ISSN Print: 2664-844X
ISSN Online: 2664-8458
NAAS Rating (2025): 4.97
IJAFS 2025; 7(11): 418-424
www.agriculturaljournals.com
Received: 02-10-2025
Accepted: 05-11-2025

Pooja Kumari Meena
Ph.D. Research Scholar, Department of Agronomy, Rajasthan College of Agriculture, Maharana Pratap University of Agriculture and Technology, Udaipur, Rajasthan, India

Jagdish Choudhary
Professor and Head, Department of Agronomy, Rajasthan College of Agriculture, Maharana Pratap University of Agriculture and Technology, Udaipur, Rajasthan, India

Premlata Meena
Assistant Professor, Department of Soil Science and Agricultural Chemistry, Agriculture University, Jodhpur, Rajasthan, India

Ashok Kumar Samota
Ph.D. Research Scholar, Department of Agronomy, Rajasthan College of Agriculture, Maharana Pratap University of Agriculture and Technology, Udaipur, Rajasthan, India

Manisha Yadav
Ph.D. Research Scholar, Department of Agronomy, Agriculture University, Jodhpur, Rajasthan, India

Corresponding Author:
Pooja Kumari Meena
Ph.D. Research Scholar, Department of Agronomy, Rajasthan College of Agriculture, Maharana Pratap University of Agriculture and Technology, Udaipur, Rajasthan, India

Zinc-solubilizing bacteria: Harnessing microbial potential for enhanced soil health, crop productivity and sustainable agriculture

Pooja Kumari Meena, Jagdish Choudhary, Premlata Meena, Ashok Kumar Samota and Manisha Yadav

DOI: https://www.doi.org/10.33545/2664844X.2025.v7.i11f.985

Abstract
Zinc is vital for plant functions such as, protein synthesis, enzyme activation and stress tolerance, yet nearly 50% of the world's arable lands are zinc-deficient. This limitation reduces crop productivity and affects human nutrition especially in areas dependents on plant-based diets. Zinc solubilizing bacteria (ZnSB) offer an eco-friendly alternative to chemical fertilizers by converting insoluble zinc into bioavailable forms through organic acid secretion, chelation and siderophore production. These beneficial microbes also strengthen soil health by enhancing microbial diversity, soil structure, nutrient cycling and enzymatic activity. Field studies consistently shows that ZnSB inoculation improves crop growth, yield and grain zinc content while lowering dependence on chemical fertilizers. Although challenges such as storage stability, field variability and regulatory barriers remain. ZnSB based biofertilizers hold strong potential for sustainable nutrient management. Advancing formulation techniques, developing more resilient strains and integrating ZnSB with precision agriculture will further enhance their effectiveness. Overall, ZnSB represent a promising, eco-friendly approach to improving soil fertility boosting crop productivity and strengthening global food and nutritional security.

Keywords: Zinc-solubilizing bacteria, soil health, crop productivity, sustainable agriculture

Introduction
The global population has expanded rapidly over last few decades, placing unprecedented pressure on agricultural systems to supply adequate and nutritious food. Among the factors limiting crop productivity, micronutrient deficiencies have emerged as a serious constraint, particularly in regions where soils are inherently poor in essential trace elements. Micronutrients such as boron (B), copper (Cu), chlorine (Cl), iron (Fe), molybdenum (Mo), manganese (Mn) and zinc (Zn) are required in small quantities, yet they play indispensable roles in plant growth and physiological processes. However, their availability varies widely among soil types, crop species and cultivars, often resulting in nutrient imbalances and deficiencies (Ahmed *et al.*, 2023) [3]. Among these micronutrients, zinc (Zn) is especially crucial due to its involvement in numerous biochemical and metabolic pathways. Zinc contributes to maintaining membrane integrity, mitigating oxidative stress and supporting root development and seed formation. More than 300 enzymatic reactions are zinc-dependent, underscoring its central role in plant growth and development (Kumar *et al.*, 2019; Upadhayay *et al.*, 2022) [27, 50]. Despite its importance, zinc deficiency is widespread. Nearly 50% of the world's arable soils contain inadequate levels of plant-available zinc, posing a major threat to crop performance and nutritional value (Solanki, 2021) [44]. Crops grown under zinc-deficient conditions commonly exhibit stunted growth, chlorosis, reduced leaf area and poor root development, along with heightened vulnerability to abiotic stresses (drought, heat) and biotic pressures (pests and diseases). The implications of zinc deficiency extend beyond crop productivity. Since zinc is an essential micronutrient for humans, deficiencies in food crops directly affect public health. Populations relying heavily on plant-based diets are particularly susceptible to zinc malnutrition, which may lead to impaired immunity, growth retardation and cognitive decline (Khan *et al.*, 2022) [24].

The agricultural importance of zinc is profound; inadequate zinc availability severely restricts crop productivity, diminishes grain quality and poses challenges to global food production systems. This highlights the urgency of implementing effective strategies to ensure adequate zinc levels in agricultural soils and food chains. The conventional approach for correcting zinc deficiency involves applying chemical fertilizers such as zinc sulphate. However, these inputs often suffer from poor solubility, low nutrient-use efficiency, leaching losses and ecological risks associated with long-term overuse. Consequently, their effectiveness is short-lived and repeated application can degrade soil quality, disrupt microbial communities and reduce long-term soil fertility (Hafeez *et al.*, 2013) [12]. Given these limitations, researchers have increasingly focused on environmentally friendly and sustainable alternatives for enhancing zinc bioavailability. Among these approaches, zinc-solubilizing bacteria (ZSB) have emerged as a promising solution. These beneficial microorganisms convert insoluble forms of zinc into plant-available forms through a variety of biochemical mechanisms. By enhancing nutrient solubility, ZSB support nutrient uptake, improve soil fertility and strengthen plant-microbe interactions essential for healthy growth (Haroon *et al.*, 2022) [13]. The utilization of ZSB aligns strongly with the principles of sustainable agriculture, which emphasize reducing chemical fertilizer dependency, preserving soil health and minimizing environmental impacts. By facilitating biological nutrient mobilization, ZSB help improve crop productivity while mitigating the negative consequences of synthetic fertilizer use, including soil degradation and pollution (Kushwaha *et al.*, 2020) [28]. Beyond improving zinc availability, ZSB also enhance overall soil health by promoting beneficial microbial activity, improving soil structure and contributing to robust nutrient cycling. Their ability to bolster plant tolerance to both abiotic (drought, heat, salinity) and biotic (pathogens) stresses further highlights their value in resilient cropping systems (Rani *et al.*, 2023) [37]. Considering their multifaceted benefits, this review examines the mechanisms of zinc solubilization by ZSB, their ecological functions within soil systems and their potential to serve as a sustainable, eco-friendly alternative to conventional zinc fertilizers capable of transforming modern agriculture.

Zinc Solubilizing Bacteria: An Eco-Friendly Tool for Sustainable Agriculture

Zinc solubilizing bacteria (ZnSB) have emerged as a promising biological alternative to chemical zinc fertilizers, particularly in soils where zinc remains unavailable due to its association with insoluble compounds. By converting these insoluble forms into plant-available Zn^{2+}, ZnSB play a crucial role in improving zinc bioavailability, enhancing soil fertility and supporting sustainable crop production (Saboor *et al.*, 2021) [38]. Numerous bacterial genera have been identified as efficient zinc solubilizers, significantly contributing to nutrient cycling, plant growth promotion and stress mitigation. The most widely studied ZnSB genera include *Pseudomonas***,** *Bacillus* and *Rhizobium***,** each known for its diverse metabolic capabilities. Other genera such as *Acinetobacter***,** *Azotobacter* and *Enterobacter* have also demonstrated strong zinc-solubilizing potential (Nitu *et al.*, 2020; Singh *et al.*, 2024) [32, 43]. Collectively, these microorganisms enhance soil biological activity, increase microbial diversity and contribute to overall soil health.

Mechanisms of Zinc Solubilization by ZnSB

Zinc solubilization by bacteria occurs through several biochemical pathways that convert insoluble zinc compounds into bioavailable forms. The major mechanisms include: Production of organic acids**,** Chelation and complexation of zinc ions and Siderophore production and release of secondary metabolites. These mechanisms are strongly influenced by environmental factors such as soil pH, temperature, moisture, organic matter content and microbial community composition.

1. Production of Organic Acids

The most widely recognized mechanism of zinc solubilization is the microbial production of organic acids**.** These acids reduce the pH of the surrounding environment, leading to the dissolution of insoluble zinc minerals (e.g., ZnO, $Zn_3(PO_4)_2$) into soluble Zn^{2+} ions that plants can absorb. ZNSB commonly produce citric acid, gluconic acid, lactic acid, acetic acid and oxalic acid**,** which either acidify the soil or form soluble complexes with zinc. Species belonging to *Pseudomonas* and *Bacillus* are known to produce significant quantities of these acids, making them highly effective zinc solubilizers. Through acidification and chelation, these bacteria enhance zinc mobility and increase its availability in the rhizosphere (Khalid *et al.*, 2022; Yadav *et al.*, 2023) [23, 57].

2. Chelation and Complexation of Zinc Ions

Chelation is another important mechanism through which bacteria enhance zinc solubility. During this process, bacterial metabolites including organic acids, amino acids and other ligands bind to zinc ions to form soluble complexes. This prevents zinc from re-precipitating into insoluble forms and keeps it readily available for root uptake. Compounds like citric acid, oxalic acid, histidine and cysteine act as potent chelators, forming stable Zn ligand complexes that increase zinc mobility in the soil. Apart from enhancing zinc availability, amino acids contribute additional benefits by serving as carbon and nitrogen sources for plants (Bhatt and Maheshwari, 2020) [8].

3. Production of Siderophores and Other Microbial Metabolites

Siderophores are low-molecular-weight compounds known primarily for their ability to chelate iron; however, many siderophores also bind zinc with considerable affinity. These compounds assist in mobilizing zinc from complex soil matrices and either facilitate its uptake by bacteria or render it accessible to plant roots (Nithyapriya *et al.*, 2024) [31]. Besides siderophores, ZnSB produce secondary metabolites such as biosurfactants, which modify the surface properties of soil particles and enhance the release of zinc ions. The production of these metabolites is regulated by environmental factors including pH, temperature, soil texture and nutrient availability (Hussain *et al.*, 2020) [14].

Impact of Zinc Solubilizing Bacteria on Soil Health

Zinc solubilizing bacteria (ZnSB) have gained significant importance in sustainable agriculture due to their ability to convert insoluble inorganic zinc compounds into forms readily available to plants. Beyond enhancing zinc availability, these bacteria play an essential role in maintaining overall soil health. Their activities influence microbial diversity, soil enzymatic functions, soil structure,

organic matter stabilization and the reclamation of zinc-deficient soils, thereby contributing to long-term agricultural productivity and sustainability.

The rhizosphere, an active zone surrounding plant roots is characterized by complex biological interactions involving plants, microorganisms and nutrients. Zinc solubilizing bacteria form a vital component of this environment where they interact with diverse microbial groups and influence soil ecological balance and biodiversity (Behera *et al.*, 2024) [7].

ZnSB engage in beneficial associations with plants by releasing acids and metabolites that solubilize zinc along with other essential macro- and micronutrients. In response, plant roots secrete various organic compounds such as sugars, amino acids and organic acids that act as substrates for these bacteria. These root exudates stimulate the microbial community and enhance the solubilization of nutrients like phosphorus, iron and zinc, ultimately supporting vigorous plant growth (Garcia and Kao-Kniffin, 2018; Schmidt *et al.*, 2018) [10, 40].

In the rhizosphere, ZnSB collaborate with nitrogen-fixing bacteria, phosphate-solubilizing microbes and mycorrhizal fungi to create an efficient nutrient acquisition system. For instance, certain Rhizobium species not only fix atmospheric nitrogen but also aid in zinc solubilization, supplying both elements to host plants. These synergistic processes enhance soil nutrient status and reduce reliance on chemical fertilizers (Khani *et al.*, 2019; Mahmud *et al.*, 2020) [25, 30].

Many zinc solubilizing bacteria also function as biocontrol agents by suppressing harmful soil pathogens. They achieve this through the production of antimicrobial substances or by competing with pathogens for habitat and nutrients. For example, Pseudomonas spp. produce diverse secondary metabolites that inhibit pathogenic fungi and bacteria while improving zinc bioavailability for plants (Ambreetha and Balachandar, 2019) [4].

Soil enzymes are crucial for mediating nutrient cycling, organic matter decomposition and the transformation of complex organic molecules. The presence of zinc-solubilizing bacteria enhances the activity of several key soil enzymes, including phosphatase, dehydrogenase, urease, protease, cellulase and amylase (Walitang *et al.*, 2019) [54]. Increased enzyme activity improves soil fertility, accelerates nutrient mineralization and promotes better nutrient availability for plants, thereby strengthening overall soil functionality (Zlobin, 2021; Ali *et al.*, 2023) [60, 3].

The physical structure of soil and the quantity of organic matter present are key indicators of soil fertility and long-term productivity. Zinc-solubilizing bacteria (ZnSB) make a significant contribution to improving soil structure through their influence on organic matter decomposition and soil aggregation processes. These bacteria produce enzymes that break down complex organic residues into simpler forms, accelerating humus formation. The resulting increase in humus content enhances the soil's ability to retain water and nutrients, supporting healthy plant growth over time. ZnSB also promote soil aggregation by synthesizing extracellular polysaccharides (EPS) and biofilms that help bind soil particles together. Stronger aggregation improves aeration and drainage two factors that determine the survival and activity of both plant roots and soil microorganisms. Adequate aeration ensures sufficient oxygen availability for root respiration, while improved drainage reduces the risk of waterlogging, root diseases and reduced microbial activity. Through enhanced organic matter turnover and aggregation, ZnSB help maintain an optimal balance between soil aeration and moisture retention, leading to healthier and more resilient soils (Jalal *et al.*, 2022; Barreto *et al.*, 2024) [20, 5].

Zinc Solubilizing Bacteria and Crop Productivity

Zinc solubilizing bacteria have attracted growing attention as an eco-friendly and sustainable strategy to improve zinc availability in agricultural soils. By increasing the amount of plant-available zinc, these bacteria help enhance physiological functions such as enzyme activation, chlorophyll formation and protein synthesis. As a result, ZnSB inoculation consistently improves plant growth, crop yield and nutritional quality across a variety of crop species (Ofori *et al.*, 2022; Obaid *et al.*, 2022) [34, 33]. Field studies in India have reported substantial yield gains in wheat following inoculation with ZnSB strains such as *Pseudomonas* and *Bacillus*. Wheat plants treated with these bacteria showed a 20-30% increase in grain yield compared to controls. The improved zinc availability enhanced tillering, spike length and grain number spike^{-1}, leading to higher overall productivity (Singh *et al.*, 2022; Yadav *et al.*, 2023) [42, 57]. Similar findings were observed in rice grown in zinc deficient soils of Bangladesh, where ZnSB inoculation resulted in a 25% increase in grain yield. The bacterial strains effectively solubilized zinc, improving plant uptake and supporting better panicle development and grain filling (Islam *et al.*, 2024) [18].

Zinc is an essential micronutrient for human health and biofortification is an important approach to addressing widespread zinc deficiency. In wheat, ZnSB inoculation has been shown to increase grain zinc content by 10-15%, alongside improvements in protein concentration and baking quality. Similarly, rice grains from ZnSB treated plants exhibited a 15-20% increase in zinc concentration, making them more nutritious and beneficial for populations in zinc deficient regions (Paramesh *et al.*, 2020; Wani *et al.*, 2022) [35, 15]. ZnSB application improves root and shoot biomass. In maize, inoculated plants demonstrated a 25% increase in shoot dry weight and a 30% increase in root biomass relative to untreated plants. Enhanced root systems improve nutrient absorption and stress tolerance, while greater shoot development supports higher photosynthetic rates and yield formation (Patel *et al.*, 2024) [36]. ZnSB inoculation also benefits horticultural crops. Tomato plants inoculated with *Pseudomonas* strains showed a 15% increase in fruit yield and enhanced zinc content in fruits. In cucumber, inoculation resulted in a 20% improvement in fruit yield and enriched micronutrient levels. These enhancements contribute not only to yield but also to the nutritional value of harvested produce (Torrejón *et al.*, 2023; Zhang *et al.*, 2023) [48, 59].

Beyond micronutrient enrichment, ZnSB can influence biochemical composition. For example, lentil crops treated with ZnSB exhibited a 10% increase in seed protein content and a 15% increase in zinc concentration. Additionally, vitamin content such as vitamin C in tomato fruits has been reported to improve in response to ZnSB inoculation, contributing to overall crop nutritional enhancement (Dhaliwal *et al.*, 2021) [9].

Zinc solubilizing bacteria (ZnSB) have emerged as highly effective bioinoculants due to their ability to mobilize zinc

and improve nutrient availability, thereby promoting sustainable plant growth. With the increasing demand for eco-friendly agricultural solutions, ZnSB based biofertilizers are gaining widespread attention as a feasible alternative to synthetic fertilizers. Their use can reduce dependency on chemical fertilizers, alleviate zinc deficiency in soils and contribute significantly to overall crop productivity (Srithaworn *et al.*, 2023) [45].

Integration of ZnSB with Traditional Fertilizers

Combining ZnSB biofertilizers with synthetic fertilizers enhances nutrient use efficiency by improving the solubilization and uptake of zinc and other micronutrients. This integrated approach not only supports vigorous plant growth but also reduces nutrient losses through leaching and volatilization (Khalid *et al.*, 2022) [23].

Several studies indicate that using ZnSB in conjunction with reduced fertilizer doses can achieve yields comparable to or higher than full chemical fertilizer application. This strategy lowers production costs, minimizes environmental contamination and promotes more sustainable nutrient management (Hussain *et al.*, 2019; Yadav *et al.*, 2023) [15, 57].

ZnSB biofertilizers help maintain a balanced nutrient supply by improving the bioavailability of zinc and other essential elements. When applied alongside nitrogen and phosphorus fertilizers, they ensure a more complete nutrient profile and promoting healthier crop growth (Singh *et al.*, 2024) [43].

ZnSB can be integrated with other beneficial microorganisms such as nitrogen fixing bacteria and phosphate solubilizing bacteria to create multi functional bioinoculant formulations. These combinations enhance soil fertility, increase crop yield and strengthen ecological sustainability (Ahmad *et al.*, 2021; Sarathambal *et al.*, 2022; Mahmood *et al.*, 2024) [1, 39, 29].

Future Perspectives and Conclusion

Zinc solubilizing bacteria (ZnSB) offer a sustainable solution to zinc deficiency and declining soil fertility by enhancing zinc bioavailability through organic acid production, chelation and other biochemical mechanisms. Their ability to improve nutrient cycling, strengthen soil microbial diversity and reduce dependence on chemical fertilizers positions them as an important component of environmentally responsible agriculture.

To fully realize their potential, future efforts must focus on developing stable, field-ready formulations through encapsulation technologies and co-inoculation with other beneficial microbes. Integrating ZnSB into precision nutrient management can further enhance zinc-use efficiency and reduce environmental losses. Advances in microbial genomics and metabolic engineering may enable the creation of more resilient strains suitable for diverse agro-ecosystems.

Research should also explore the combined effects of ZnSB with organic amendments and sustainable farming practices to optimize soil fertility and crop productivity. Alongside scientific progress, supportive policies, farmer training and awareness programs will be essential to promote the widespread adoption of ZnSB based biofertilizers. Overall, ZnSB represent a promising, eco-friendly strategy for improving soil health, increasing zinc availability and strengthening the sustainability and resilience of agricultural systems.

Table 1: Zinc solubilizing bacteria (ZnSB) and their effects on various crops (Sethi *et al*., 2025) [41]

Crop	Bacterial Strain(s)	Observed Effect	References
Rice	*Burkholderia*, *Acinetobacter*	Improved zinc absorption by plants	Vaid *et al.* (2014) [53]
	Enterobacter cloacae	Enhanced zinc uptake efficiency	Krithika *et al.* (2016) [26]
	Bacillus sp.	Stimulated overall metabolic activity	Zeb *et al.* (2018) [58]
	Bacillus aryabhattai	Increased grain yield and plant performance	Kour *et al.* (2019)
	Burkholderia cepacia	Improved zinc assimilation and growth	Upadhayay *et al.* (2022) [22]
Wheat	*Pantoea dispersa*, *P. agglomerans*, *Pseudomonas fragi*, *Rhizobium* sp., *Enterobacter cloacae*	Enhanced zinc bioavailability in soil and plant	Kamran *et al.* (2017) [21]
	Trichoderma harzianum, *Bacillus amyloliquefaciens*	Promoted plant growth and vigor	Singh *et al.* (2021) [9]
	Bacillus spp.	Improved zinc biofortification in grains	Yadav *et al.* (2022)
	Pantoea sp., *Klebsiella* sp., *Brevibacterium* sp., *Acinetobacter* sp., *Alcaligenes* sp. NCCP-650, *Citrobacter* sp., *Exiguobacterium* sp., *Raoultella* sp.	Enhanced overall plant growth and nutrient uptake	Ali *et al.* (2023) [3]
Maize	*Bacillus* sp. AZ6	Increased biomass production	Hussain *et al.* (2015) [16]
	Bacillus aryabhattai ZM31, *B. subtilis* ZM63	Improved zinc uptake efficiency	Mumtaz *et al.* (2020)
	Serratia sp.	Enhanced plant physiological performance	Jain *et al.* (2020) [19]
	Burkholderia cepacia, *Acinetobacter baumannii*	Facilitated zinc acquisition and plant growth	Upadhyay *et al.* (2021) [52]
	Acinetobacter calcoaceticus, *Bacillus proteolyticus*, *Stenotrophomonas pavanii*	Promoted zinc solubilization and uptake	Sultan *et al.* (2023) [46]
Green gram	*Neisseria*, *Staphylococcus* spp., *Escherichia coli*, *Bacillus* sp.	Enhanced biomass accumulation	Iqbal *et al.* (2010) [17]
Chickpea	*Enterobacter* sp.	Improved grain nutritional quality	Ullah *et al.* (2020) [49]
	Ochrobactrum intermedium, *Paenibacillus polymyxa*, *Bacillus cereus*, *Stenotrophomonas maltophilia*, *Streptomyces*, *Arthrobacter globiformis*	Increased zinc solubilization and bioavailability	Batool *et al.* (2021) [6]
Soybean	*Streptomyces* spp.	Enhanced plant biomass and vigor	Suriyachadkun *et al.* (2022) [47]
Pigeonpea	*Pseudomonas plecoglossicida* SRI-156, *Brevibacterium antiquum* SRI-158	Improved grain yield and plant growth	Gopalakrishnan *et al.* (2016) [11]
Lentil	*Rhizobium* spp. RL9	Enhanced biomass production and grain protein content	Wani *et al.* (2008) [56]

Acknowledgement
The authors sincerely express their gratitude to all research institutions and scientists whose valuable contributions and work on zinc solubilizing bacteria provided the foundation for this study.

Data Availability
No datasets were analysed during the current study.

Conflict of Interest
The Authors declare no conflict of interest.

References
1. Ahmad I, Ahmad M, Hussain A, Jamil M. Integrated use of phosphate-solubilizing *Bacillus subtilis* strain IA6 and zinc-solubilizing *Bacillus* sp. strain IA16: A promising approach for improving cotton growth. Folia Microbiol. 2021;66(1):115-125.
2. Ahmed N, Zhang B, Chachar Z, Li J, Xiao G, Wang Q, *et al*. Micronutrients and their effects on horticultural crop quality, productivity and sustainability. Sci Hortic. 2024;323:112512.
3. Ali M, Ahmed I, Tariq H, Abbas S, Zia MH, Mumtaz A, *et al*. Growth improvement of wheat (*Triticum aestivum*) and zinc biofortification using potent zinc-solubilizing bacteria. Front Plant Sci. 2023;14:1140454.
4. Ambreetha S, Balachandar D. Rhizobacteria-mediated root architectural improvement: A hidden potential for agricultural sustainability. In: Plant Growth Promoting Rhizobacteria for Agricultural Sustainability: From Theory to Practices. 2019. p. 111-128.
5. Barreto MSC, Elzinga EJ, Rouff AA, Siebecker MG, Sparks DL, Alleoni LRF. Zinc speciation in highly weathered tropical soils affected by large-scale vegetable production. Sci Total Environ. 2024;916:170223.
6. Batool S, Asghar HN, Shehzad MA, Yasin S, Sohaib M, Nawaz F, *et al*. Zinc-solubilizing bacteria-mediated enzymatic and physiological regulations confer zinc biofortification in chickpea (*Cicer arietinum*). J Soil Sci Plant Nutr. 2021;21(3):2456-2471.
7. Behera PR, Behera KK, Sethi G, Prabina BJ, Bai AT, Sipra BS, *et al*. Enhancing agricultural sustainability through rhizomicrobiome: A review. J Basic Microbiol. 2024;64(11):e2400100.
8. Bhatt K, Maheshwari DK. Zinc solubilizing bacteria (*Bacillus megaterium*) with multifarious plant growth-promoting activities alleviates growth in *Capsicum annuum*. 3 Biotech. 2020;10(2):36.
9. Dhaliwal SS, Sharma V, Shukla AK, Kaur J, Verma V, Singh P, *et al*. Enrichment of zinc and iron micronutrients in lentil (*Lens culinaris* Medik.) through biofortification. Molecules. 2021;26(24):7671.
10. Garcia J, Kao-Kniffin J. Microbial group dynamics in plant rhizospheres and their implications on nutrient cycling. Front Microbiol. 2018;9:1516.
11. Gopalakrishnan S, Vadlamudi S, Samineni S, Sameer Kumar C. Plant growth promotion and biofortification of chickpea and pigeonpea through inoculation of biocontrol-potential bacteria isolated from organic soils. SpringerPlus. 2016;5:1-11.
12. Hafeez BM, K Y, Khanif YM, Saleem M. Role of zinc in plant nutrition: A review. Am J Exp Agric. 2013;3(2):374-391.
13. Haroon M, Khan ST, Malik A. Zinc-solubilizing bacteria: An option to increase zinc uptake by plants. In: Microbial Biofertilizers and Micronutrient Availability: The Role of Zinc in Agriculture and Human Health. 2022. p. 207-238.
14. Hussain A, Zahir ZA, Asghar HN, Imran M, Ahmad M, Hussain S. Integrating the potential of *Bacillus* sp. Az6 and organic waste for zinc oxide bio-activation to improve growth, yield, and zinc content of maize grains. Pak J Agric Sci. 2020;57(1).
15. Hussain A, Zahir ZA, Ditta A, Tahir MU, Ahmad M, Mumtaz MZ, *et al*. Production and implication of bio-activated organic fertilizer enriched with zinc-solubilizing bacteria to boost maize (*Zea mays*) production and biofortification under two cropping seasons. Agronomy. 2019;10(1):39.
16. Hussain A, Arshad M, Zahir ZA, Asghar M. Prospects of zinc-solubilizing bacteria for enhancing growth of maize. Pak J Agric Sci. 2015;52(4).
17. Iqbal U, Jamil N, Ali I, Hasnain S. Effect of zinc-phosphate-solubilizing bacterial isolates on growth of *Vigna radiata*. Ann Microbiol. 2010;60:243-248.
18. Islam MA, Hasan MM, Akter T, Islam SMS. Development of iron and zinc biofortified rice variety for nutrition improvement in Bangladesh. Food Sci Eng. 2024. p. 322-330.
19. Jain D, Kour R, Bhojiya AA, Meena RH, Singh A, Mohanty SR, *et al*. Zinc-tolerant plant-growth-promoting bacteria alleviate phytotoxic effects of zinc on maize through zinc immobilization. Sci Rep. 2020;10(1):13865.
20. Jalal A, Galindo FS, Freitas LA, da Silva Oliveira CE, de Lima BH, Pereira ÍT, *et al*. Yield, zinc efficiencies and biofortification of wheat with zinc sulfate application in soil and foliar nanozinc fertilisation. Crop Pasture Sci. 2022;73(7-8):749-759.
21. Kamran S, Shahid I, Baig DN, Rizwan M, Malik KA, Mehnaz S. Contribution of zinc-solubilizing bacteria in growth promotion and zinc content of wheat. Front Microbiol. 2017;8:2593.
22. Kaur H, Garg N. Zinc toxicity in plants: A review. Planta. 2021;253(6):129.
23. Khalid S, Amanullah, Ahmed I. Enhancing zinc biofortification of wheat through integration of zinc, compost, and zinc-solubilizing bacteria. Agri. 2022;12(7):968.
24. Khan ST, Malik A, Alwarthan A, Shaik MR. The enormity of the zinc deficiency problem and available solutions: An overview. Arab J Chem. 2022;15(3):103668.
25. Khani AG, Enayatizamir N, Norouzi Masir M. Impact of plant growth-promoting rhizobacteria on different forms of soil potassium under wheat cultivation. Lett Appl Microbiol. 2019;68(6):514-521.
26. Krithika S, Balachandar D. Expression of zinc transporter genes in rice as influenced by zinc-solubilizing *Enterobacter cloacae* strain ZSB14. Front Plant Sci. 2016;7:446.
27. Kumar A, Dewangan S, Lawate P, Bahadur I, Prajapati S. Zinc-solubilizing bacteria: A boon for sustainable agriculture. In: Plant Growth Promoting Rhizobacteria for Sustainable Stress Management. 2019. p. 139-155.
28. Kushwaha P, Kashyap PL, Pandiyan K, Bhardwaj AK. Zinc-solubilizing microbes for sustainable crop

production: Current understanding, opportunities, and challenges. In: Phytobiomes: Current Insights and Future Vistas. 2020. p. 281-298.
29. Mahmood I, Sami A, Asad SA, Shah GA, Rana RM, Raja NI, *et al*. Zinc-oxide nanoparticles in conjugation with Zn-solubilizing bacteria improve Zn biofortification and nitrogen use efficiency in wheat. J Soil Sci Plant Nutr. 2024;24(3):5565-5585.
30. Mahmud K, Makaju S, Ibrahim R, Missaoui A. Current progress in nitrogen-fixing plants and microbiome research. Plants. 2020;9(1):97.
31. Nithyapriya S, Lalitha S, Devi SU, Perveen K, Alshaikh NA, Sayyed RZ, *et al*. Purification and characterization of desferrioxamine B of *Pseudomonas fluorescens* and its application to improve oil content, nutrient uptake, and plant growth in peanuts. Microbiol Ecol. 2024;87:60.
32. Nitu R, Rajinder K, Sukhminderjit K. Zinc-solubilizing bacteria to augment soil fertility—A comprehensive review. Int J Agric Sci Vet Med. 2020;8:38-44.
33. Obaid H, Shrestha RK, Liu D, Elsayed NS, Ni J, Ni C. Biofortification of maize with zinc and its effect on human health. J Soil Sci Plant Nutr. 2022;22(2):1792-1804.
34. Ofori KF, Antoniello S, English MM, Aryee AN. Improving nutrition through biofortification: A systematic review. Front Nutr. 2022;9:1043655.
35. Paramesh V, Dhar S, Dass A, Kumar B, Kumar A, El-Ansary DO, *et al*. Role of integrated nutrient management and agronomic fortification of zinc on yield, nutrient uptake and quality of wheat. Sustainability. 2020;12(9):3513.
36. Patel JN, Alam MS. Impact of foliar fortification of zinc and iron on nutrient content and their uptake by maize crop. J Exp Agric Int. 2024;46(7):973-982.
37. Rani N, Chauhan A, Kaur S, Solanki MK, Tripathi M, Jain D, *et al*. Molecular mechanisms of Zn-solubilizing bacteria for agronomic eminence: Recent updates and futuristic development. J Plant Growth Regul. 2023;1-15.
38. Saboor A, Muhammad AA, Hussain S, El Enshasy HE, Hussain S, Ahmed N, *et al*. Zinc nutrition and arbuscular mycorrhizal symbiosis effects on maize (*Zea mays*) growth and productivity. Saudi J Biol Sci. 2021;28(11):6339-6351.
39. Sarathambal C, Dinesh R, Srinivasan V, Sheeja TE, Jeeva V, Manzoor M. Changes in bacterial diversity and composition in response to co-inoculation of arbuscular mycorrhizae and zinc-solubilizing bacteria in turmeric rhizosphere. Curr Microbiol. 2022;79:1-9.
40. Schmidt H, Nunan N, Höck A, Eickhorst T, Kaiser C, Woebken D, *et al*. Recognizing patterns: Spatial analysis of observed microbial colonization on root surfaces. Front Environ Sci. 2018;6:61.
41. Sethi G, Behera KK, Sayyed R, Adarsh V, Sipra BS, Singh L, *et al*. Enhancing soil health and crop productivity: The role of zinc-solubilizing bacteria in sustainable agriculture. Plant Growth Regul. 2025;1-17.
42. Singh J, Singh AV, Upadhayay VK, Khan A, Chandra R. Prolific contribution of *Pseudomonas protegens* in Zn biofortification of wheat under saline and non-saline conditions. World J Microbiol Biotechnol. 2022;38(12):227.
43. Singh S, Chhabra R, Sharma A, Bisht A. Harnessing the power of zinc-solubilizing bacteria: A catalyst for a sustainable agrosystem. Bacteria. 2024;3(1):15-29.
44. Solanki M. The Zn as a vital micronutrient in plants. J Microbiol Biotechnol Food Sci. 2021;11(3):e4026.
45. Srithaworn M, Jaroenthanyakorn J, Tangjitjaroenkun J, Suriyachadkun C, Chunhachart O. Zinc-solubilizing bacteria and their potential as bioinoculant for growth promotion of green soybean (*Glycine max*). PeerJ. 2023;11:e15128.
46. Sultan A, Youssef HIA. Biofertilizer effect of some zinc-dissolving bacteria free and encapsulated on *Zea mays* growth. Arch Microbiol. 2023;205(5):202.
47. Suriyachadkun C, Chunhachart O, Srithaworn M, Tangchitcharoenkhul R, Tangjitjareonkun J. Zinc-solubilizing *Streptomyces* spp. as bioinoculants for promoting the growth of soybean (*Glycine max*). J Microbiol Biotechnol. 2022;32(11):1435.
48. Torrejón BP, Cáceres A, Sánchez M, Sainz L, Guzmán M, Bermúdez-Perez FJ, *et al*. Multifunctional nanomaterials for biofortification and protection of tomato plants. Environ Sci Technol. 2023;57(40):14950-14960.
49. Ullah A, Farooq M, Nadeem F, Rehman A, Hussain M, Nawaz A, *et al*. Zinc application with zinc-solubilizing *Enterobacter* sp. MN17 improved productivity, profitability, zinc efficiency and quality of desi chickpea. J Soil Sci Plant Nutr. 2020;20(4):2133-2144.
50. Upadhayay VK, Singh AV, Khan A, Sharma A. Contemplating the role of zinc-solubilizing bacteria in crop biofortification: An approach for sustainable bioeconomy. Front Agron. 2022;4:903321.
51. Upadhayay VK, Singh AV, Khan A, Singh J, Pareek N, Raghav A. FE-SEM/EDX based zinc mobilization analysis of *Burkholderia cepacia* and *Pantoea rodasii* and their functional annotation in crop productivity, soil quality, and zinc biofortification of paddy. Front Microbiol. 2022;13:852192.
52. Upadhyay H, Gangola S, Sharma A, Singh A, Maithani D, Joshi S. Contribution of zinc-solubilizing bacterial isolates on enhanced zinc uptake and growth promotion of maize (*Zea mays*). Folia Microbiol. 2021;66:543-553.
53. Vaid SK, Kumar B, Sharma A, Shukla AK, Srivastava PC. Effect of Zn-solubilizing bacteria on growth promotion and Zn nutrition of rice. J Soil Sci Plant Nutr. 2014;14(4):889-910.
54. Walitang D, Samaddar S, Roy Choudhury A, Chatterjee P, Ahmed S, Sa T. Diversity and plant growth-promoting potential of bacterial endophytes in rice. In: Plant Growth Promoting Rhizobacteria (PGPR): Prospects for Sustainable Agriculture. 2019. p. 3-17.
55. Wani SH, Gaikwad K, Razzaq A, Samantara K, Kumar M, Govindan V. Improving zinc and iron biofortification in wheat through genomics approaches. Mol Biol Rep. 2022;49(8):8007-8023.
56. Wani PA, Khan MS, Zaidi A. Effect of metal-tolerant plant growth-promoting *Rhizobium* on performance of pea grown in metal-amended soil. Arch Environ Contam Toxicol. 2008;55:33-42.
57. Yadav RC, Sharma SK, Varma A, Singh UB, Kumar A, Bhupenchandra I, *et al*. Zinc-solubilizing *Bacillus* spp. with chemical fertilizers enhance growth, yield, nutrient

content and zinc biofortification in wheat. Front Microbiol. 2023;14:1210938.
58. Zeb H, Hussain A, Naveed M, Ditta A, Ahmad S, Jamshaid MU, *et al*. Compost enriched with ZnO and Zn-solubilising bacteria improves yield and Zn-fortification in flooded rice. Ital J Agron. 2018;13(4):310-316.
59. Zhang L, Zuluaga MYA, Pii Y, Barone A, Amaducci S, Miras-Moreno B, *et al*. A *Pseudomonas* plant growth-promoting rhizobacterium and arbuscular mycorrhiza differentially modulate growth, photosynthetic performance, nutrient allocation and stress responses under zinc and cadmium stress in tomato. Plant Sci. 2023;337:111873.
60. Zlobin IE. Current understanding of plant zinc homeostasis regulation mechanisms. Plant Physiol Biochem. 2021;162:327-335.