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RESEARCH ARTICLE
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Impact of Zinc Solubilizing Bacteria on Growth and Yield of Maize and Tomato Plants

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ABSTRACT

Zinc (Zn) is a vital micronutrient for plant growth and reproduction, with 10 to 300mg/kg of soil concentrations. In Pakistan, over 70% of agricultural soil have zinc level below critical thresholds, severely hindering crop productivity. Conventional zinc fertilizers, such as $ZnSO_4$ (containing 33% zinc), exhibit low efficiency, with only 4-8% of applied zinc absorbed by plants, while the remaining is immobilized in the soil. Zinc oxide (ZnO), a more cost-effective alternative containing 80% of zinc, is largely insoluble and unavailable for plant uptake. An emerging strategy to address this deficiency involves zinc-solubilizing bacteria (ZSB), which convert insoluble zinc forms into bioavailable species that facilitate plant absorption. This study has screened bacterial isolates capable of solubilizing ZnO (Bacillus spp) and evaluated their effectiveness in promoting plant growth under sterile conditions. The results indicated that the application of different concentrations (4mL, 3mL, 2mL, and 1mL) of zinc solubilizing bacteria significantly improved growth parameters such as stem length, root length, leaf size, and total plant length of both maize (*Zea mays*) and tomato (*Solanum lycopersicum*) compared to control groups. These results demonstrate that ZSBs offer an eco-friendly and effective approach to mitigate zinc deficiencies in soils, thereby enhancing agricultural productivity in regions where zinc depletion limits crop performance.

Keywords: Zinc solubilizing bacteria, Plant Growth Promotion, Zinc deficiency, Micronutrients.

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INTRODUCTION

Zinc (Zn) is an essential micronutrient crucial for the growth and development of plants. It plays a significant role in various physiological processes, including auxin and glucose metabolism, and is a vital antioxidant (Karnwal, 2021). Zn influences fundamental plant activities such as nitrogen metabolism, photosynthesis, and resistance to both biotic and abiotic stresses, as well as mitigating oxidative damage. Zinc solubility is closely associated with soil pH and moisture levels (Hakim et al., 2021). In Pakistan, where soils are often alkaline or acidic, zinc deficiency is prevalent due to the naturally low availability of zinc (Hussain et al., 2018). Zinc deficiency in plants leads to various adverse effects, including reduced flowering and fruit development, delayed crop maturity, diminished grain yield, and nutritional quality, decreased phytohormone production, and impaired photosynthesis and nitrogen metabolism (Verma et al., 2023).

Zinc deficiency in agricultural plants is caused by a variety of causes, the main one being the low solubility of zinc in soils. A necessary micronutrient is zinc and a healthy supply of it is essential for plant development and maximum productivity. For optimal plant growth and development, a steady supply of zinc was required due to its poor mobility in plants. Zinc is an essential component of many enzymes and is involved in several pathways that mediate plant metabolic processes. A zinc deficit has a detrimental effect on crop plants' development and growth. The sole micronutrient that could be responsible for this is zinc (Naseem et al., 2022).

Plant roots enable water and nutrient uptake through several channels, such as the production of a wide range of chemicals, and they also provide mechanical support to plants. The solubilization of Zn compounds is facilitated by the action of organic acids generated by microorganisms

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(Pratiwi et al., 2024). The relationship between the roots of plants and ZSB is related to the zinc pool's solubilization, biofortification, and mineralization. Even ZSs can solubilize zinc from both inorganic and organic pools that make up the total soil zinc, which can be employed to boost zinc availability to plants. ZSBs are known for their ability to solubilize zinc because they interact with plant roots to produce root exudates that act as chemo-attractants (Bashir et al., 2021).

ZSB depletes the group of unavailable zinc in the soil to release the necessary quantity of zinc. Poor plant growth and low-quality seeds, grains, rhizomes, etc. have been linked to reduced zinc bioavailability in plants (Bashir et al., 2021). Bioinoculants can therefore be used to raise the concentration of zinc in soil and substitute for the inorganic zinc fertilizers' poor solubility. The ZSB increases the bioavailability of zinc to plants by either lowering the fixation of applied zinc fertilizers or solubilizing fixed zinc. It is therefore a viable and affordable substitute technique for raising the soil's zinc bioavailability (Yadav et al., 2023).

Conventional zinc fertilizers ($ZnSO_4$), contain 33% of zinc but exhibit low efficiency, with only 4-8% of the applied zinc being absorbed by plants, while the remainder becomes immobilized in the soil (Shakeel et al., 2024). Zinc oxide (ZnO), a more cost-effective alternative with 80% of zinc content, remains largely insoluble and inaccessible to plants. The solubilization of Zn compounds is facilitated by organic acids produced by microorganisms, which can transform insoluble zinc forms into bioavailable ones (10 to 50%) (Prathap et al., 2022). While inorganic fertilizers like $ZnSO_4$ are used to address zinc deficiencies and enhance plant yield, up to 90% of applied zinc can become unavailable due to soil interactions (Rani et al., 2023). Consequently, there is a growing need for alternative methods, such as the use of plant growth-promoting rhizobacteria (PGPR), which offer a more sustainable and environmentally friendly solution (Ali et al., 2023).

PGPR~~,~~ species such as *Thiobacillus thiooxidans*, *Acinetobacter* sp., *Bacillus* sp., *Glucoacetobacter* sp., *Thiobacillus ferrooxidans*, *Pseudomonas* sp., and facultative thermophilic iron oxidizers, have demonstrated the ability to solubilize zinc and enhance plant growth (Zhao et al., 2023). These bacteria improve plant development by colonizing the rhizosphere, producing organic acids, and promoting nutrient uptake through processes of acidification and chelation (She et al., 2021). The ability of PGPR to solubilize inaccessible forms of zinc and enhance plant growth has been well-documented, with these bacteria contributing to increased soil fertility and reduced reliance on chemical fertilizers. Applications of PGPR increase soil fertility and depletion usage of chemicals and produce organic acids (Zhang et al., 2023).

Maize (Zea mays L) is the important chief food in most parts of the world as well as in nutrient-deficient countries. It is a monocot plant means it consists of only one embryonic leaf or cotyledon. One crop being tested for photosynthesis is maize, a C4 plant with a lot of genetic potential. It is grown mostly for grain and animal feed (Kim & Lee, 2023). Among cereal crops, it produces and is the most productive. The climates in which it has been grown include semiarid, sub-humid, and areas that are humid. maize is vulnerable to diseases and stress and can benefit from PGPR applications to enhance growth and resistance against pests (Faddetta et al., 2023). Zinc deficiency is particularly damaging to maize, which results in reduced agricultural productivity (Verma et al., 2022).

Tomatoes are one of the foods that are most protective due to their nutrient content. Tt is a rich source of antioxidants and minerals such as phenolic compounds, vitamin C, E, and carotenoids. It's also helpful to research other aspects of plants, such as how fruits develop, how hormones are produce, and how vitamins are form. During the development of tomatoes, enzymatic activities involving zinc are important for cell proliferation (Bouizgarne et al., 2023). It also benefits from zinc, which is crucial for enzymatic activities during their development (Rahman et al., 2024).

This study offers a novel approach by examining the dual role of PGPR in enhancing seed vigor and simultaneously increasing zinc bioavailability. By addressing both seed quality and micronutrient enrichment, this research presents a comprehensive strategy for improving performance and nutritional value of maize and tomato ultimately contributing to more sustainable agricultural practices.

MATERIALS & METHODS

The investigation was carried out under controlled in vitro conditions within a growth chamber in Biotechnology Laboratory, the Institute of Molecular Biology and Biotechnology (IMBB), the University of Lahore. The study focused on evaluating the impact of zinc-solubilizing bacterial strains on the growth, yield, and quality of maize and tomato plants. Specifically, the research utilized H6 and H7 maize varieties, along with treated tomato seeds (Rio Grande variety), to assess their response to the bacterial treatments, which were applied to confer antifungal properties and enhance overall plant performance.

Sample Site and Collection

A medium-dark brown soil was collected from the University of Lahore and then subjected to autoclaving to eliminate debris, stones, weeds, and clods. The rhizosphere soil was collected in sterilized bags and transported to the Laboratory of Microbiology at the IMBB, the University of Lahore, Pakistan. Upon arrival, the soil was stored at 4°C until it was processed for bacterial isolation.

Seed Treatment

A weighted portion of 1.5g NaCl, 1.5g yeast, and 3/2.5g Trypton powder were properly mixed and then added to distilled water in a 500mL flask. Then the flask is placed in an autoclave for 2 hours. The 5 Seeds of Maize and tomato, each were dipped in the broth flask and placed in a shaker for 24 hours.

Zinc Solubilization

In 500mL of distilled water, 1g of yeast extract, 1g of Trypton, 40g of Dextrose agar, 2g of $(NH_4)_6 Mo_7O_{24}$, 0.2g of KCl, 0.1g of $MgSO_4$, 0.3g of K_2HPO_4, and 0.1% of ZnO were weighed and dissolved. The mixture was then autoclaved and cooled to 40–45°C. After proper mixing, it was poured onto petri plates. Once a creamy white coloration appeared, colonies were selected, transferred to plates, and then incubated for 3–4 days at 35–37°C.

Formula

$$SE = \frac{\text{Solubilizationdiameter}}{\text{Growthdiameter}} \text{ X } 100$$

$$SI = \frac{\text{Colonydiameter} + \text{Halozonediameter}}{\text{Colonydiameter}}$$

Treated Seed Sowing

Ten pots were appropriately labeled and filled with soil, with five seeds sown in each pot. Zinc-solubilizing bacteria were introduced alongside 5mL of distilled water. For the maize varieties H6 and H7, Pots 1 to 4 received inoculum concentrations of 4, 3, 2, and 1mL, respectively. In the case of tomato plants, Pots 1 and 2 were treated with 4mL, Pots 3 and 4 with 3mL, Pots 5 and 6 with 2mL, and Pots 7, 8 and 9 with 1mL of inoculum. The control group was provided only 5mL of distilled water, with no inoculum added. This experimental design was intended to assess the influence of different bacterial inoculum concentrations on the growth of both maize and tomato varieties.

Observation Record

The maize and tomato seedlings were examined and their germination period was compared with those of the control plants after 12 weeks.

Growth Parameters

Both plants were measured, including height, stem diameter, intermodal length, number of leaves and branches per plant, leaf area, and crop duration (Fig. 1).

RESULTS

Pot Trials

The pot study demonstrated that a 4mL dosage of bacterial inoculum significantly enhances the growth of both tomato and maize seedlings, while other concentrations also exhibited some improvement in growth for both plant species. The development of maize seedlings of varieties H6 and H7 and tomatoes was notably stimulated within 21 days of germination by zinc-solubilizing rhizobacterial isolates.

Root Length

After the inoculation of zinc-solubilizing bacteria (ZSB) isolates, there was a significant increase in root length for both tomato and maize (H6, H7) compared to the control, as indicated in Table 1 and 2 for maize and Table 3 for tomato. In contrast, the control group exhibited minimal root length without the inoculation of isolates. When tomato seedlings were treated with the isolated strains, the maximum root length increased by 20% to 25% compared to the control. Conversely, the lowest root length measurements were recorded during the inoculation phase.

A) Soil Sample **B) LB broth media** **C) Zinc Solubilizing Bacterial plate**

D) Treated Seed with LB broth **E) Control plant** **F) Pots with maize and tomato seeds**

Fig. 1: Illustration of methodology.

Table 1: Measurement of 5 pots of Maize H6 Variety with varying concentrations including control

MAIZE (H6 VARIETY)					
Pot and plant no	Root Length (cm)	Stem Length (cm)	Leave Length (cm)	Total fresh weight (g)	Total dry weight (g)
Pot 1 (4mL ZSB concentration)					
Plant 1	9.6	10.8	12.4	1.67	0.62
Plant 2	6.2	9.5	10.7	1.88	0.50
Plant 3	3.6	8.7	3.5	1.67	0.32
Plant 4	4.8	6.5	4	1.98	0.37
Plant 5	3.7	3.1	1	1.58	0.21
Pot 2 (3mL ZSB concentration)					
Plant 1	4.4	7.8	6.2	1.22	0.42
Plant 2	6.5	11	7.1	1.16	0.36
Plant 3	4.7	8.1	2.1	0.79	0.21
Plant 4	0	0	0	0	0
Plant 5	0	0	0	0	0
Pot 3 (2mL ZSB concentration)					
Plant 1	3.7	8.2	5.5	1.67	0.32
Plant 2	3.9	6.5	6.9	1.58	0.12
Plant 3	4.7	7.9	5.1	1.23	0.16
Plant 4	0	0	0	0	0
Plant 5	0	0	0	0	0
Pot 4 (1mL ZSB concentration)					
Plant 1	4.2	5.9	4.1	1.87	0.36
Plant 2	4.1	4.2	3.9	1.56	0.15
Plant 3	0	0	0	0	0
Plant 4	0	0	0	0	0
Plant 5	0	0	0	0	0
Control					
Plant 1	2.3	4.1	1.7	1.20	0.11
Plant 2	0	0	0	0	0
Plant 3	0	0	0	0	0
Plant 3	0	0	0	0	0
Plant 4	0	0	0	0	0
Plant 5	0	0	0	0	0

Table 2: Measurement of 5 pots of Maize H7 Variety with varying concentrations including control

MAIZE (H7 VARIETY)					
Pot and plant no	Root Length (cm)	Stem Length (cm)	Leave Length (cm)	Total fresh weight (g)	Total dry weight (g)
Pot 1 (4mL ZSB concentration)					
Plant 1	6.3	9.4	11.9	1.71	0.04
Plant 2	5.6	6.8	9.9	1.02	0.1
Plant 3	5.1	8.6	10.3	1.16	0.06
Plant 4	4.6	9.1	11.1	1.54	0.18
Plant 5	4.5	6.2	1.7	0.94	0.09
Pot 2 (3mL ZSB concentration)					
Plant 1	6.5	8.8	9	1.61	0.19
Plant 2	4	7	2.3	0.92	0.16
Plant 3	0	0	0	0	0
Plant 4	0	0	0	0	0
Plant 5	0	0	0	0	0
Pot 3 (2mL ZSB concentration)					
Plant 1	6.2	12	9.6	1.27	0.14
Plant 2	5.1	10.6	9.9	1.52	0.1
Plant 3	5.6	8.9	5.5	1.37	0.27
Plant 4	5.9	8.2	4.8	1.79	0.14
Plant 5	0	0	0	0	0
Pot 4 (1mL ZSB concentration)					
Plant 1	10.7	4.3	7.6	1.33	0.21
Plant 2	6.6	7.2	5.4	1.03	0.1
Plant 3	0	0	0	0	0
Plant 4	0	0	0	0	0
Plant 5	0	0	0	0	0
Control					
Plant 1	2.3	3.6	1.8	0.65	0.7
Plant 2	0	0	0	0	0
Plant 3	0	0	0	0	0
Plant 4	0	0	0	0	0
Plant 5	0	0	0	0	0

Leaf Length

After bacterial inoculum treatment, the H6 variety of maize showed an increase in leaf length of 17.9cm (Table 1) compared to the control, while the H7 variety showed an increase in leaf length of 18.2cm (Table 2). However, in contrast to the control plant (Table 3), the tomato plant has also shown maximum growth.

Table 3: Tomato plant measurements from 10 pots with varying ZSB concentrations, including a control group.

RIO GRANDE VARIETY (TOMATO)					
Pot and plant no	Root Length (cm)	Stem Length (cm)	Leave Length (cm)	Total fresh weight (g)	Total dry weight (g)
Pot 1 (4mL ZSB concentration)					
Plant 1	4.6	8.5	3.6	2.2	1.16
Plant 2	5.6	5.8	2.1	4.6	1.14
Plant 3	6	6.6	2.2	5.5	1.11
Plant 4	6.2	7.1	2.7	6.3	1.1
Plant 5	6.3	6.1	1.1	6.5	1.0
Pot 2 (4mL ZSB concentration)					
Plant 1	10.4	13.5	3.1	2.68	1.4
Plant 2	8.8	8.8	1.8	3.3	1.5
Plant 3	9.5	7.3	1.1	4.5	1.6
Plant 4	4.6	8.2	0.4	1.4	0.7
Plant 5	0	0	0	0	0
Pot 3 (3mL ZSB concentration)					
Plant 1	5.4	10	3.4	1.48	0.6
Plant 2	5.5	5.3	3.6	1.2	0.47
Plant 3	6.5	6.7	2.6	1.4	0.32
Plant 4	0	0	0	0	0
Plant 5	0	0	0	0	0
Pot 4 (3mL ZSB concentration)					
Plant 1	5.8	8.1	2.3	1.46	1.5
Plant 2	6.4	7.6	1.9	1.36	1.3
Plant 3	0	0	0	0	0
Plant 4	0	0	0	0	0
Plant 5	0	0	0	0	0
Pot 5 (2mL ZSB concentration)					
Plant 1	5.3	7	5.5	1.2	0.5
Plant 2	6.6	6.7	3.7	1.4	1.2
Plant 3	6.4	6.8	3.4	1.1	0.9
Plant 4	7.3	7.1	3.7	1.3	0.3
Plant 5	0	0	0	0	0
Pot 6 (2mL ZSB concentration)					
Plant 1	6.7	7.5	4.3	0.23	0.23
Plant 2	7.1	7.6	2.1	1.4	0.8
Plant 3	0	0	0	0	0
Plant 4	0	0	0	0	0
Plant 5	0	0	0	0	0
Pot 7 (1mL ZSB concentration)					
Plant 1	3.9	8.5	2.8	1.3	0.9
Plant 2	5.2	14	3.2	1.5	0.7
Plant 3	5.7	11.4	0.8	1.7	0.4
Plant 4	5.5	11.6	1.1	1.6	0.42
Plant 5	0	0	0	0	0
Pot 8 (1mL ZSB concentration)					
Plant 1	5.4	8.7	1.4	4	0.3
Plant 2	5.9	6.7	3.6	4.2	0.5
Plant 3	5.3	8	2	2.7	0.2
Plant 4	0	0	0	0	0
Plant 5	0	0	0	0	0
Pot 9 (1mL ZSB concentration)					
Plant 1	3.3	12	9.9	1.3	0.8
Plant 2	2.3	4	5.9	1.2	0.4
Plant 3	1.6	12	2.8	1.1	0.1
Plant 4	0	0	0	0	0
Plant 5	0	0	0	0	0
Control					
Plant 1	3.6	11.5	3.8	6	1
Plant 2	5	9.7	4.8	1.5	0.8
Plant 3	0	0	0	0	0
Plant 4	0	0	0	0	0
Plant 5	0	0	0	0	0

Stem Length

The outcome demonstrated that ZSB isolates strain aids in extending the stem's length. The research showed that, when compared to the control plant, the ZSB strain lengthens the stem by up to 15% in maize and tomato plants as shown in Fig. 2 and Fig. 3.

Total Fresh Weight

Inoculating the tomato and maize (H6, H7) seedlings with ZSB isolates boosts the total fresh weight of the plants as shown in Fig. 4. When compared to the control, all of the tested rhizobacterial isolates increased the total fresh weight of the tomato plant by 0.3g to 1.15g. Compared to the H6 type H7 exhibits a greater growth in weight (Fig. 5).

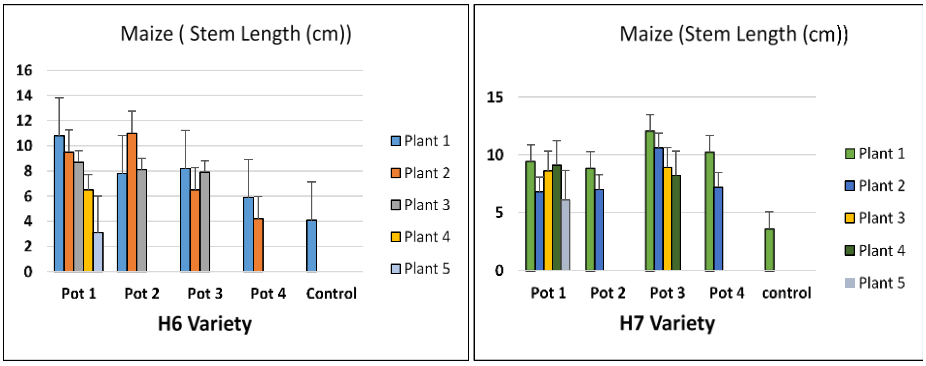

Fig. 2: Various Stem length comparisons of maize plants (H6 variety and H7 Variety); **Note:** This graph compares the stem length of both H6 and H7 varieties of Maize plants with different concentrations of ZSB. Length of each stem per pot is observed.

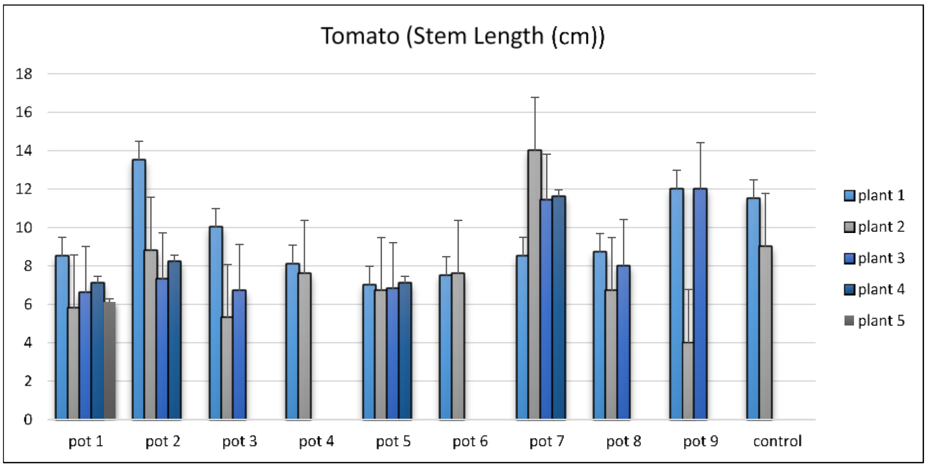

Fig. 3: Various Stem length comparisons of tomato plants; **Note:** In this graph comparison between stem length of tomato plants is done with varying concentrations of ZSB. The length of each stem per pot is observed.

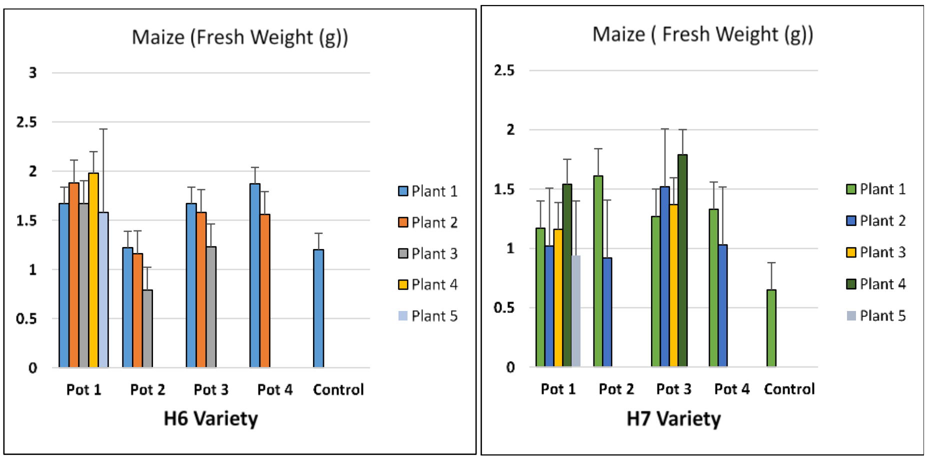

Fig. 4: Comparison of Total fresh weight of maize plant (H6 and H7 Variety); **Note:** In this graph comparison between the fresh weight of both H6 and H7 varieties of Maize plants with different concentrations of ZSB. fresh weight of each plant per pot is measured.

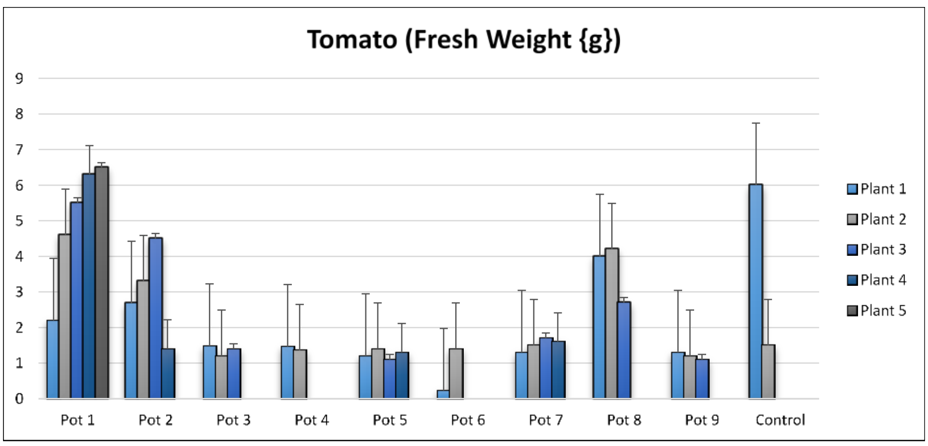

Fig. 5: Comparison of Total fresh weight of tomato plant in 10 pots; **Note:** In this graph comparison between the fresh weight of tomato plants is done with varying concentrations of ZSB. fresh weight of each plant per pot is measured.

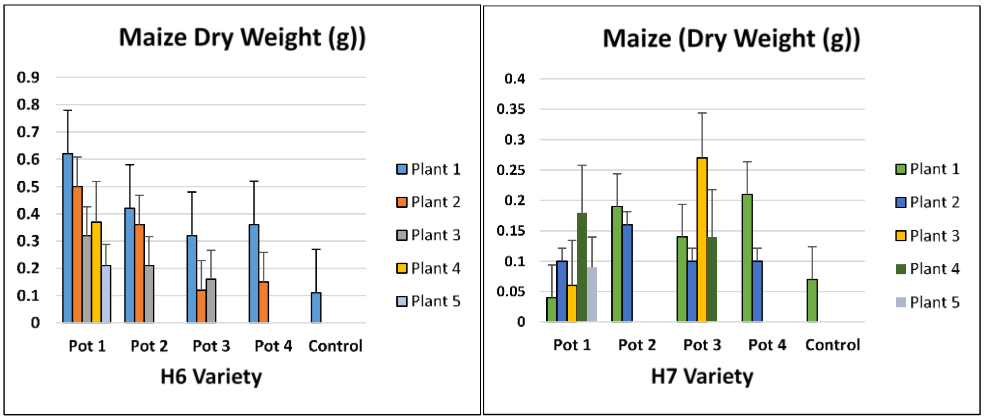

Fig. 6: Comparison of Total dry weight of maize plant (H6 and H7 Variety) in 10 pots; **Note:** In this graph, the dry weights of both H6 and H7 varieties of Maize plants are compared with different concentrations of ZSB. The dry weight of each plant per pot is observed after the reduction of water in the plants at room temperature.

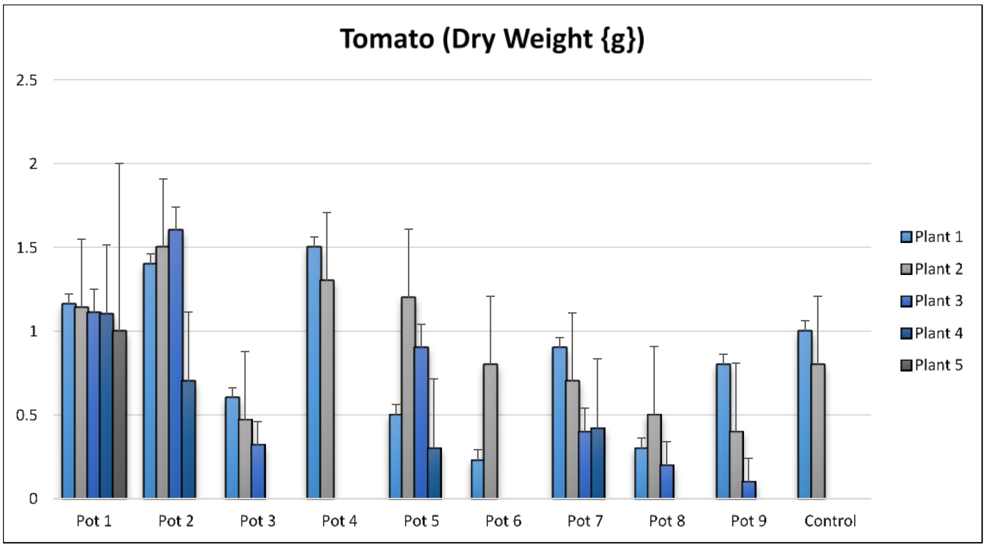

Fig. 7: Comparison of Total dry weight of tomato plant in 10 pots; **Note:** In this graph comparison between the dry weight of tomato plants is done with varying concentrations of ZSB. Dry wet of each plant per pot is observed after the reduction of water in plants at room temperature.

Total Dry Weight

The inoculation of ZSB isolates increased the total dry weight of tomato and maize (H6, H7) seedlings as illustrated in Fig. 6 and Fig. 7. Inoculation of investigated rhizobacterial isolates increased total dry weight ranging from 0.01g to 1.16g.

DISCUSSION

Zinc is an essential micronutrient for plant growth and development, with its deficiency critically impeding crop productivity. In numerous regions, including Pakistan, zinc availability has been significantly reduced due to economic constraints and the alkaline soil conditions that cause applied zinc fertilizers to rapidly convert into insoluble forms. This conversion leads to zinc-deficient soils that hinder crop growth, particularly affecting rice yields (Ibáñez et al., 2021). Nevertheless, the bioavailability of zinc can be improved through the action of zinc-solubilizing microorganisms. These microbes facilitate the breakdown of insoluble zinc compounds, thereby enhancing nutrient availability and boosting crop yields. They utilize various direct and indirect mechanisms to elevate zinc levels in crops, including wheat (Asghar et al., 2024). The dual function of PGPR in improving seed vigor and concurrently raising zinc bioavailability was studied in this work, providing a novel strategy.

The study evaluated the role of zinc-solubilizing bacteria in enhancing the growth, yield, and quality of maize and tomato plants under controlled conditions. Pot experiments were conducted using autoclaved soil to assure sterility and remove external factors, enabling an accurate evaluation of the ZSB inoculum's effects isolated from Rhodes grass (*Chloris gayanakunth*) (Muhammad et al., 2023). In comparison to the untreated controls, treated tomato and maize seeds showed significant improvements in growth parameters, and germination rates (Boubekri et al., 2021).

The improved yields of the tomato (Rio Grande) variety and the maize varieties H6 and H7 indicate that ZSB treatments have a positive effect on these crops. zinc-solubilizing bacteria had a positive effect on vegetative growth, as demonstrated by the notable increase in leaf length, which was observed in maize varieties H6 and H7 (17.9 and 18.2cm, respectively), and tomato plants. Better photosynthesis, which is essential for plant growth and productivity, is made possible by larger leaves, and the increased availability of zinc, which ZSBs facilitated, probably contributed to enhanced chlorophyll production and more efficient photosynthetic activity. Additionally, ZSBs may have stimulated the synthesis of growth hormones like auxins and gibberellins, which are known to promote leaf and stem elongation (Prajapati et al., 2022).

Additionally, Stem length significantly increased after ZSB inoculation, with both tomato and maize seedlings showing a 15% improvement. The increased availability of zinc, which is necessary for important processes like cell division and elongation, is the cause of the observed rise in stem length. Zinc is crucial for stem growth because it is a necessary cofactor for enzymes that produce proteins and cellular structures (Mansinhos et al., 2024). Furthermore, ZSBs aid in the synthesis of compounds that promote plant growth, including cytokinins and auxins, which are known to promote stem elongation. By coordinating the growth of various plant structures and fostering the overall structural growth of the plant, these hormones aid in the regulation of plant development (Saboor et al., 2021).

Increases in Plant height, stem diameter, root length, and other metrics were all significantly improved by higher inoculum concentrations (4 mL and 3 mL). However, variations in inoculum concentrations also affected the growth results. These findings demonstrate the dose-dependent nature of ZSB treatments, with larger concentrations typically resulting in improved plant growth. Previous research has highlighted that zinc-solubilizing bacterial strains, including species of *Bacillus* and *Pseudomonas*, act as effective plant growth-promoting rhizobacteria (PGPR) (Sukhwal et al., 2023). These bacteria help increase nutrient intake by solubilizing zinc, which is necessary for important physiological functions like photosynthesis, enzyme activity, and plant hormones. ZSBs contribute to stronger plant growth by boosting zinc availability, which results in higher plant height and better overall development (Othman et al., 2022)The results show that varying inoculum concentrations can maximize the benefits of ZSB treatments on crop productivity.

The Results highlight the double advantages of applying ZSB, especially in pathogen control and nutrient solubilization. ZSB improves crucial physiological functions like hormone regulation and enzyme activation, essential for strong plant growth, by solubilizing zinc and making it easily accessible to plants (Hussain et al., 2022). ZSB's antifungal qualities are also essential for reducing the risk of soil-borne infections, which supports stronger root systems and increased plant resistance in general (Hyder et al., 2024)This combination improves crop quality and yield and promotes greater biomass production. The study's controlled environment enabled precisely monitoring these effects, removing outside influences and offering clear insights into the underlying mechanism.

ZSB's potential as an environmentally friendly and sustainable substitute for chemical fertilizers is shown by these findings. ZSB treatments can aid in increased crop yields and improved quality by enhancing nutrient availability and encouraging healthier plant development, hence decreasing dependency on synthetic inputs (Saleem & Khan, 2022) . To optimize the benefits of ZSB treatments for agricultural productivity, future research should look into their long-term impacts, interactions with soil bacteria, and field application optimization. This method promotes nutritional quality and resilience in horticultural and cereal crops, which is in line with the larger goals of sustainable farming.

Conclusion

The findings indicate that a specific strain of zinc-solubilizing bacteria can effectively transform insoluble zinc sources, thereby promoting the growth and development of maize plants. This suggests that microbial inoculation enhances nutrient uptake, leading to the production of high-quality plants. The application of such biological processes in soil can substantially improve agricultural productivity while mitigating environmental impacts. The strain exhibits several beneficial traits that support plant growth and root colonization, making it a promising candidate for inoculants aimed at enhancing maize and tomato productivity and nutritional quality. Consequently, this approach could help address malnutrition by improving the zinc content in crops. The use of this zinc-solubilizing strain as a bio-inoculant demonstrates significant potential for improving the development of maize and tomato plants.

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