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REVIEW ARTICLE OPEN ACCESS

Pioneering Biofertilization: Advanced Zinc Solubilizing Bacteria Use as a Biostimulants for Transforming Mustard Yields: A Review

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Abstract

Zinc (Zn) is a vital element for the growth of plants. However, soils often suffer from its deficiency, which adversely affects crops. Zn supplementation using chemical fertilizers is ineffective and negatively affects the environment. Zn is converted from an insoluble state to a soluble state by ZSB which improves the absorption of Zn by plants and promotes overall plant health. Integrating these microbes into agricultural practices through seed inoculation, soil amendment, and foliar sprays offers a sustainable solution to Zn deficiency, promoting healthier crops and contributing to food security. Field trials provide empirical evidence of the extent to which Zinc Solubilizing Bacteria enhances both the quality and quantity of the crops. ZSB into agricultural practices can improve agricultural land productivity, also food security, and promote environmentally sustainable farming practices. This review examines the potential of zinc solubilizing bacteria as an effective alternative for enhancing plant growth and increasing the availability of Zn.

Keywords: *Brassica juncea* L., Biostimulants, Zinc Solubilizing Bacteria, Sustainable Agriculture

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INTRODUCTION

Biostimulants are compounds or microorganisms that improve plant growth, development, and overall plant health. They improve plant physiological processes to increase nutrient uptake, stress tolerance, and yield. Among the most frequent bio-stimulants used in plant cultivation are: Organic compounds such as humic and fulvic acids promote nutrient availability, water retention capacity, and soil structure.[1,2] They enhance root development, nutrient uptake, and plant vigor. Seaweed extracts are another important biostimulant that is derived from marine algae, and they contain various growth-promoting compounds, such as auxins, cytokinins, and microelements.[3] They boost nutrient absorption, enhance stress tolerance, and encourage plant development.[4] Microbial Inoculants: Beneficial microorganisms like mycorrhizal fungi and Rhizobacteria that promote plant development (PGPR) are known as bio-stimulants. They increase the availability of nutrients, encourage the growth of roots, guard against diseases, and boost the general health of plants.[5] Amino acid-based bio-stimulants provide a readily available source of organic nitrogen and stimulate plant metabolic processes. They promote root growth, flowering, and fruit development. Various plant extracts, such as extracts from algae, herbs, or plant tissues, are used as bio-stimulants. They contain natural growth-promoting compounds that improve nutrient uptake, photosynthesis, and stress tolerance. Chitin and Chitosan which are mainly derived from crustacean shells, chitin and chitosan bio-stimulants enhance plant growth, induce defence responses, and improve Nutrient absorption and abiotic stress resistance.[6] Silicon Bio-stimulants: Silicon bio-stimulants increase plant resistance to pests, diseases, and abiotic stressors.[7] They improve cell strength, photosynthesis, and nutrition uptake. Enzymes: Enzyme-based Biostimulants improve nutrient availability and soil fertility. They boost nutrient cycling, break down organic materials, and encourage root growth. Seed treatments, foliar sprays, soil drenches, and fertigation systems can all be used to apply bio-stimulants. Specific application methods and dosages are determined on the crop, growth stage, and product instructions.[8] Their application is often complementary to good agricultural practices, including proper nutrient management, irrigation, and pest control. However, Zn shortage is a ubiquitous problem that reduces crop output and nutritional quality, particularly in Zn-deficient soils. Traditional methods to address Zn deficiency, such as applying Zn fertilizers, have limitations, including environmental concerns and cost implications. These bacteria employ various mechanisms to solubilize Zn, including producing Siderophores chelating agents, and organic acids.[9] For instance, organic acids such as gluconic acid and citric acid lower the pH of the soil microenvironment, thereby increasing Zn solubility. Conversely, Siderophores are high-affinity iron-chelating compounds that can also bind to Zn, facilitating plant mobilization and uptake.[10] Applying ZSB as bioinoculants has shown promising results in enhancing Zn uptake and improving plant growth and yield.[11] Studies have demonstrated that inoculating crops with ZSB can significantly increase Zn concentration in plant tissues, leading to better growth performance and higher nutritional quality of the produce.[12] Furthermore, ZSB can boost plant growth by creating phytohormones including indole-3-acetic acid (IAA) and gibberellins, which stimulate root formation and general plant vigour.[13]

Vital macro and micro nutrients: the cornerstones of optimal plant growth

The number of micro and macro nutrients in soil varies greatly based on factors such as soil type, geographical location, land use, and management approaches (Table 1). It is hard to offer exact tabular statistics without taking these aspects into account.[14,15] It's crucial to remember that these ranges are general guidelines, and specific nutrient levels can vary depending on factors such as soil type, climate, fertilization practices, and cropping history. Soil testing is the most accurate way to determine the actual nutrient levels in a particular soil sample.[16] Professional soil testing laboratories can provide detailed reports of nutrient concentrations in soil, helping to guide nutrient management and fertilization practices. The ranges below are estimates that may change based on particular soil conditions.

Brassica juncea L.: A resilient oilseed crop with multifaceted agricultural significance

India is home to the world's fourth-largest oilseed economy. Rapeseed-mustard, one of the Second only to groundnuts, which account for 27.8% of India's oilseed industry, seven edible oilseeds are grown there, accounting for 28.6% of the nation's total oilseed production.[22] Many types of rapeseed-mustard are cultivated all throughout India, and the agroclimatic conditions in the mustard-growing regions vary greatly. Under limited resource conditions, rapeseed-mustard agriculture becomes less profitable for farmers.[23] As a result, there is a significant imbalance between mustard demand and supply in India. As a result, Site-specific control of nutrients based on soil-test recommendations should be implemented to increase the current production levels attained by farmers in their fields.[24] Boosting and maintaining the yield of rapeseed and mustard and production will necessitate efficient natural resource management, spreading rapeseed-mustard agriculture to additional regions under different cropping methods, and using an integrated approach to plant-water, nutrition, and pest management.[25]

Brassica juncea L.*,* commonly known as Indian mustard or mustard greens, is a crop that is sensitive to zinc deficiency. Several studies have investigated the use of ZSB as bio-stimulants to enhance zinc availability and improve the growth and productivity of *Brassica juncea* L. The application of zinc solubilizing bacteria can lead to several beneficial effects on plants. Firstly, these bacteria can enhance zinc uptake by increasing its solubility in the rhizosphere, which is the soil region influenced by plant roots. Improved zinc uptake can then promote various physiological processes in plants, including enzyme activities, hormone synthesis, and carbohydrate metabolism.[26] Furthermore, zinc-solubilizing bacteria can help promote plant development by producing chemicals including indole-3-acetic acid (IAA), gibberellins, and cytokinins which can promote root development, improve nutrient absorption, and boost overall plant vigour. Figure 1 shows an overview of *Brassica juncea* L. and its importance in agriculture, environment, and medicine. Overall, the use of zinc solubilizing bacteria as bio-stimulants for *Brassica juncea* L.

Table 1. Micro and macro nutrients typical range in soil and impact of its deficiency on plants.

No.	Micro and Macro Nutrients	Typical Range in Soil (mg/kg)	Impact of Nutrients Deficiency on Plants	Ref.
1.	Iron (Fe)	20-1000	Interveinal chlorosis in young leaves, reduced chlorophyll production, poor photosynthesis	[14,17]
2.	Manganese (Mn)	10-1000	Yellowing between veins, poor photosynthesis, weak enzyme activation	[18]
3.	Zinc (Zn)	1-100	Shortened stem length, small leaves, reduced hormone production, poor growth	[19]
4.	Copper (Cu)	0.5-100	Wilting, dieback of shoots, poor enzyme activity, weak stem structure	[19]
5.	Boron (B)	0.2-10	Death of growing points, brittle leaves, poor cell division, reduced root growth	[18]
6.	Molybdenum (Mo)	0.01-10	Yellowing of older leaves, poor nitrogen fixation, reduced growth	[19]
7.	Nickel (Ni)	0.01-10	Reduced seed germination, leaf distortion, impaired enzyme activity, stunted growth	[16]
8.	Nitrogen (N)	0.1-10	Yellowing of older leaves, stunted growth, reduced yield	[14,16,20]
9.	Phosphorus (P)	0.01-2	Poor root development, delayed maturity, weak stems	[14,16]
10.	Potassium (K)	0.5-50	Yellow or brown leaf margins, poor fruit development	[14,16,19]
11.	Calcium (Ca)	1-50	Deformed new leaves, blossom end rot in fruits, weak cell walls	[19]
12.	Magnesium (Mg)	0.2-10	Yellowing between leaf veins, poor photosynthesis	[21]
13.	Sulfur (S)	0.1-10	Yellowing of young leaves, reduced growth	[14,16]
14.	Nitrogen (N)	20-1000	Interveinal chlorosis in young leaves, reduced chlorophyll production, poor photosynthesis	[14,17]

holds promise for improving zinc availability and promoting plant growth. It's crucial to remember, though, that the precise bacterial strain, soil type, and crop management techniques can all affect how successful ZSB is.

Reviving Micronutrient Dynamics: The plant growth-promoting potential of ZSB

Zinc solubilising bacterial bio-stimulants, beneficial bacteria, promote sustainable *Brassica juncea* plant growth by improving nutrient availability naturally, replacing chemical fertilizers that can harm the environment.[27] Zinc solubilizing bacteria (ZSB) can aid *Brassica juncea* producers in reducing zinc shortage, increasing nutrient uptake, and promoting crop growth by solubilizing zinc in soil.[28] Impact of zinc solubilizing bacteria on various plants (Table 2). Crop specificity is crucial for *Brassica juncea,* as it has high zinc demand for chlorophyll synthesis, enzyme activation, and hormone regulation. Enhancing zinc solubility and availability can address these requirements. Currently Scientists studying zinc-solubilizing bacteria, particularly *Brassica juncea*, to increase availability of zinc and stimulate plant growth, with extensive research on their isolation, identification, and characterization.[29-31] To increase the current production levels in farmers' fields, site-specific fertilizer management based on soil test recommendations should be implemented.[24] The expansion of rapeseed-mustard cultivation to newer areas under various cropping systems, an integrated approach to plant-water, nutrient, and pest management, and effective natural resource management will all contribute to the growth and stabilization of rapeseed-mustard production and productivity. Biostimulants based on zinc-sulfur improve the zinc-deficient crop *Brassica juncea* L. By promoting physiological functions and raising zinc production and availability, these biostimulants boost root growth, nutrient absorption, and plant vigor, suppress weeds, control soil erosion, and benefit traditional medicine.[32]

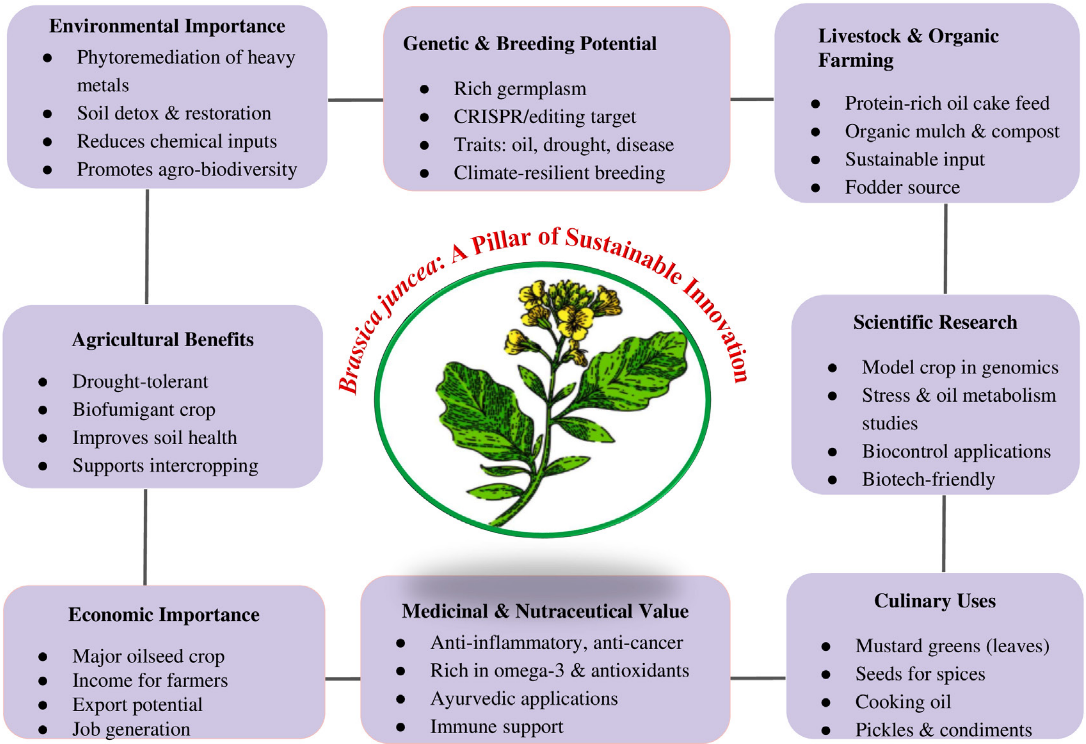

Figure 1. Overview of *Brassica Juncea* L. and its importance

Table 2. Impact of zinc solubilizing bacteria on various plants

No.	Zinc Solubilizing Bacteria (ZSB)	Insoluble Zinc Compound	Impact on different plant	Ref.
1.	*Azospirillum* spp.	Zinc oxide (ZnO)	Enhanced growth and zinc uptake in wheat, maize, and rice.	[29,33]
2.	*Pseudomonas* spp.	Zinc phosphate $Zn_3(PO_4)_2$	Improved zinc uptake and growth in soybean and tomato.	[33]
3.	*Bacillus* spp.	Zinc carbonate ($ZnCO_3$)	Increased zinc availability and plant growth in various crops.	[34-36]
4.	*Enterobacter* spp.	Zinc silicate ($ZnSiO_3$)	Enhanced zinc acquisition and growth in sunflower and mustard.	[37,38]
5.	*Rhizobium* spp.	Zinc sulfate ($ZnSO_4$)	Improved zinc uptake and growth in legumes	[39,40]
6.	*Bacillus paramycoides*	Zinc oxide (ZnO)	Enhanced growth and zinc uptake in rice.	[41]
7.	*Microbacterium oxydans*	Zinc phosphate $Zn_3(PO_4)_2$	Enhanced growth and zinc uptake in wheat, vegetable.	[20]
8.	*Enterococcus hirae*	Zinc oxide (ZnO)	Enhancing the quality of wheat grains.	[42]
9.	*Stenotrophomonas maltophilia*	ZnO and $ZnCO_3$	Increased zinc availability and plant growth in chickpea.	[43]
10.	*Burkholderia* and *Acinetobacter*	Zinc sulfate ($ZnSO_4$)	Improved growth and zinc uptake in grains, etc.	[44]

Factors influencing the interaction between zinc-solubilizing bacteria and different crops for enhanced plant growth promotion

Environmental factors, such as soil properties, and local conditions, can impact ZSB-*Brassica juncea* interactions. Research and field trials in relevant agricultural environments should be conducted to determine optimal conditions for plant development.[45] The sensitivity of *Brassica juncea* to ZSB varies across geographical regions, making it essential to refer to specific research papers and field experiments for comprehensive information on its effects on this crop.[10,46] The response of *Brassica juncea* to ZSB may vary based on geographical conditions, so it's recommended to refer to specific research studies and field trials for context-specific information on the effects of ZSB on various crop, like wheat, Rice, Maize, Soyabean, Tomato, Potato, and Spinach.[47-51] *Bacillus* sp. (SS9) and *Enterobacter* sp. (SS7) inoculation reduced Zn toxicity, promoting plant development and mobilizing Zn, N, and P to plant parts.[36] Quantitative real-time reverse transcription PCR was used to examine the function of the zinc-solubilizing bacterial strain *Enterobacter cloacae* strain ZSB14 in the regulation of iron (Fe)-regulated transporter-like protein (ZIP) genes and Zn-regulated transporters in rice under iron-deficient and iron-sufficient conditions. Zinc oxide in the growth medium boosted the expression of all ZIP genes in rice seedling roots and shoots. ZSB was inoculated into rice seedlings cultured in growth medium containing insoluble zinc oxide.[52] Inoculation of *B. juncea* plants with these strains increased plant growth and Pb uptake in metal-contaminated soil. A greenhouse experiment with *Brassica juncea* analysed bacterial inoculation's impact on heavy metal uptake from Pb-Zn mining tailings, revealing beneficial bacteria that boost plant growth and protect against metal toxicity.[53,54] Rhizobacteria infection reduced metal concentrations in plant tissues but increased above-ground biomass and soil metal bioavailability, enhancing phytoextraction efficiency compared to control treatments. A study found ZSB in wild legume root nodules, with *Bacillus* sp. and *Enterobacter* sp. isolates SS9 and SS7 effective in tolerating 1 g Zn. Inoculation plants showed greater mung bean plant growth and biomass, with reduced Zn toxicity resulting in better plant development and mobilization.[36,55] Because of the abundance of nutrients available in the form of root exudates, the rhizosphere is a dynamic environment where microbe-microbe and microbe-plant interaction is at its greatest.[56,57] There are many other species of Zinc Solubilizing Bacteria that may have an impact on different plant species. Some Environmental Factors given below:

- **Soil pH:** Acidic soil conditions, with a pH range of 5.0-6.5, are generally favourable for zinc solubilization by ZSB, promoting plant uptake.[58]
- **Soil organic matter content:** Soil organic matter enhances ZSB growth and activity by providing carbon and contributing to the production of organic acids, promoting zinc solubilization.[59]
- **Moisture and water availability:** Soil moisture is crucial for zinc solubilization and activity of ZSB, while drought stress can negatively affect populations; hence, proper irrigation management is essential.
- **Temperature:** Temperature significantly influences ZSB growth and activity, with mesophilic temperatures (25-30 °C) generally promoting ZSB activity and plant growth for each bacterial strain.
- **Nutrient availability:** Essential nutrients like phosphorus, nitrogen, and potassium are crucial for ZSB activity and *Brassica juncea's* nutrient status, while temperature significantly influences ZSB growth and activity.
- **Heavy metal contamination:** Heavy metals in soil can affect ZSB populations and activity, with some strains showing tolerance, potentially aiding in phytoremediation of contaminated soils.
- **Pesticide and chemical application:** Chemical inputs like pesticides can negatively impact ZSB populations, necessitating careful consideration to maintain beneficial interactions between ZSB and *Brassica juncea*.[60]

Rhizospheric Revolution: Mechanisms of zinc-solubilizing bacteria driving plant vitality

Zinc solubilizing bacteria (ZSB) enhance plant development and zinc uptake on *Brassica juncea* by converting insoluble zinc compounds into soluble forms and increasing soil nutrient availability.[61] ZSB's organic acids enhance nutrient mobilization, growth, and communication with *Brassica juncea* roots, overcoming zinc shortage and promoting symbiotic interaction, thereby boosting plant growth.[47] *Brassica juncea's* zinc uptake enhances growth, development, and yield, while its unique Defence Mechanism Induction mechanism induces systemic resistance against infections and creates antimicrobial compounds in rice (Figure 2). The activation of a plant's immune system enhances its defence against diseases and stress conditions, thereby promoting overall plant health Zinc solubilizing bacteria (ZSB) can be used as bio-stimulants to promote plant growth in *Brassica juncea,* depending on factors like soil conditions and bacterial strains.[62] Combination with Fertilisers or Bio-stimulants ZSB can be enhanced by blending it with other bio-stimulants, such as micronutrient-enriched fertilisers, to boost plant growth, depending on the crop, stage, soil conditions, and local practices.[63,64] To optimize ZSB's use as bio-stimulants in agriculture, it's crucial to assess its compatibility with other inputs, bacterial culture formulation, and treatment rates through field trials and consultations.[65] Zinc is an essential micronutrient for the growth and development of *Brassica juncea* (Indian mustard). While zinc is crucial for plant health, excessive or deficient levels of zinc can have adverse effects on *Brassica juncea*.[66] Here are some potential side effects of zinc on *Brassica juncea.*[67-70] Zinc poisoning in *Brassica juncea* plants can cause chlorosis, slowed growth, diminished root development, necrosis, and impair nutrient uptake, leading to total plant stress and yield loss.[67] Zinc deficiency in *Brassica juncea* can lead to nutritional imbalances and deficient symptoms due to the interference of excess zinc with the absorption of other metals. Zinc deficiency in *Brassica juncea* can hinder photosynthesis, seed germination, and physiological processes, leading to reduced growth and compromised plant well-being. This can be due to soil conditions, zinc availability, and plant genotype. Zinc levels can also disrupt hormone regulation, enzyme activity, and cellular functions, affecting overall plant health.[71]

ZSB interact with other bio-stimulants and fertilizers in soil

Zinc Solubilizing Bacteria (ZSB) interact with other bio-stimulants and fertilizers in various ways, enhancing Increased plant growth

Table 3. List of Various Zinc-Solubilizing Bacterial Strains and Their Efficacy on Plant Growth

No.	Isolated Microbial Strains	Area and Sites of Isolation	Plants	Impact	Ref.
1.	*Pseudomonas aeruginosa*	Soil, water	Wheat, Maize, Rice Potato, Apple	Enhanced zinc solubilization aiding Grapes, Banana overall growth, flowering, and fruit development	[76,77]
2.	*Pseudomonas fra*	Environmental sources, spoiled foods	Wheat, Maize, Potato, Apple, Grapes	Improved zinc availability benefiting plant development	[47]
3.	*Pantoea dispersa*	Soil, plants, water, clinical samples	Wheat, Maize, Potato, Apple, Grapes, Banana	Potential positive effect on zinc uptake by plants	[71]
4.	*Pantoea agglomerans*	Plants, soil, water, insects, clinical samples	Wheat, Maize, Potato, Apple, Grapes	Potential enhancement of zinc absorption by plants. formation of enzymes and proteins crucial for fruit maturation	[47,78]
5.	*E. cloacae*	Soil, water, clinical samples, plants	Wheat, Maize, Potato, Apple, Grapes, Rice, Tomato	Influence on zinc availability for better plant growth	[47]
6.	*Rhizobium* sp.	Root nodules of legume plants, soil	Wheat, Maize, Potato, Apple, Rice, Grapes, Chickpea	Possible improvement in zinc utilization by wheat, maize. Improve legume crop yield and protein content	[79,80]
7.	*Pseudomonas striata*	Water, soil, plants	Wheat, Maize Seed yield and shoot	Unknown impact, further research is dry mass needed	[81]
8.	*Gluconacetobacte rdiazotrophicus*	Sugarcane plants, other crops	Wheat, Maize, Potato, Apple, Grapes, Tomato,	Potential enhancement of zinc uptake by these plants	[82]
9.	*Enterobacter cloacae*	Soil, water, clinical	Maize, Potato, Apple, Grapes samples, plants	Impact on zinc availability for different plant species.	[52]
10.	*Bacillus mycoide*	Soil, water, plants, clinical samples	Wheat, Maize, Potato, Apple, Grapes	Improved zinc solubilization for various plants	[49]
11.	*P. megaterium*	Soil, water, plants, clinical samples	Wheat, Maize, Potato, Grapes	Enhanced zinc absorption aiding plant growth	[83,84]
12.	*P. aryabhattai*	Soil, water, plants	Wheat, Maize, Potato, Apple, Grapes	Potential positive effect on zinc uptake by plants. Increased grain yield and quality	[84]
13.	*Bacillus megaterium*	Soil, water, plants, clinical samples	Rice, Wheat, Maize, Potato, Apple, Grapes	Improved zinc availability for different plant species	[83]

Table 3. Cont...

No.	Isolated Microbial Strains	Area and Sites of Isolation	Plants	Impact	Ref.
14.	*B. thuringiensis*	Soil, plants, insects	Wheat, Maize, Potato, Apple, Grapes	Possible enhancement of zinc absorption by these plants	[83]
15.	*B. tequilensis*	Soil, plants	Maize, Potato, Apple, Grapes, Banana	Potential improvement in zinc availability for plants	[83]
16.	*B. clausii* and *B. pumilus*	Soil, water, plants	Wheat, Maize, Potato, Apple, Grapes, Banana	Potential positive effect on zinc uptake by plants	[85]
17.	*B. licheniformis*	Soil, water, plants	Wheat, Maize, Potato, Apple, Grapes	Influence on zinc uptake by different plant species	[86]
18.	*Enterobacter cloacae*	Soil, water, plants, clinical samples	Wheat, Maize, Potato, Apple, Grapes, Banana	Impact on zinc availability for different plant species	[52]
19.	*Enterobacter kobei*	Soil, water, plants, clinical samples	Wheat, Maize, Potato, Apple, Grapes	Potential enhancement of zinc absorption by plants	[18]
20.	*E. hormaechei*	Soil, water, plants	Wheat, Maize, Potato, Apple, Grapes	Potential positive effect on zinc uptake by plants	[19]
21.	*E. ludwigii*	Soil, water, plants	Rice, Walnut	Unknown impact, further research needed	[19]
22.	*E. radicincitans*	Soil, water, plants	Wheat, Maize, Potato, Apple, Grapes	Possible improvement in zinc utilization by wheat, maize	[87]
23.	*E. gergoviae*	Soil, water, plants	Wheat, Maize, Tomato, Banana	Enhanced zinc solubilization aiding plant growth	[87]
24.	*E. soli*	Soil, water, plants	Wheat, Maize, Potato, Apple, Grapes	Improved zinc availability benefiting plant development	[20]
25.	*E. taylorae*	Soil, water, plants	Wheat, Maize, Potato, Apple, Grapes	Potential positive effect on zinc uptake by plants	[20]
26.	*E. turicensis*	Soil, water, plants	Wheat, Maize, Potato, Apple, Grapes, tomato	Potential enhancement of zinc absorption by plants	[17]
27.	*E. arachidis*	Soil, water, plants	Wheat, Maize, Potato, Apple, Grapes	Influence on zinc availability for better plant growth	[17,20]
28.	*E. asburiae*	Soil, water, plants	Wheat, Maize, Potato, Apple, Grapes	Possible improvement in zinc utilization by wheat, maize	[88]
29.	*E. hormaechei*	Soil, water, plants	Wheat, Maize, Potato, Apple, Grapes	Impact on zinc availability for different plant species	[88]

Table 4. Summarizing commercially available zinc-solubilizing bacteria formulations

No.	Formulation	Bacterial Strain	Commercial Name	Ref.
1.	Liquid	*Bacillus* sp.	BioZinc	[28]
2.	Powder	*Pseudomonas* sp.	ZincSol	[89]
3.	Granules	*Gluconacetobacter* sp.	ZnGrow	[90]
4.	Biofertilizer	*Acinetobacter* sp.	ZnBoost	[91]
5.	Liquid	*Burkholderia* sp.	ZnMax	[92]
6.	Powder	*Enterobacter* sp.	ZnPower	[93]
7.	Granules	*Microbacterium* sp.	ZnMicro	[94]
8.	Biofertilizer	*Rhizobium* sp.	ZnRhizo	[95]
9.	Liquid	*Serratia* sp.	ZnSerr	[96]
10.	Powder	*Thiobacillus* sp.	ZnThio	[97]
11.	Granules	*Agrobacterium* sp.	ZnAgro	[98]
12.	Biofertilizer	*Azospirillum* sp.	ZnAzo	[99]
13.	Liquid	*Klebsiella* sp.	ZnKleb	[100]
14.	Powder	*Ralstonia* sp.	ZnRal	[101]
15.	Granules	*Ericoid mycorrhizal* fungi	ZnFungi	[102]
16.	Biofertilizer	*Bacillus subtilis*	ZnSub	[103]
17.	Liquid	*Pseudomonas fluorescens*	ZnFluo	[91,104]
18.	Powder	*Gluconacetobacter diazotrophicus*	ZnDiazo	[105]
19.	Granules	*Acinetobacter calcoaceticus*	ZnCalc	[106]
20.	Biofertilizer	*Burkholderia cepacia*	ZnCep	[39,107]

and soil health (Table 3). ZSB primarily increase the bioavailability of zinc by solubilizing it from insoluble compounds in the soil, which enhances plant zinc uptake. This process can synergise with other bio-stimulants and fertilizers, promoting overall nutrient availability and plant health.

Interaction with microbial inoculants

ZSB can improve root and shoot growth, increase nutrient availability, and defend plants from diseases by interacting with other beneficial microbes such as Plant Development-Promoting Rhizobacteria (PGPR) or mycorrhizal biofertilizers.[28,72]

Combination with organic fertilizers

When combined with organic fertilizers, ZSB can Improve plant nutrient absorption by boosting the solubilization of various nutrients such as phosphorous, through microbial activity.[73]

Effect of chemical fertilizers

Applying chemical fertilizers can sometimes affect ZSB activity. In some cases, high levels of synthetic inputs may suppress microbial populations, including ZSB. Therefore, balanced use of fertilizers is essential to maintain the beneficial effects of ZSB.[74]

Synergy with humic and fulvic acids

Organic compounds like humic acid and fulvic acids, which are commonly used as bio-stimulants, can enhance ZSB activity by improving soil structure and providing organic matter, which serves as a source of carbon for microbial growth.

Integration in sustainable farming

Integrating ZSB with micronutrient-enriched fertilizers or other Biostimulants can improve overall soil fertility and plant resilience, promoting sustainable agricultural practices and reducing the need for synthetic fertilizers also maintain the pH of the soil.[75]

Future prospects and contributes to the existing knowledge on zinc-solubilizing bacteria in agriculture

ZSB Interactions with multiple Crops

The manuscript highlights the variable response of Wheat, Rice, Maize and *Brassica juncea* to ZSB based on geographical and environmental factors, suggesting the need for site-specific research to optimize ZSB use under different agro-climatic conditions. Future research could focus on field trials across different regions to fine-tune ZSB applications tailored to specific crops and environmental conditions.

Synergistic Use with other bio-stimulants

The potential of combining ZSB with other bio-stimulants (e.g., micronutrient-enriched fertilizers) is mentioned, but this combination needs further research. To assess its effectiveness across various crops, comprehensive field studies are necessary. Investigating the compatibility and efficacy of ZSB with other agricultural inputs can provide a deeper understanding of how these bio-stimulants interact and their optimal use, thereby paving the way for practical application in agriculture.

Environmental and soil health impacts

Since the manuscript discusses ZSB's positive impact on environmental sustainability by reducing the reliance on chemical fertilizers, future research could delve deeper into its long-term effects on soil health, especially in contaminated or zinc-deficient soils. Exploring its role in phytoremediation and broader environmental benefits could provide new insight.

Scaling up ZSB use in agriculture

The manuscript mentions the role of ZSB in sustainable agriculture, but future research should address the challenges in scaling up its use on a commercial level. Investigations into the formulation, application methods, and cost-effectiveness of ZSB in large-scale farming systems could provide practical solutions for broader adoption.

The study contributes to the knowledge of zinc-solubilizing bacteria (ZSB) in agriculture by offering empirical evidence and in-depth analysis of how ZSBs can enhance zinc availability in crops like *Brassica juncea* and other crops. It adds to the current understanding of the role ZSBs play in promoting sustainable agriculture through several key aspects:

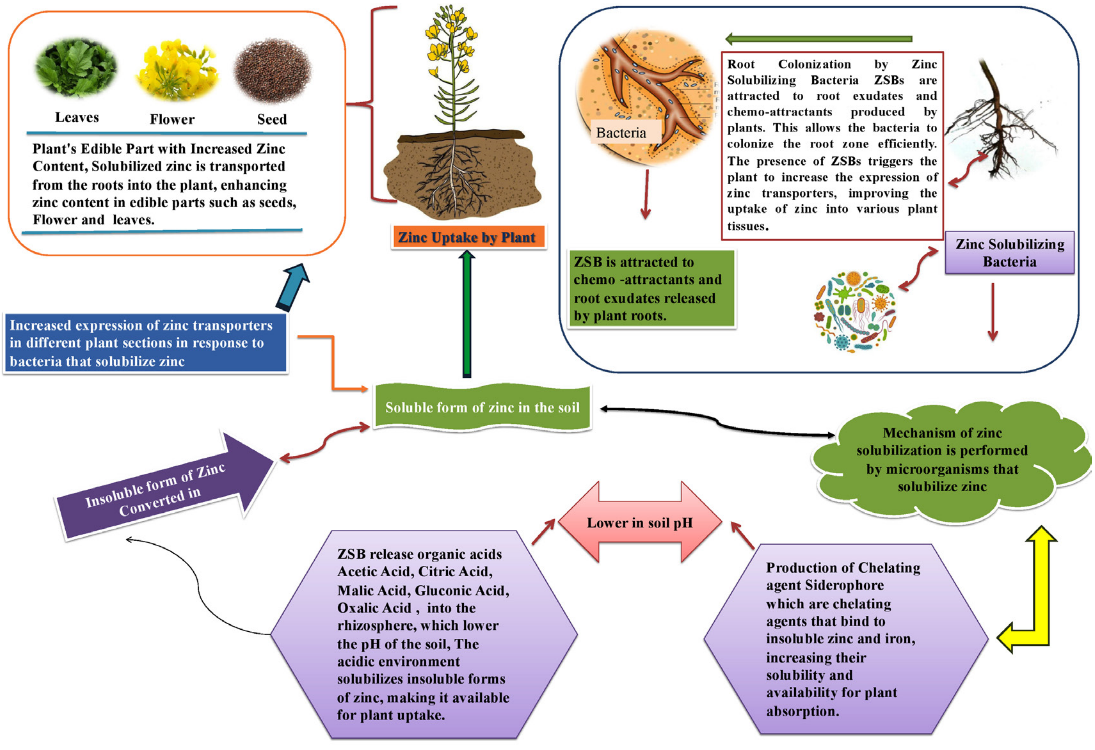

Figure 2. Depiction of Mechanism of zinc solubilizing bacteria promotes plant growth

Reduction of chemical fertilizer dependency

The study emphasizes the potential of ZSBs as a replacement to chemical fertilizers that are frequently damaging to the environment. By converting insoluble zinc compounds into soluble forms, ZSBs make zinc more accessible to plants, improving plant growth while reducing environmental pollution.

Improvement in crop growth and yield

ZSBs promote plants' zinc absorption, enhancing crop growth, particularly in zinc-deficient soils. This contributes to better yields and overall plant health, especially in crops with high zinc demands, such as *Brassica juncea*, wheat, maize, rice, etc.

Sustainable agricultural practices

The research underscores how applying ZSBs aligns with and reinforces sustainable farming methods. By promoting nutrient uptake, enhancing soil health and cultivating eco-friendly farming techniques, ZSBs contribute significantly to sustainable agriculture.

Field trials and crop specificity

The manuscript provides data from field trials that demonstrate the effectiveness of ZSBs in specific crops. It also outlines the crop *Brassica juncea*, wheat, maize, etc., explaining how ZSBs address zinc shortages, which is crucial for chlorophyll synthesis and enzyme activation in this crop.

Environmental and economic benefits

By efficiently facilitating the use of natural resources, ZSBs reduce reliance on synthetic inputs, lowering farmers' costs and mitigating environmental contamination this contributes to a better balance between agricultural productivity and sustainability.

ZSB innovation: a sustainable alternative to conventional zinc bio-stimulants

This study presents a scientifically innovative and focused technique for boosting the growth, development, and productivity of important food crops such as *Brassica juncea*, wheat, maize, and rice. Unlike traditional bio-stimulants, such as seaweed extracts, humic substances, and general microbial inoculants, which primarily provide broad-spectrum support for nutrient uptake or stress mitigation, this study focuses on resolving zinc-specific nutrient deficiencies, which are common in zinc-depleted agricultural soils commercially available zinc-solubilizing bacterial formulations (Table 4).

The main distinctness of this study is its capacity to use naturally existing ZSB strains to successfully convert insoluble zinc into plant-available forms via biological solubilization. This approach not only solves zinc's poor bioavailability but also provides an ecologically benign alternative to synthetic zinc fertilizers, which are often ineffectual over time, dangerous to the environment, and unsustainable for long-term agricultural application. Aside from zinc mobilization, the ZSB strains tested in this study display other plant growth-promoting characteristics, such as phytohormone (e.g., auxin) synthesis, phosphate solubilization, and improved root system development. These multifunctional features work together to meet the physiological demands of nutrient-demanding crops like Brassica juncea by increasing nutrient absorption efficiency, plant vigor, and tolerance to abiotic stress.

Most importantly, this study presents empirical, field-based data supporting the use of ZSB as a feasible technique for improving crop production, quality, and soil health. By providing a targeted, sustainable, and crop-specific solution, this study establishes ZSB-based bio stimulants as a next-generation tool in climate-resilient and ecologically aware agriculture.

CONCLUSION

Furthermore, with the inescapable impacts of abiotic stress caused by soil contamination and climate change, Biostimulants may provide a strategy to mitigate their impact on the farming sector. However, a number of things must be considered that effects can fluctuate between agricultural species, productivity and extraction techniques for Biostimulants and constituent quantities, bioactive and effects might vary, and separate Biostimulants can operate differently in the same species. When there is a zinc deficiency, IAA degrades quickly, carbon dioxide fixation becomes less effective, and tiny organic compounds like amino acids, potassium ions and carbohydrates leak out Zinc solubilizing bacteria (ZSB) are significant in today's environment for various reasons, including their ability to provide a sustainable strategy to enhance soil fertility and plant nutrition. ZSB reduces the need for fertilizers made with chemicals, which may have significant environmental consequences, by increasing zinc availability. ZSB use can help to promote sustainable agriculture practices by lowering dependency on synthetic fertilizers and reducing environmental pollution by solubilizing zinc compounds, ZSB can help with environmental remediation by helping in the detoxification and removal of excess zinc from contaminated soils. This can aid in the restoration of ecosystem health and functionality. ZSB has potential applications outside of agriculture. We can increase agricultural output, reduce environmental impacts, and address zinc deficiency and contamination issues by leveraging ZSB's strengths. In today's world, they provide a natural and sustainable alternative to increase zinc availability, boost food security, and encourage more ecologically friendly agricultural practices.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHORS' CONTRIBUTION

UV and GG conceptualized the study. GG performed supervision. UV, AD, DK and GG performed visualization. UV, ST, PN, and GG wrote the original draft. UV, ST and GG wrote and reviewed the manuscript. AD and DK edited the manuscript. All authors read and approved the final manuscript for publication.

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DATA AVAILABILITY

All datasets generated or analyzed during this study are included in the manuscript.

ETHICS STATEMENT

Not applicable.

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