn. This makes Zn deficiency more common in sandy soils. Although clay can adsorb Zn, some of it remains unavailable to plants. Kaolinite fixes less Zn than bentonite or illite, which have higher CECs and bind Zn more strongly, reducing its accessibility for plants (Kausar, MA *et al*., 1976) [12].

Phosphate fertilizers

Soils with high phosphate levels can cause zinc deficiency in crops, as excessive phosphate fertilizers reduce zinc uptake due to physiological imbalances in plants, a condition known as "P-induced Zn deficiency" (Singh JP *et al.*, 1986) [25].

Soil temperature

Temperatures below 16ºC reduce Zn uptake in maize, indicating a link between Zn deficiency and cool, wet seasons. Soil temperature influences Zn mineralization rates, and Zn deficiency can arise from high light intensity, long day lengths, poor soil management, drought, or soil compaction.

Zinc Interaction with Other Nutrients

The condition known as 'P-induced Zn deficiency' occurs in plants when there are high levels of available phosphorus (P) or P is applied to the soil. This deficiency can be influenced by nitrogen fertilizers, and macronutrient cations like calcium (Ca), magnesium (Mg), and potassium (K) can inhibit zinc (Zn) absorption in plants.

Visual Symptoms of Zinc (Zn) Deficiency in Plants

Visual symptoms of zinc (Zn) deficiency in plants are distinctive and relatively easy to identify. These signs are useful for detecting acute Zn deficiency and for identifying soils that are likely to respond to zinc fertilization. However, they are not reliable indicators of hidden or marginal deficiencies.

The most common symptoms include stunted growth, shortened internodes and petioles, and the development of small, malformed leaves—often referred to as "little leaf." In dicotyledonous plants, early-stage deficiency can lead to a "rosette" appearance, while in monocotyledons, it may produce "fan-shaped" stems, as well as Yellowing and brown spots seen in paddy well known as khaira disease.

Symptoms generally appear first on younger leaves because zinc is immobile within the plant during deficiency. These younger leaves tend to remain undersized, curl upward, and show interveinal chlorosis along with necrotic spots on their upper surfaces. As the deficiency progresses, the necrotic spots may coalesce into large, brown, brittle patches.

Middle-aged leaves often exhibit more severe necrosis over time, which can result in wilting, bending, and eventual collapse. Zinc deficiency symptoms are typically patchy within a single field and can develop rapidly, though the severity and speed of symptom development depend largely on the degree of stress experienced by the plants (Kubota, J., Allaway, W.H. *et al*., 1972) [13].

Effect of Zinc on Microbial Activity

Zinc (Zn) is an essential micronutrient for microorganisms, acting as a cofactor and metal activator for numerous enzymes. While required in trace amounts, excessive zinc levels (above 13.60 mg kg^{-1}) can inhibit microbial growth, reduce soil microbial populations, and impair overall activity (Vankatakrishnan *et al*., 2002) [33].

The mode of action of Zinc -solubilizing bacteria

Zinc-solubilizing microorganisms play a crucial role in enhancing zinc availability in soil through various mechanisms, the most prominent being acidification. These microbes produce organic acids that sequester zinc cations and lower the surrounding soil pH. Additionally, the anions released can chelate zinc, further increasing its solubility. Other mechanisms involved in zinc solubilization include the production of siderophores (Saravanan *et al*., 2007) [21] and the action of oxidoreductive systems on cell membranes, along with chelating ligands.

Several plant growth-promoting rhizobacteria (PGPR) have been shown to enhance plant growth and zinc uptake when inoculated into plants. Notable examples include strains of *Pseudomonas* and *Rhizobium*, *Bacillus aryabhattai* (Ramesh *et al*., 2014) [18], *Bacillus* sp., and *Azospirillum*. Other bacterial strains known for their zinc-solubilizing abilities include *Pseudomonas aeruginosa* (Fasim *et al*., 2002) [6], *Gluconacetobacter diazotrophicus* (Saravanan *et al*., 2007) [21], *Pseudomonas striata*, *Pseudomonas fluorescens*, *Burkholderia cenocepacia*, *Serratia liquefaciens*, *Serratia marcescens*, and *Bacillus thuringiensis*0 ex- Multiplex Zinc B.

Effect on different crops

Several **plant growth-promoting rhizobacteria (PGPR)**, such as *Pseudomonas*, *Rhizobium*, *Bacillus aryabhattai*, *Azospirillum*, and *Gluconacetobacter diazotrophicus*, have shown effectiveness in solubilizing zinc and improving plant growth (Fasim *et al*., 2002; Saravanan *et al*., 2007) [6, 21]. These microbes offer an eco-friendly alternative to chemical fertilizers by mobilizing zinc from insoluble sources in the soil.

The effects of zinc-solubilizing bacteria on various crops are described as follows:

Paddy

Zinc (Zn) deficiency is common in flooded and submerged soils due to the transformation of soluble Zn into insoluble forms like $Zn(OH)_2$ in acidic soils and ZnS in alkaline or sulfur-rich conditions. Increasing soil pH further reduces Zn solubility. In submerged soils, Zn binds with manganese oxides and carbonates, affecting translocation more than uptake. Calcareous soils with high bicarbonate (HCO_3^-) and anaerobic conditions promote insoluble Zn-phosphate formation, lowering Zn availability. Although some Zn can be released from acid-soluble fractions, acidic rhizospheres and organic acids can hinder uptake. Rice, being a submerged crop, requires higher Zn due to low redox potential, high pH, and low organic matter in such environments (Dobermann *et al*., 2000; Tapiero and Tew, 2003) [5, 28].

Agronomic and Nutritional Implications

Zinc deficiency can cause yield losses of up to 80% in cereals like rice and wheat, which are dietary staples in many malnourished regions (Singh *et al*., 2017) [26]. It also increases heavy metal accumulation in grains and fodder, posing health risks (Hart, 1998) [8]. Around 85% of rice-wheat systems in the Indo-Gangetic Plains are grown on high pH calcareous soils, making zinc supplementation crucial for crop productivity and nutritional security.

Factors Contributing to Zinc Deficiency

The intensification of agriculture—characterized by the adoption of high-yielding crop varieties, excessive use of chemical fertilizers and pesticides, and minimal application of organic manure—has further aggravated zinc deficiencies in rice ecosystems. These practices disrupt soil microbial activity and deplete naturally occurring zinc reserves, reducing the nutrient's long-term availability.

Role of Zinc-Solubilizing Bacteria (ZSB) in Rice Productivity

Zinc-solubilizing bacteria (ZSB) offer an eco-friendly and effective solution to counter zinc deficiency. Strains such as AGM3 and AGM9 have shown notable improvements in the growth and yield of rice when applied alone or in combination with insoluble zinc sources like ZnO and $ZnCO_3$ (Gandhi and Muralidharan, 2016) [7].

In pot culture studies, zinc fertilizer applications have led to:

- 12.9% increase in dry matter yield
- 15.1% increase in productive tillers per plant
- 13.3% increase in number of panicles
- 12.8% increase in grains per panicle
- 17.0% increase in grain yield
- 12.4% increase in straw yield (Vaid *et al*., 2014) [32]

When used with chemical zinc fertilizers, *Bacillus cereus* (ZSB) significantly boosts growth and biochemical parameters, including:

- Plant height: 102-118 cm
- Tillers per plant: 8.5-11.5
- Chlorophyll content: 29.5-35.1 SPAD
- Superoxide dismutase activity: 396-570 U/g FW
- Carbonic anhydrase activity: 10-15.06 U/g FW
- Grain yield: 3.0-3.8 tons per hectare (Shakeel *et al.*, 2024) [23]

Inoculating rice plants with ZSB has been found to increase the zinc content in rice grains by 15-20%, enhancing the nutritional value of the crop and helping to address malnutrition in zinc-deficient regions (Das *et al*., 2019) [4].

These findings highlight ZSB's potential as a bio-inoculant for improved nutrient uptake and plant productivity.

Wheat

Zinc deficiency in plants can cause several issues, including stunted shoot growth, chlorosis (yellowing of leaves), reduced leaf size, increased susceptibility to heat, light, and fungal infections, as well as negative impacts on grain yield, pollen formation, root development, and water uptake and transport (Tavallali *et al*., 2010) [29]. In wheat, zinc deficiency specifically results in yellowing leaves and stunted growth, which can also lead to zinc deficiency in humans when they consume zinc-deficient wheat.

Zinc-solubilizing endophytes can enhance the translocation and enrichment of zinc to wheat grains, regardless of their differing nutrient use efficiency. This method can be integrated into modern agricultural strategies. The application of *Pseudomonas* along with zinc sulfate has been shown to improve plant height, chlorophyll content, and the number of grains per plant, leading to a 31% increase in yield. Furthermore, this approach positively influences the levels of maleic acid, oxalic acid, α-ketoglutaric acid, and fumaric acid, while also increasing the amounts of valine, leucine, sugars, proteins, and phenolic compounds in root exudates (Joshi *et al*., 2013) [10].

Wheat grains from plants treated with zinc-solubilizing bacteria (ZSB) tend to have higher protein content and better baking qualities.

Zinc solubilizing bacteria, such as *Pantoea dispersa*, *P. agglomerans*, *Pseudomonas fragi*, *Rhizobium sp.*, *E. cloacae*, and Bacillus spp., facilitate the uptake and availability of zinc in wheat.

Maize

Prospective zinc solubilizing bacteria (ZSB) can enhance nutrition and zinc uptake in *Zea mays* L. Field trials have demonstrated that ZSB-treated maize plants exhibit a 25% increase in shoot dry weight and a 30% increase in root biomass compared to control plants. This improved biomass leads to stronger plant growth, better stress tolerance, and higher yields (Patel *et al*., 2024) [17]. The bacteria *B. aryabhattai, B. subtilis, Burkholderia cepacia, Acinetobacter baumannii, Acinetobacter calcoaceticus, Bacillus proteolyticus,* and *Stenotrophomonas pavanii* contribute to zinc solubilization in maize.

Turmeric

The application of zinc and zinc-solubilizing bacteria resulted in a 21.6% increase in turmeric rhizome yield. Zinc-solubilizing bacteria also positively affected the availability of nitrogen, phosphorus, potassium, copper, and manganese.

Soyabean

The soybean followed by wheat cropping system often experiences deficiencies in zinc (Zn) and phosphorus (P). The use of Zn solubilizing bacteria (ZNB) can enhance the production of indole-3-acetic acid (IAA), promote better apical growth, produce siderophores, and improve nitrogen uptake. Additionally, ZNB can decrease soil pH and facilitate increased zinc absorption by plants. This process also leads to improvements in shoot and seed weight. Zinc solubilizing bacteria (ZSB) enrich the zinc content in seeds. Particular strains, such as *Bacillus aryabhattai*, can effectively solubilize and mobilize zinc, thereby improving the growth, mobilization, and accumulation of zinc in soybean plants.

Moong bean

Zinc phosphate significantly enhanced the growth of mung bean plants when water-insoluble. This finding suggests its potential use to improve economically important cash crops. (Iqbal, U *et al*., 2010) [9].

Onion

Zinc is a crucial micronutrient necessary for the growth of onions, as it plays a key role in cell division, nitrogen and carbohydrate metabolism, and water regulation. Onions are particularly vulnerable to zinc deficiency, which can result in stunted growth, twisted stems, and pale interveinal chlorosis of the leaves (Sharma and Singh, 2018) [24]. This deficiency is notably prevalent in Indian soils, affecting approximately 60% of them, underscoring the need to address this issue to ensure optimal onion yields (Mangond *et al*., 2023) [15].

Zinc-solubilizing bacterial strains, especially those from the *Pseudomonas* and *Bacillus* species, facilitate zinc solubilization and enhance the overall nutritional status of onions. Appropriate use of both zinc-solubilizing bacteria (ZSB) and chemical zinc fertilizers is essential to achieve soil fertility and improve crop quality.

Tomato

Tomatoes are among the most important "protective foods" due to their high nutritional value. They are also a versatile ingredient in Indian culinary traditions. Since zinc is a limiting factor in tomato crop production, studying the solubilization of zinc by bacteria is crucial for improving zinc nutrition in tomato plants (Saravanan *et al*., 2007) [21]. Furthermore, it is essential to identify straightforward methods to enhance zinc concentrations in food to address the malnutrition problem in our country.

In experiments, tomato seedlings treated with *Bacillus* sp. (PAN-TM1) exhibited the highest growth parameters, including plant height (94.1 cm), number of branches per plant (27.6), stem girth (2.05 cm), and total biomass (30.7 g). Additionally, plants treated with *Bacillus aryabhattai* showed significantly higher yield and quality parameters, such as the number of flowers per plant (84.7), fruit weight (62.1 g), fruit diameter (7.5 cm), number of fruits per plant (49.6), and fruit yield per plant (3.08 kg). The quality parameters for these plants included chlorophyll content (1.57 mg/g), phenol content (2.32 µg/g), ascorbic acid content (14.09 mg/100 g), and lycopene content (3.23 mg/100 g) (Vidyashree *et al*., 2018) [34].

For instance, tomato plants inoculated with *Pseudomonas* species demonstrated a 15% increase in fruit yield and an improvement in zinc concentration in the fruits, thereby enhancing their nutritional quality. Additionally, the level of vitamin C in tomatoes has been shown to improve with zinc solubilizing bacteria (ZSB) inoculation.

Cucumber

Cucumber plants showed a 20% increase in fruit yield and enhanced micronutrient content (Torrejón *et al*. 2023) [31].

Mustard

The combination of zinc sulphate and zinc-solubilizing bacteria produces better results than using either one alone. This mixture enhances yield and promotes the overall growth and development of plants (Aye, K.S., 2011) [1].

Cotton

The ZSB strains that possess multiple plant growth-promoting traits can enhance nutrient availability, particularly zinc and phosphorus, for crop plants. When these strains are used in conjunction with the solubilization of fixed, unavailable zinc, they can significantly improve cotton plant growth and yield. Additionally, they contribute to enhanced soil fertility through their multifunctional properties. The combined use of selected zinc-solubilizing strains has been shown to be effective in promoting cotton growth under controlled conditions. Notably, the best results were achieved with the combined application of *Bacillus subtilis and Bacillus aryabhattai* strains. These strains exhibit multiple plant growth-promoting traits and hold promise for enhancing cotton growth in semi-arid conditions.

Lentil

Lentils, ZSB inoculation led to a 10% increase in protein content and a 15% increase in the zinc concentration in the seeds, making the crop more nutritious. Additionally, the vitamin content of certain crops.

Ginger

Pseudomonas striata and 40 kg of Zinc sulphate level had a significant effect on the growth parameters like plant height, number of leaves, leaf area, and rhizome yield, also improved the zinc solubilizing capacity (Satwadhar, P.P., 2020) [22].

Groundnut 000

The inoculation of zinc solubilizing microorganisms along with NPK increased yield of groundnut. Results indicated that significantly highest kernel and haulm yield of groundnut was noted in inoculated plots with liquid form of *Rhizobium* and *Pseudomonas striata* over other treatments. The significant improvement in economics (GMR, NMR and B:C) of groundnut crop was also noted with inoculation of *Rhizobium* and *Pseudomonas striata* along with recommended dose of fertilizers (Sable, P.P *et al*., 2017) [19].

Sugarcane

The use of *G. diazotrophicus* in the field might result in the solubilization of available Zn in the soil and increase Zn uptake by the plant, which in turn would lead to improved plant growth and yield. Inoculation with N-fixing endophytic bacterium may represent an alternative to the use of chemical N fertilizers and is associated with decreased production costs as well as a considerable increase in sugarcane production. (Natheer, S.E. and Muthukkaruppan, S., 2012) [16].

Conclusion

The integration of zinc-solubilizing bacteria (ZSB) into crop production systems presents a transformative approach to addressing zinc deficiency in Indian agriculture. The evidence from diverse crops—including rice, wheat, maize, soybean, turmeric, and horticultural species—demonstrates ZSB's capacity to enhance plant growth, grain quality, and micronutrient content. Beyond nutrient solubilization, ZSB inoculants contribute to improved enzyme activity, biomass accumulation, chlorophyll content, and stress tolerance. This microbial intervention offers particular promise for regions with calcareous, sandy, and organic-matter-deficient soils where zinc availability is often critically low.

With promising results under controlled and field conditions, the next step lies in developing stable, region-specific ZSB formulations, refining carrier systems, and standardizing application protocols. Long-term adoption will require awareness-building, capacity development, and integration with national soil health and biofortification programs. Ultimately, ZSB-based solutions not only improve crop yield and soil fertility but also contribute meaningfully to alleviating zinc malnutrition in vulnerable populations.

References

1. Aye KS. Investigation on the effectiveness of zinc sulphate and biofertilizer on the mustard plant. World Acad. Sci. Eng. Technol. 2011;75:335-337.
2. Cakmak I. Plant nutrition research priorities to meet human needs for food in sustainable ways. Plant Science. 2002;247:3-24.
3. Dang HR, Li Y, Sun X, Zhang, YL. Absorption, accumulation and distribution of zinc in highly yielding winter wheat. Agr. Sci. China. 2010;9(7):965-973.
4. Das A, Singh SK, Kumar M, Kumar O. Evaluation of different methods of zinc application on growth, yield and biofortification of zinc in rice (*Oryza sativa* L). J Indian Soc Soil Sci. 2019;67(1):92-102.
5. Dobermann A, Fairhurst T. *Rice: Nutritional Disorders and Nutrient Management*. Potash and Phosphate Institute and Potash and Phosphate Institute of Canada (PPI/PPIC) and International Rice Research Institute (IRRI), Singapore and Makati City, the Philippines; 2000.
6. Fasim F, Ahmed N, Parsons R, Gadd GM. Solubilization of zinc salts by a bacterium isolated from the air environment of a tannery. FEMS Microbiol. Lett. 2002;213:1-6.
7. Gandhi A, Muralidharan G. Assessment of zinc solubilizing potentiality of *Acinetobacter* sp. isolated from rice rhizosphere. *European Journal of Soil Biology*. 2016;76:1-8.
8. Hart JJ, Norvell WA, Welch RM, Sullivan LA, Kochian LV. Characterization of zinc uptake, binding, and translocation of bread and durum wheat cultivars. Plant Physiol. 1998;118:219-226.
9. Iqbal U, Jamil N, Ali I, Hasnain S. Effect of zinc-phosphate-solubilizing bacterial isolates on the growth of Vigna radiata. Annals of Microbiology. 2010;60(2):243-248.
10. Joshi D, Negi G, Vaid S, Sharma A. Enhancement of wheat growth and Zn content in grains by zinc-solubilizing bacteria. International Journal of Agriculture, Environment and Biotechnology. 2013;6(3):363-370.
11. Kapoor S, Kobayashi A, Takatsuji H. Silencing of the Tapetum-Specific Zinc Finger Gene TAZ1 Causes Premature Degeneration of Tapetum and Pollen Abortion in Petunia. Plant Cell Online. 2002;14(10):2353-2367.
12. Kausar MA, Chaudry FM, Rashid A, Latif A, Alam SM. Micronutrient availability to cereals from calcareous soils. I. Comparative Zn and Cu deficiency and their mutual interaction in rice and wheat. Plant and Soil. 1976;45:397-410.

13. Kubota J, Allaway WH. In Micronutrients in Geographic Distribution of Trace Metal Problems; 1972.
14. Legg SP, Sears L. Zinc sulphate treatment for parakeratosis in cattle. Nature. 1980;186:1061.
15. Mangond A, Nandagavi R, Patil S, Kumara B. Effect of zinc and iron on growth, yield and quality parameters of onion. *Journal of Farm Sciences*. 2023;36(02):145-149.
16. Natheer SE, Muthukkaruppan S. Assessing the *in vitro* zinc solubilization potential and improving sugarcane growth by inoculating *Gluconacetobacter diazotrophicus*. Annals of Microbiology. 2012;62(1):435-441.
17. Patel JN, Alam MS. Impact of Foliar Fortification of Zinc and Iron on Nutrient Content and their uptake by Maize Crop. J Exp Agri Internat. 2024;46(7):973-982.
18. Ramesh A, Sharma SK, Sharma MP, Yadav N, Joshi OP. Inoculation of zinc solubilizing *Bacillus aryabhattai* strains for improved growth, mobilization and biofortification of zinc in soybean and wheat cultivated in Vertisols of central India. Appl Soil Ecol. 2014. doi:10.1016/j.apsoil.2013.08.009.
19. Sable PP, Ismail SS, Sonwane N. Effect of zinc solubilizing microorganisms on yield and economics of groundnut grown on vertisol. Int J Tropical Agric. 2017;35:653-656.
20. Sarathambal C, Thangaraju M, Paulraj C, Gomathy M. Assessing the Zinc solubilization ability of *Gluconacetobacter diazotrophicus* in maize rhizosphere using labelled 65Zn Compounds. Indian J Microbiol. 2010;50(1):103-109.
21. Saravanan VS, Madhaiyan M, Osborne J, Thangaraju M, Sa TM. Ecological occurrence of *Gluconacetobacter diazotrophicus* and nitrogen-fixing Acetobacteraceae members: Their possible role in plant growth promotion. Microb Ecol. 2007;55:130-140.
22. Satwadhar PP. Response of ginger to graded levels of zinc and zinc solubilizing biofertilizers [Doctoral dissertation, Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani]; 2020.
23. Shakeel M, Hafeez FY, Malik IR, Rauf A, Jan F, Khan I, *et al*. Zinc solubilizing bacteria synergize the effect of zinc sulfate on growth, yield and grain zinc content of rice (*Oryza sativa*). Cereal Research Communications. 2024;52(3):961-971.
24. Sharma M, Singh Y. Effect of foliar application of zinc sulphate on onion. Journal of Krishi Vigyan. 2018;6(2):43-45.
25. Singh JP, Karamonas RE, Stewart JWB. Phosphorus-induced zinc deficiency in wheat on residual phosphorus plots. Agronomy Journal. 1986;78:668-675.
26. Singh D, Rajawat MVS, Kaushik R, Prasanna R, Saxena AK. Beneficial role of endophytes in biofortification of Zn in wheat genotypes varying in nutrient use efficiency grown in soils sufficient and deficient in Zn. Plant and Soil. 2017;416(1):107-116.
27. Stein AJ. Global impacts of human mineral malnutrition. Plant Soil. 2010;335:133-54.
28. Tapiero H, Tew KD. Trace elements in human physiology and pathology: zinc and metallothioneins. Biomed Pharmacother. 2003;57:399-411.
29. Tavallali V, Rahemi M, Eshghi S, Kholdebarin B, Ramezanian A. Zinc alleviates salt stress and increases antioxidant enzyme activity in the leaves of pistachio (*Pistacia vera* L. 'Badami') seedlings. Turk. J. Agr. Forest. 2010;34(4):349-359.
30. Tisdale SL, Nelson WL, Beaten JD. Zinc in Soil Fertility and Fertilizers. Fourth edition, Macmillan Publishing Company, New York; 1984. p. 382-391.
31. Torrejón BP, Cáceres A, Sánchez M, Sainz L, Guzmán M, Bermúdez Perez FJ, Ramírez-Rodríguez GB, Delgado-López JM. Multifunctional nanomaterials for biofortification and protection of tomato plants. Environ Sci Technol. 2023;57(40):14950-14960.
32. Vaid SK, Kumar B, Sharma A, Shukla AK, Srivastava PC. Effect of Zn solubilizing bacteria on growth promotion and Zn nutrition of rice. Journal of soil science and plant nutrition. 2014;14(4):889-910.
33. Vankatakrishnan SS, Sudlayandy RS, Savariappan AR. Assessing *in vitro* solubilization potential of different zinc solubilizing Bacteria (ZSB) isolates. Brazilian J. Microbiol. 2003;34:121-125.
34. Vidyashree DN, Muthuraju R, Panneerselvam P. Evaluation of zinc solubilizing bacterial (ZSB) strains on growth, yield and quality of tomato (*Lycopersicon esculentum*). Int. J Curr. Microbiol. App. Sci. 2018;7(4):1493-1502.
35. Welch RM. The impact of mineral nutrients in food crops on global human health. Plant and Soil. 2002;247:83-90.