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Effect of Zinc and Silica Solubilizing Bacterial Consortia on Yield and Soil Enzyme Activity of Direct Sown Rice

S. V. Babu[1], A. V. Gopal[1], N. Trimurtulu[1], G. K. Babu[2] and S. L. Bhattiprolu[3]

[1]Dept. of Agricultural Microbiology, Advanced Post Graduate Centre, Acharya N. G. Ranga Agricultural University, Guntur, Andhra Pradesh (522 034), India

[2]Dept. of Soil Science, [3]Dept. of Plant Pathology, Regional Agricultural Research Station, Acharya N. G. Ranga Agricultural University, Guntur, Andhra Pradesh (522 034), India

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Corresponding vinodsandamala22@gmail.com

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ABSTRACT

The study was conducted during late *kharif* (November, 2019) and late *rabi* (April, 2020) seasons, 2019 with 13 treatments, replicated thrice, at Agricultural Research Station, Jangamaheswarapuram, Andhra Pradesh, India to evaluate the effect of zinc and silica solubilizing bacterial consortia on yield and yield attributes of rice, zinc and silica content in plant and grain, soil enzyme activity. Among the treatments viz., T_1: RDF (Control); T_2: RDF+$ZnSO_4$ at 25 kg ha^{-1}; T_3: RDF + Calcium silicate at 120-200 kg ha^{-1}, T_4: RDF+$ZnSO_4$ at 25 kg ha^{-1}+ Calcium silicate at 120-200 kg ha^{-1}; T_5: RDF+ZnKJJ-4; T_6: RDF+ZnPGG-1; T_7: RDF+SiKPP-1; T_8: RDF+SiPYY-3; T_9: RDF+ZnKJJ-4 and ZnPGG-1; T_{10}: RDF+SiKPP-1 and SiPYY-3; T_{11}: RDF+ZnKJJ-4+SiKPP-1; T_{12}: RDF+ZnPGG-1+SiPYY-3 and T_{13}: RDF+ZnKJJ-4 and ZnPGG-1+SiKPP-1 and SiPYY-3, highest zinc (0.79 and 0.81ppm) and silica content (0.89 and 0.99ppm) in plant was recorded with RDF + ZnKJJ-4 and ZnPGG-1+SiKPP-1 and SiPYY-3 at 45 days after sowing (DAS) and 120 DAS, respectively. At 120 DAS, highest zinc (0.58 ppm) and silica content (0.98ppm) in grain; highest dehydrogenase enzyme activity (390.4 and 499.6 µg TPF g^{-1} day^{-1}), acid phosphatase activity (58.15 and 68.35 µg pNP g^{-1} h^{-1}), alkaline phosphatase activity (130.52 and 136.81 µg pNP g^{-1} h^{-1}) and urease enzyme activity (40.04 and 50.06 µg of NH_4^+ -N g^{-1} soil $2h^{-1}$) at 45 DAS and 120 DAS; highest plant height at 45 DAS and 90 DAS (38.4 and 96.6 cm), total no. of tillers (496 m^2), highest panicle length at harvest (18.2 cm), no. of grains $panicle^{-1}$ (157), no. of filled grains $panicle^{-1}$ (140), 1000 grain weight (19.2 g), grain yield (5523 kg ha^{-1}) and straw yield (6893 kg ha^{-1}) were recorded with this treatment. Hence application of zinc and silica solubilizing bacterial consortia was better in improving enzyme activities in soil, releasing essential plant nutrients and thus quantity and quality of Rice yields.

KEYWORDS: Rice, zinc and silica solubilizing bacterial consortia

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1. INTRODUCTION

Rice (*Oryza sativa* L.) is the highest cultivated crop in India in respect of area. It is more than 80% of people's staple food in India. Integrated application of alternate sources of nutrients is important for sustaining the desired crop productivity (Pattanayak et al., 2007). Biofertilizers are low cost and eco-friendly input have tremendous potential for supplying nutrients which canreduce the chemical fertilizer dose by 25–50% (Vance, 1997). For increased supply of nutrients through bio-fertilizers, the efficiency of the biological system to be improved by inoculating the soil with effective strains of micro-organismsand thereby improving nutritional environment of the soil (Pattanayak et al., 2000). Rice is prone to various stresses, if the available soil silicon is low for absorption. Adequate supply of silicon to rice from tillering to elongation stage increased the rice productivity (Srivani et al., 2024). Silicon can alleviate both biotic and abiotic stresses (Mostofa et al., 2021; Etesami et al., 2018). Sufficient Si supply increases rice grain yield by enhancing the number of panicles per plant as well as the number of spikelets and the percentage of filled grains with positive response (Singh et al., 2005, Ma et al., 1989, Detmann et al., 2012). Additionally, grain yield increases by Si application have been found to be associated with Si concentration in the shoot and grain (Tamai and Ma, 2008). Silica as beneficial element has function for its cell strength in growth and development of paddy, which is accumulated 10% of its dry weight (Lanning et al., 1958). Silicate solubilizing bacteria (SSB) can play an effective role in soil by solubilizing insoluble forms of silicates. In addition, some SSB can also solubilize potassium and phosphates, thus increase soil fertility and enhance plant defence mechanisms (Peera et al., 2016a). One of the important elements for optimal plant growth is Zn. From an agronomic perspective, zinc is important to rice for a number of reasons like Nitrogen assimilation and protein metabolism. Approximately 10% of proteins in plants require Zn for structural function and integrity. Zinc is one of the trace elements, and while it is only required in small supply to produce its dramatic growth-promoting effects, it plays a huge role in many processes related to enzymatic functions, protein synthesis, and metabolic pathways (Upadhayay et al., 2022a, b, c; Younas et al., 2023). Low Zn supply limits the rice plant's ability to convert amino acids to proteins. Zinc-solubilizing bacteria act as natural bio-fortifiers that can solubilize the unavailable form of zinc by secreting organic acids, siderophores, and other chelating compounds (Rodriguiz et al., 2004) by enhancing the supply of mineral nutrients of low mobility in the soil like P, Zn and Cu (Thompson, 1996). Microbial biofortification, especially using ZSB consortia, improves zinc uptake sustainably by enhancing solubilization, plant-microbe interactions, and stress resilience, reducing reliance on chemical inputs (Singh et al., 2025). Unlike individual bacterial strains, microbial consortia harness the synergistic interactions between multiple species leading to enhanced zinc solubilization efficiency and improved plant responses (Singh et al., 2025).The use of Zn-solubilizing bacteria (ZSB) is a low-cost alternative technique for Zn biofortification, providing the optimal sustainable approach to environmentally friendly farming. Hence an experiment was conducted to assess the zinc and silica content in plant and grain, enzyme activity in soil and yield and yield attributes in rice plants by inoculating selected zinc and silica solubilizing isolates and their combinations under field conditions.

2. MATERIALS AND METHODS

The study was conducted during late *kharif* (November, 2019)and late *rabi* (April, 2020) seasons, 2019 with 13 treatments, replicated thrice, at Agricultural Research Station, Jangamaheswarapuram, Andhra Pradesh. Field evaluation of zinc and silica solubilizing bacteria and their consortia on zinc and silica content in plant and grain, soil enzyme activity and yield and yield attributes of Rice was performed. Rice variety, MTU-7029 (Swarna) was sown in black soil by adopting 20×10 cm^2 spacing. Recommended agronomic practices including weed management, fertilizer management and plant protection were adopted. The fertilizers were applied as per the treatment combinations. An entire uniform dose of 23 kg N, 60 kg P_2O_5 and 60 kg K_2O ha^{-1} was applied as basal at the time of sowing through urea, single super phosphate and muriate of potash, respectively to all the plots. Thirteen treatments, replicated thrice, were imposed incompletely randomized design viz., T_1: RDF (Control); T_2: RDF+ZnSO4 at 25 kg ha^{-1}; T_3: RDF+Calcium silicate at 120-200 kg ha^{-1}, T_4: RDF+ZnSO4 at 25 kg ha^{-1}+Calcium silicate at 120-200 kg ha^{-1}; T_5: RDF+ZnKJJ-4 (Zinc isolate from Kurnool Dist., Jupadu bunglow village and Mandal soil sample-4); T_6: RDF+ZnPGG-1 (Zinc isolate from Prakasam Dist., Giddaluru village and Mandal soil sample-1); T_7: RDF+SiKPP-1 (Silica isolate from Kurnool Dist., Pamulapadu village and Mandal soil sample-1); T_8: RDF+SiPYY-3 (Silica isolate from Prakasham Dist., Yerragondapalem village and Mandal soil sample-3); T_9: RDF+ZnKJJ-4 and ZnPGG-1; T_{10}: RDF+SiKPP-1 and SiPYY-3; T_{11}: RDF+ZnKJJ-4+ SiKPP-1; T_{12}: RDF+ZnPGG-1+SiPYY-3 andT_{13}: RDF+ZnKJJ-4 and ZnPGG-1+SiKPP-1 and SiPYY-3 where, RDF=Recommended dose of fertilizer; ZnKJJ-4, ZnPGG-1, SiKPP-1 and SiPYY-3: Efficient zinc and silica solubilizing isolates.

2.1. *Yield and yield attributes*

2.1.1. *Plant height (cm)*

The plant height was recorded by measuring the total height from the base of the plant to the tip of the top most panicle at the time of harvest and was expressed in cm.

2.1.2. Panicle length (cm)

The panicle length was recorded by measuring the height from the base of the panicle to the tip of the panicle at the time of harvest and was expressed in cm.

2.1.3. Total number of tillers (m^2)

Total number of tillers were counted for the m^2 area of the field plots as well as total number of tillers per hill of the pot at the time of maturity and expressed as total number of tillers m^{-2}.

2.1.4. Number of grains panicle^{-1}

Total number of grains panicle^{-1} were manually counted infive randomly selected panicles and average number of grains panicle^{-1} was worked out at the time of maturity and expressed as total number of grains panicle^{-1}.

2.1.5. Test weight (g)

1000 grains were counted from each experimental plot, weighed on electronic weighing balance and expressed in g.

2.1.6. Paddy yield (kg ha^{-1})

The harvested plants from the field were threshed manually and each plot yield was separately sun dried, cleaned by winnowing and weighed. Grain yield was computed at 14 percent moisture content and expressed in kg ha^{-1}.

2.2. Statistical Analysis

The data obtained in different experiments were statistically analysed using Completely Randomized Design (CRD) as per the procedures of Snedecor and Cochron (1967). Data on different characters viz., growth, yield and yield components were subjected to analysis of variance procedures as outlined for CRD. Statistical significance was tested by F-value at 5% level of probability and the critical difference was worked out where ever the effects were significant. The data were analysed statistically following analysis of variance (ANOVA) technique suggested (Panse and Sukhatme, 1985) for randomized block design. The statistical hypothesis of equalities of treatment means was tested by the F-test in ANOVA at p=0.05 level of significance. The critical difference was correlated at p=0.05 level of significance to compare different treatment means.

2.3. *Estimation of zinc content in plant and grain at different crop intervals*

Atomic Absorption Spectrophotometer (AAS) was employed to determine Zn content (Lindsay et al., 1978). 1 g of cleaned sample of whole plant or grain was placed in a 100 volumetric flask, added 10 ml di-acid mixture (Prepared by mixing Nitric acid and per chloric acid at 9:4 ratio in 500 ml volumetric flask) and then placed on hot plate. The flask was heated at higher temperature until the production of red NO_2 fumes ceased. The content was further evaporated until the volume was reduced to 2–3 ml but not to dryness. After cooling the flask, the colourless liquid was transferred to 100 ml volumetric flask by repeated washing and finally volume was made up to 100 ml. Finally, the AAS (PerkinElmer, Model- Analyst 200AA) was calibrated by standard solution (1000 ppm Zn standard solution available commercially) of different concentration and reading of the unknown solution was recorded as given below.

Reading of unknown solution=X
Dilution factor=2
Concentration in plant and grain=X×2 ppm

2.4. Estimation of Silica content in plant and grain at different crop intervals

The powdered grains (dehusked) or straw or husk or any other plant samples were dried in an oven at 70°C for 2–3 h prior to analysis. The sample (0.1 g) was then pre-digested in mixture of 3 ml 50% NaOH in test tube, then autoclaved at 121°C for 20 min., transferred to volumetric flask and adjusted to 50 ml with double distilled water. To 1 ml sample solution 30 ml of 20% acetic acid and 10 ml ammonium molybdate solution were added. Immediately after 5 min, 5 ml of 20% tartaric acid and 1 ml of reducing solution were added and the volume was adjusted to 50 ml with 20% acetic acid, 30 min., later the absorbance was measured at 650 nm in a spectrophotometer using sodium meta silicate as standard as per the procedure outlined by Dai et al. (2005).

Reading of unknown solution=X
Dilution factor=2
Concentration in plant and grain=X×2 ppm

2.5. Estimation of soil enzymes

2.5.1. Urease activity

Urease activity in soil was assayed by quantifying the ratio of release of NH_4^+ from the hydrolysis of urea (Tabatabai et al., 1969). Five g of soil was taken in a 50 ml volumetric flask; after adding 0.2 ml of toluene and 9 ml THAM buffer, the flask was swirled for a few seconds to mix the contents and 1 ml of 0.2M urea solution was added and swirled the flask again for a few seconds. After 2 h of incubation at 37°C, approximately 35 ml of KCl-Ag_2SO_4solution was added, swirled the flask for a few seconds, and allowed to stand until the contents have cooled to room temperature (about 5 min). The contents were made to 50 ml by addition of KCl-Ag_2SO_4 solution, the flask was stoppered and inverted several times to mix the contents. NH^+_4- N was determined in the resulting soil suspension, by pipetting out 20 ml aliquot of the suspension distilling with 0.2 g of MgO for 4 min. Controls were performed similarly, but for the addition of 1ml of 0.2M urea solution after the addition of KCl-Ag_2SO_4 solution.

2.5.2. Dehydrogenase enzyme activity

To the soil samples (1 g) in screw capped glass tubes, 0.2 ml of 3% aqueous solution of 2,3,5-Triphenyl tetrazolium chloride (TTC) and 0.5 ml of 1% of glucose solution were added. Mixed contents were incubated at 28+0.5°C for 24 h in BOD incubator. 10 ml of methanol was added, shaken for 1 min. and then the suspension was filtered through a glass funnel plugged with absorbent cotton into 100 ml volumetric flask. The screw capped glass tubes were repeatedly washed with methanol and the soil was quantitatively transferred to the funnel. Additional methanol was added to the funnel until reddish colour disappeared from the cotton plug. The filtrate was diluted to 100 ml volume with methanol and the intensity of reddish colour was measured at 485 nm using a spectrophotometer (Casida et al., 1964).The amount of Triphenylformazan (TPF) produced was calculated by reference to a calibration graph prepared from Triphenylformazan standards. The standards curves were run parallel with each set of dehydrogenase determination.The enzyme activities were calculated from the Triphenylformazan produced and expressed in µg of TPF produced gram^{-1} of soil day^{-1}.

2.5.3. Phosphatases activity

The procedures of Tabatabai et al. (1969) for Acid phosphatases and Eivazi and Tabatabai (1977) for Alkaline phosphatases were adopted. To one gram of soil sample in glass tube, 0.2 ml of toluene was added followed by 4 ml of MUB buffer pH 6.5 (for acid phosphatase), 4ml MUB buffer pH 11.0 (for alkaline phosphatase) and 1 ml of p- nitro phenyl phosphate (only for samples) was added. Glass tubes were swirled for few seconds, stoppered and incubated for 1 h at 37°C. After incubation, 1 ml of 0.5M $CaCl_2 2H_2O$ and 4 ml of 0.5M NaOH were added, swirled and filtered. The intensity of yellow colour was measured with spectrophotometer at 420 nm. Controls were run simultaneously following the same procedure except adding 1ml of p-nitro phenyl phosphate solution.

3. RESULTS AND DISCUSSION

3.1. Influence of zinc and silica solubilizing bacterial isolates and their consortia on direct sown rice crop growth and yield attributes under field conditions

3.1.1. Plant height (cm)

Zinc and silica solubilizing bacterial isolates and their consortia showed drastic impact on the plant height under field conditions (Table 1). At 45 DAS, T_{13} (RDF+ZnKJJ-4 and ZnPGG-1+SiKPP-1 and SiPYY-3) resulted in highest plant height (38.4 cm), followed by T_{12} (RDF+ZnPGG-1+SiPYY-3) i.e., 36.9 cm and T_1 (Control) registered the lowest plant height (28.4 cm). At 90 DAS, significantly highest plant height (77.1 cm) was observed in T_{13} and the lowest plant height was recorded in T_1 (57.4 cm). At 120 DAS, T_{13} (96.6 cm) recorded significantly highest plant height. The least plant height (73.8 cm) was recorded in T_1 (Control).

The combined inoculation of MZSB 6+MZSB 8+75% RDF showed maximum plant height of 31.2 cm in rice (Manasa et al., 2019). Similar results were observed by Adhikari et al. (2020) where *Enterobacter ludwigii* GAK2 enhanced plant growth promoting characteristics including fresh shoot and root weight, plant height, and chlorophyll content in rice. It also mitigated heavy metal toxicity in rice crop.

3.1.2. Total no. of tillers (m^2)

Under experimental field conditions total number of tillers (m^2) was affected by the zinc and silica solubilizing bacterial isolates and their consortia. At the time of harvest T_{13} (RDF+ZnKJJ-4 and ZnPGG-1+SiKPP-1 and SiPYY-3) had significantly highest (496) total number of tillers (m^2) superior to T_{12} (RDF+ZnPGG-1+SiPYY-3) i.e., 461. T_1 (Control) registered the lowest (302) total number of tillers (m^2) (Table 1).

The combined inoculation of MZSB 6+MZSB 8+75% RDF showed maximum number of tillers per hill (Manasa et al., 2019). Similar findings were observed by Qurban et al. (2020) where the highest number of tillers plant^{-1} (16), plant height (90.33 cm) and leaf chlorophyll content (38.05) were determined in the GML plus zinc bio-fertilizer, followed by RHB plus bio-fertilizer treatment.

3.1.3. Panicle length (cm)

Panicle length was influenced by the availability of zinc and silica nutrients to plants along with recommended dose of fertilizers. At the time of harvest panicle length was recorded highest in T_{13} (RDF+ZnKJJ-4 and ZnPGG-1+SiKPP-1 and SiPYY-3) i.e., (18.2 cm) and found superior to all the treatments. T_1 (Control) reported the lowest plant height (13.3 cm) (Table 1).

The above results were in accordance with (Qurban et al., 2020) who observed that combination of rice straw compost, calcium silicate along with silica solubilizing bacteria gave the highest panicle length (20.57 cm) and 1000-grains weight (18.56 g) in rice. Utilization of a combination including rice husk, silica gel, and *Bacillus mucilaginosus* as a source of biological silicon fertilizer resulted in a considerable improvement in yield attributes viz., panicle length, 1000-grains weight, percentage of filled grains, and number of panicles m^{-2} of Egyptian Japonica green super rice (Elekhtyar and AL-Huqail, 2023).

3.1.4. Number of grains panicle^{-1}

Zinc and silica solubilizing bacterial isolates and their consortia influenced the number of grains panicle^{-1} among the treatments (Table 1). After harvest significantly highest

Table 1: Influence of zinc and silica solubilizing bacterial isolates and their consortia on direct sown rice growth and yield attributes under field conditions

Treatments	Plant height (cm)			Total No. of tillers (m^2)	Panicle length (cm)	No. of grains panicle^{-1}	No. of filled grains panicle^{-1}	1000 grain weight (g)	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})
	45 DAS	90 DAS	120 DAS							
T_1	28.4	57.4	73.8	302	13.3	106	88	14.2	3361	4782
T_2	28.8	58.1	75.0	313	14.1	108	91	14.5	3623	4861
T_3	29.6	59.4	79.5	317	14.5	112	96	14.6	3721	4970
T_4	31.0	60.9	81.2	325	14.6	114	99	14.8	3719	5085
T_5	31.4	60.6	81.6	333	15.1	117	101	14.7	3923	5623
T_6	31.7	63.6	84.3	342	15.2	118	101	14.9	4303	6045
T_7	32.1	66.7	84.4	373	15.5	120	101	15.7	4537	6056
T_8	32.7	66.9	85.9	391	15.7	125	107	15.8	4601	6378
T_9	33.9	68.8	89.8	420	15.8	128	112	16.7	4761	6411
T_{10}	34.2	69.8	91.4	441	16.1	132	116	16.9	4787	6585
T_{11}	35.3	73.7	92.0	448	16.4	138	122	17.0	5014	6728
T_{12}	36.9	75.0	93.8	461	16.5	143	127	17.8	5213	6706
T_{13}	38.4	77.1	96.6	496	18.2	157	140	19.2	5523	6893
SEm±	0.826	1.381	1.709	6.286	0.779	0.825	1.038	0.768	100.6	48.32
CD ($p \leq 0.05$)	2.426	4.053	5.017	18.458	2.289	2.423	3.047	2.254	298.8	145.3
CV (%)	4.381	3.621	3.468	2.850	8.714	1.144	1.664	8.313	14.08	9.876

T_1: RDF (Control); T_2: RDF+$ZnSO_4$; T_3: RDF+Calcium silicate; T_4: RDF+$ZnSO_4$+Calcium silicate; T_5: RDF+ZnKJJ-4; T_6: RDF+ZnPGG-1; T_7: RDF+SiKPP-1; T_8: RDF+SiPYY-3; T_9: RDF+ZnKJJ-4 and ZnPGG-1; T_{10}: RDF+SiKPP-1 and SiPYY-3 T11: RDF + ZnKJJ-4 + SiKPP-1; T12: RDF + ZnPGG-1+SiPYY-3; T_{13}: RDF+ZnKJJ-4 and ZnPGG-1+ SiKPP-1 and SiPYY-3

(157) number of grains panicle^{-1}was recorded in T_{13} (RDF+ZnKJJ-4 and ZnPGG-1+SiKPP-1 and SiPYY-3); T_{12} (RDF+ZnPGG-1+SiPYY-3) recorded 143 and T_1 (Control) reported the least (106) number of grains panicle^{-1}.

Similar results were recorded by (Vaid et al., 2014) where three zinc bacterial strains namely; BC, AX and AB, used individually or in combination, were found effective in significantly increasing thenumber of grains panicle^{-1} (12.8%) and grain yield (17.0%) over the control. The maximum number of grains per panicle was observed in rice which received the treatment combination of MZSB 6 and MZSB 8 along with 75% RDF (Manasa et al., 2019).

3.1.5. Number of filled grains panicle^{-1}

Number of filled grains panicle^{-1} was influenced by the zinc and silica solubilizing bacterial isolates and their consortia. Data on the number of filled grains panicle^{-1} attained at harvest were given in Table 1. Considerable variation in the results among the treatments was noticed. Total number of filled grains panicle^{-1}was significantly highest in T_{13} (RDF+ZnKJJ-4 and ZnPGG-1+SiKPP-1 and SiPYY-3) i.e., 140; T_{12} (RDF+ZnPGG-1+SiPYY-3) and T_{11} (RDF+ZnKJJ-4+SiKPP-1) recorded i.e., 127 and 122 respectively. T_1 (Control) recorded the least number of grains panicle^{-1} (88). By the inoculation of zinc and silica solubilizing bacterial isolates and their consortia number of filled grains panicle^{-1} was affected due to efficient availability of the zinc and silica nutrients to the plants.

The above findings were in accordance with (Muralidharan and Gandhi, 2017) who observed the highest (103) number of filled grains panicle^{-1} in AGM3 and AGM9 combined treatment as against control (99). Srithaworn et al. (2023) observed that Inoculation of soil with *Priestia megaterium* KAH109 and *P. aryabhattai* KEX505 considerably increased plant dry weight by 26.96% and 8.79%, respectively, and the number of grains plant^{-1} by 48.97% and 35.29% in soybean when compared to those of the uninoculated control.

3.1.6. 1000 grain weight (g)

1000 grain weight (g) was influenced by the zinc and silica solubilizing bacterial isolates and their consortia (Table 1). The variations among treatments were found significant. 1000 grain weight (g) of grains among treatments ranged from 14.2-19.6 g. Significantly highest 1000 grain test weight (g) was observed in T_{13} (RDF+ZnKJJ-4 and ZnPGG-1+SiKPP-1 and SiPYY-3) i.e., 19.6 g where as T_{12} (RDF+ZnPGG-1+SiPYY-3) recorded 17.8 g. comparatively lowest test weight of the grain was found in T_1 (Control) i.e., 14.2 g.

Rice husk biochar at 4 t ha^{-1} recorded significantly higher plant height (106.05±1.23 cm) and the number of tillers $hill^{-1}$ in aerobic rice whereas number of panicles $hill^{-1}$, Panicle length, test weight, straw, grain and total biomass yield was recorded in treatment receiving SA at 4 ml l^{-1} (Anjum et al., 2022). Field application of calcium silicate at 400 kg ha^{-1}+silicate solubilizing bacteria at 5 kg ha^{-1} in addition to soil test based N, P_2O_5 , K_2O, enhanced the growth and yield attributes of maize hybrid Co 6 (Prabha et al., 2022).

3.1.7. Grain yield (t ha^{-1})

At harvest grain yield (t ha^{-1}) was influenced by zinc and silica solubilizing bacterial isolates and their consortia in all the treatments (Table 1). Grain yield (t ha^{-1}) was significantly highest in T_{13} (RDF+ZnKJJ-4 and ZnPGG-1+SiKPP-1 and SiPYY-3) i.e., 5523 t ha^{-1} followed by T_{12} (RDF+ZnPGG-1+SiPYY-3) i.e., 5213 t ha^{-1} and $T_{11:}$ RDF+ZnKJJ-4+SiKPP-1 i.e., 5014 t ha^{-1}. Comparatively lowest grain yield was found in T_1 (Control) i.e., 3361 t ha^{-1}.

Tariq et al. (2007) observed the activity of plant growth promoting rhizobacteria (PGPR) to mobilize indigenous soil zinc (Zn) in rice (*Oryza sativa* L.) rhizosphere in a net house micro plot experiment and compared with available form of chemical Zn source as Zn–EDTA. The PGPR application alleviated the deficiency symptoms of Zn and invariably increased the total biomass (23%), grain yield (65%) and harvest index as well as Zn concentration in the grain. Manasa et al. (2019) reported the maximum grain yield of 5245 kg ha^{-1} with dual application of MZSB6 and MZSB8 along with 75% RDF. PGPR consortium of T_{19}, T_{29}, and S_7 consistently and significantly outperformed individual isolates by increasing wheat yields even with reduced fertilizer rates (Breedt et al., 2025). Yield parameters and yield were higher with application 100% RDF+FYM enriched with microbial consortia at 1 t ha^{-1} compared to other INM practices in pigeonpea (Kumar et al., 2022). Application of silica gel as a chemical Si fertilizer, rice husk as an organic Si fertilizer, and *Bacillus mucilaginosus* as a Si-solubilizing bacteria or biological Si fertilizer source resulted in significantly higher yields of grain in Egyptian Japonica green super rice (Elekhtyar, and AL-Huqail, 2023).

3.1.8. Straw yield (t. ha^{-1})

Zinc and silica solubilizing bacterial isolates and their consortia were strongly affected the straw yield (t ha^{-1}) in all the treatments (Table 1). After the harvest of the crop, straw yield (t ha^{-1}) significantly highest was observed in T_{13} (RDF+ZnKJJ-4 and ZnPGG-1+SiKPP-1 and SiPYY-3) i.e., 6893 t ha^{-1} followed by T_{11} (RDF+ZnKJJ-4+SiKPP-1) and T_{12} (RDF+ZnPGG-1+SiPYY-3) i.e., 6728 and 6706 t ha^{-1} which were statistically on par. Comparatively lowest straw yield was found in T_1 (Control) i.e., 4782 t ha^{-1}.

Similar results were observed by Singh et al. (2007) where combination of rice straw compost, calcium silicate along with silica solubilizing bacteria gave the highest grain yield (6.4 t ha^{-1}) and straw yield (10.0 t ha^{-1}) over the control. Application of silica gel as a chemical Si fertilizer, rice husk as an organic Si fertilizer, and *Bacillus mucilaginosus* as a Si-solubilizing bacteria or biological Si fertilizer source significantly increased straw yields in Egyptian Japonica green super rice (Elekhtyar, and AL-Huqail, 2023).

3.2. Zinc content in plant

Zinc content in the shoot of the plant was influenced by the zinc and silica solubilizing bacterial isolates and their consortia due the availability of the efficient zinc nutrient in inoculated treatments. At 45 DAS the highest zinc content was attained in T_{13}, RDF+ZnKJJ-4 and ZnPGG-1+SiKPP-1 and SiPYY- 3 (0.79 ppm) followed by T_{12} (RDF+ZnPGG-1+SiPYY-3) i.e., 0.68 ppm. All the treatments at 90 DAS showed increased zinc content over 45 DAS. At 90 DAS highest zinc content was observed in T_{13} (0.96 ppm) followed by T_{12} (0.86 ppm), T_{11} (0.85 ppm) and T_{10} (0.83 ppm). At 120 DAS zinc content was decreased over 90 DAS and the highest zinc content was noticed in T_{13} (0.81 ppm) followed by T_{12} (0.77 ppm) (Table 2).

Similar results were observed by Kamran et al. (2017) where highest zinc content was found in the shoots of *Enterobacter cloacae* (PBS 2) treated plants and in the roots of *Pantoea agglomerans* (EPS 13) treated wheat plants. Application of ZnO with *Gluconacetobacter diazotrophicus* showed better uptake of the zinc in maize (Sarathambal et. al., 2010). Krithika and Balachandar, 2016) demonstrated that ZSB inoculation as PGPR could regulate the zinc uptake and translocation in rice plant and thereby zinc fortification in rice grains. The highest solubilization of zinc oxide was demonstrated by strain PUCM1005 (SE: 918), followed by PUCM1005 (SE: 344) and PUCM1009 (SE: 333) in *Pennisetum glaucum* (Rokhbakhsh-Zamin et al., 2011). Total zinc content per plant at different growth stages increased with increasing zinc supply in rice genotypes (Impa et al., 2013). Highest zinc content in rice plant was reported with application of dual bacterial culture of MZSB 6, MZSB 8 along with the 75% of RDF (Manasa et al., 2019).

3.3. Silica content in plant

Zinc and silica solubilizing bacteria isolated and their consortia influenced the availability of the silica in soil that resulted in the plant. At 45 DAS, the highest silica content in the shoot of the plant was recorded in T_{13}, RDF+ZnKJJ-4

Table 2: Influence of zinc and silica solubilizing bacterial isolates and their consortia on zinc and silica content (ppm) in plant of direct sown rice under field condition

Treatments	Zinc content (ppm)			Silica content (ppm)		
	45 DAS	90 DAS	120 DAS	45 DAS	90 DAS	120 DAS
T_1	0.30	0.50	0.41	0.74	0.91	0.83
T_2	0.32	0.52	0.43	0.76	0.96	0.85
T_3	0.38	0.54	0.46	0.80	0.98	0.88
T_4	0.40	0.61	0.52	0.78	0.97	0.86
T_5	0.41	0.63	0.55	0.82	0.99	0.91
T_6	0.43	0.64	0.56	0.83	1.00	0.92
T_7	0.45	0.66	0.58	0.85	1.02	0.94
T_8	0.51	0.72	0.64	0.84	1.01	0.95
T_9	0.53	0.75	0.66	0.86	1.03	0.96
T_{10}	0.60	0.83	0.72	0.87	1.05	0.97
T_{11}	0.62	0.85	0.75	0.87	1.04	0.97
T_{12}	0.68	0.86	0.77	0.88	1.06	0.98
T_{13}	0.79	0.96	0.81	0.89	1.08	0.99
SEm±	0.005	0.007	0.004	0.005	0.009	0.008
CD ($p\leq$ 0.05)	0.016	0.019	0.013	0.017	0.028	0.024
CV (%)	2.451	1.615	1.265	1.354	2.264	1.164

and ZnPGG-1+SiKPP-1 and SiPYY-3 (0.89 ppm), followed by T_{12} (RDF+ZnPGG-1+SiPYY-3) i.e., 0.88 ppm. All the treatments at 90 DAS showed increased silica content compared with 45 DAS and silica content recorded was highest in T_{13} (1.08 ppm) followed by T_{12} (1.06 ppm). From 90 to 120 DAS silica content wasdecreased drastically. At 120 DAS silica content was highest in T_{13} (0.99 ppm), followed by T_{12} (0.98 ppm) and lowest was observed in T_1 (0.83 ppm) (Table 2).

Highest silica content in T_{13} was possible due to supply of sufficient amount of silica to the plant by two silica solubilizing bacterial isolates applied along with zinc isolates. Similar results were recorded by (Lee et al., 2019) where silica solubilizing bacterial isolate, *Enterobacter ludwigii* GAK2 along with insoluble silica sources showed the maximum silica content (232.14 mg ka^{-1}) in plant than in control at vegetative stage of the rice crop. During the degradation of silicate by bacteria, the release of Si was reported (Hutchens et al., 2003).

Desplanques et al. (2006) reported that the accumulation of Si in rice is directly linked with the yield increment in the rice. The absorbing ability of plants for Si varies significantly, and was even different in genotypes of the same species and sometimes varied in tissues (Deshmukh and Bélanger, 2016). Silicate-solubilizing bacterial strain, *Burkholderia eburnean* CS4-2 promoted the growth of japonica rice (*Oryza sativa* L. cv. Dongjin) (Kang et al., 2017). Si content and uptake by rice plant as influenced by different sources of Si was reported by Anjum et al., 2022. The silicon content of plant was significantly and positively correlated with all growth parameters of maize while testing the silicon solubilising bacteria in maize by Prabha et al. (2022). Mixed bacterial inoculum of *Rhizobium* sp. IIRRN1, a silicate solublizer and *Gluconacetobacter diazotrophicus*, a plant growth promoting bacteria along with insoluble silicates like diatomaceous earth and rice straw when used in combination as a organo-mineral biofertilizer, increased silicon content in rice tissue, root and shoot biomass and also significantly increased the antioxidant enzyme activities (viz., superoxidase dismutase, catalase and ascorbate peroxidase) compared to other treatments with sole application of either silicon or bacteria (Chaganti et al., 2023). Phosphorus, potassium, and silicon-solubilizing bacteria from forest soils increased P, K, and Si cumulative contents in roots and shoots and promoted the growth of rice (Zhang et al., 2024).

3.4. Influence of zinc and silica solubilizing bacterial isolates and their consortia on zinc and silica content in grain

3.4.1. Zinc content in grain

Zinc content in grain was influenced by the zinc and silica solubilizing bacterial isolates and their consortia due to the enormous availability of the zinc and other nutrients during the crop growth period. Zinc content in grain was highest in T_{13}, RDF+ZnKJJ-4 and ZnPGG-1+SiKPP-1 and SiPYY-3 (0.58 ppm) followed by T_{12} (RDF+ZnPGG-1+SiPYY-3) *i.e.,* 0.56 ppm. Lowest zinc content in grain was noted in T_1 (control) i.e., 0.41 ppm (Figure 1).

Available zinc was more in T_{13} treatment in the soil showing zinc solubilizing bacteria helped accumulation of more zinc content in grain compared to the control. Irum et al. (2016) found that in wheat grain, the highest zinc (32.33 mg kg^{-1}) concentration was recorded with consortium of zinc solubilizing bacteria i.e., *Rhizobium, Pseudomonas* and *Azospirillum* treated plots.

3.4.2. Silica content in grain

Zinc and silica solubilizing bacterial isolates and their consortia influenced the silica content in grain by the action of accumulation silica in plant as well as grain. Silica content in grain was highest in T_{13}, RDF+ZSB 1 and 2+SSB 1 and 2 (0.98 ppm), followed by T_{11} (RDF+ZSB 1+SSB 1) i.e., 0.97 ppm. Lowest silica content in grain was recorded in T_1 (control) i.e., 0.84 ppm (Figure. 1).

Highest silica content in grain of T_{13} treatment might be due to efficient utilization of natural silica minerals by

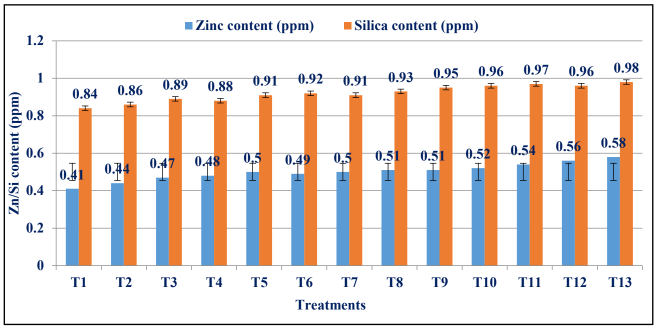

Figure 1: Influence of zinc and silica solubilizing bacterial isolates and their consortia on zinc and silica content (ppm) in grain under field conditions; T_1: RDF (Control); T_2: RDF+$ZnSO_4$; T_3: RDF+Calcium silicate; T_4: RDF+$ZnSO_4$+Calcium silicate; T_5: RDF+ZnKJJ-4; T_6: RDF+ZnPGG-1; T_7: RDF+SiKPP-1; T_8: RDF+SiPYY-3; T_9: RDF+ZnKJJ-4 and ZnPGG-1; T_{10}: RDF+SiKPP-1 and SiPYY-3 T11: RDF + ZnKJJ-4 + SiKPP-1; T12: RDF + ZnPGG-1+SiPYY-3; T_{13}: RDF+ZnKJJ-4 and ZnPGG-1+ SiKPP-1 and SiPYY-3

silica solubilizing bacteria supplying silica to the plants. These results were in accordance with (Peera et al., 2016b) who observed the highest zinc content (1.46 ppm) in rice treated with silica solubilizing bacteria+farm yard manure+recommended dose of fertilizer.

3.5. Effect of zinc and silica solubilizing bacterial isolates and their consortia on soil enzymatic activities

3.5.1. Dehydrogenase enzyme activity in soil

Dehydrogenase enzyme activity was 200.6 μg TPF g^{-1} soil day^{-1}in the initial soil. Soil health was influenced by several enzymatic activities. Dehydrogenase enzyme has significant role in maintaining soil health. Increase in dehydrogenase enzyme activity was observed in all the treatments at 45 DAS. Significantly highest dehydrogenase enzyme activity was recorded in T_{13}, RDF+ZnKJJ-4 and ZnPGG-1+SiKPP-1 and SiPYY-3 (390.4 μg TPF g^{-1} soil day^{-1}), followed by T_{12} (RDF+ZnPGG-1+SiPYY-3) i.e., 381.9 μg TPF g^{-1} soil day^{-1}. From 45 DAS to 90 DAS all the treatments showed increased dehydrogenase enzyme activity. At 90 DAS significantly highest dehydrogenase enzyme activity was recorded in T_{13} (583.6 μg TPF g^{-1} soil day^{-1}). At 120 DAS dehydrogenase enzyme activity decreased than 90 DAS but higher than at 45 DAS. At 120 DAS significantly highest (499.6 μg TPF g^{-1} soil day^{-1}) dehydrogenase enzyme activity (Table 3) was recorded in T_{13}, followed by T_{12} (487.6 μg TPF g^{-1} soil day^{-1}). Similar results were obtained by (Kohler et al., 2006) where highest dehydrogenase and phosphatase activity (21–89%) were observed in the soil treated with *Pseudomonas mendocina*.

3.5.2. Acid phosphatase enzyme activity

Acid phosphatase enzyme activity was 25.8 μg pNP g^{-1} soil h^{-1}in the initial. From 45 to 90 DAS all the treatments exhibited increased acid phosphatase enzyme activity compared to initial stage. Soil fertility was maintained by the action of enzymes that helped decompose the organic matter in the soil. At 45 DAS significantly highest acid phosphatase activity (58.15 μg pNP g^{-1} soil h^{-1}) was recorded in T_{13}, RDF+ZnKJJ-4 and ZnPGG-1+SiKPP-1 and SiPYY-3 followed by 53.31 μg pNP g^{-1} soil h^{-1} in T_{12} (RDF+ZnPGG-1+SiPYY-3). Significantly highest acid phosphatase enzyme activity at 90 DAS was attained in T_{13} (90.18 μg pNP g^{-1} soil h^{-1}), as against T_{12} (82.02 μg pNP g^{-1} soil h^{-1}). At 120 DAS acid phosphatase enzyme activity was less in some of the treatments compared to 90 DAS but higher than at 45 DAS. At 120DAS significantly highest acid phosphatase enzyme activity (Table 3) was recorded in T_{13} (68.35 μg pNP g^{-1} soil h^{-1}).

3.5.3. Alkaline phosphatase enzyme activity

Alkaline phosphatase activity was 93.80 μg pNP g^{-1} soil h^{-1} in the initial. Alkaline phosphatase enzyme activity increased from 45 to 90 DAS in all the treatments compared to initial stage. At 45 DAS, highest alkaline phosphatase activity (130.52 μg pNP g^{-1} soil h^{-1}) was observed in T_{13}, RDF+ZnKJJ-4 and ZnPGG-1+SiKPP-1 and SiPYY-3 which significantly differed from T_{12} (RDF+ZnPGG-1+SiPYY-3) i.e., 129.23 μg pNP g^{-1} soil h^{-1}. The highest alkaline phosphatase enzyme activity at 90 DAS was attained in T_{13} (148.69 μg pNP g^{-1} soil h^{-1}) and found superior to T_{12} (147.02 μg pNP g^{-1} soil h^{-1}). At 120 DAS alkaline phosphatase enzyme activity was less in some of the treatments compared to 90 DAS but higher than at 45 DAS. At 120 DAS significantly highest alkaline phosphatase enzyme activity (Table 3) was recorded in T_{13} (136.81 μg pNP g^{-1} soil h^{-1}), followed by T_{12} (135.32 μg pNP g^{-1} soil h^{-1}).

Among all the time intervals, decrease in soil acid and alkaline phosphatase activity was recorded at 120 DAS. This might be due to the reason that the crop attained maturity stage, and so there was no production of root exudates which lead to lowering in activity of acid and alkaline phosphatase. These results were in accordance with (Goyal et al., 1991).

Significant positive correlation was observed between the moisture content of the soil and the enzymatic activities of acid, alkaline phosphatases by (Song et al., 2012). Phosphatase activities were increased to the greatest extent after the application of *P. fluorescens* in the unfertilized soil. Under these conditions applied bacteria increased acid phosphatase (52 %) and alkaline phosphatase (103 %) (Krey et al., 2011).

3.5.4. Urease enzyme activity

Urease enzyme activity was 19.43 μg of NH_{4+}-N g^{-1} soil $(2h)^{-1}$ in the initial soil. Urease was one of the important enzymes that transform the plant nutrient levels in soils. From 45 DAS to 90 DAS all the treatments showed increased urease enzyme activity. At 45 DAS significantly highest urease enzyme activity was recorded in T_{13}, RDF+ZnKJJ-4 and ZnPGG-1+SiKPP-1 and SiPYY-3 (40.04 μg of NH_{4+}-N g^{-1} soil $(2h)^{-1}$) followed by T_{12} RDF+ZnPGG-1+SiPYY-3 (38.46 μg of NH_{4+}-N g^{-1} soil $(2h)^{-1}$). At 90 DAS urease enzyme activity was considerably increased. At 90 DAS the highest urease enzyme activity was recorded in T_{13} (72.72 μg of NH_{4+}-N g^{-1} soil $2h^{-1}$), which significantly differed with T_{12} (68.65 μg of NH_{4+}-N g^{-1} soil $2h^{-1}$). At 120 DAS urease enzyme activity decreased slightly compared to 90 DAS but highest than at 45 DAS. At 120 DAS significantly highest (50.06 μg of NH_{4+}-N g^{-1} soil $2h^{-1}$) urease enzyme activity (Table 3) was recorded in T_{13}, followedby T_{12} (48.14 μg of NH_{4+}-N g^{-1} soil $2h^{-1}$). Urease enzyme activity was often measured as an indicator of the health of microbial communities in the absence of plants. In the present study urease activity was high in T_{13} as ammonium strongly interfered both with the expression of the urea uptake by *Pseudomonas sp.* and its activity.

Similar results were found by (Blonska, 2010) who conducted an experiment to determine the activity of dehydrogenases and urease in forest peat soils of different fertility. The results obtained on urease activity were high in wet soils, and the lowest in raised dry soils. The activity of urease was negatively correlated with the content of carbon, C/N ratio, hydrolytic acidity and moisture resulted in the increase in enzymatic activity accompanied by the increase in pH.

Table 3: Influence of zinc and silica solubilizing bacterial isolates and their consortia on soil enzymes of rice rhizosphere under field conditions

Treatments	Dehydrogenase (μg TPF g^{-1} day^{-1})			Acid phosphatase (μg pNP g^{-1} h^{-1})			Alkaline phosphatase (μg pNP g^{-1} h^{-1})			Urease (μg of NH_4^+-N g^{-1} soil $2h^{-1}$)		
	45 DAS	90 DAS	120 DAS	45 DAS	90 DAS	120 DAS	45 DAS	90 DAS	120 DAS	45 DAS	90 DAS	120 DAS
T_1	227.9	410.3	325.6	33.36	64.15	45.02	105.06	124.60	112.16	24.16	54.35	33.48
T_2	233.2	421.5	336.4	37.06	68.13	49.16	118.16	128.18	124.06	27.85	57.27	37.28
T_3	247.5	430.7	345.2	39.61	70.17	50.16	116.46	130.15	120.16	25.21	56.40	35.69
T_4	258.2	448.5	356.4	40.48	71.11	51.84	115.85	133.81	119.05	26.29	57.90	36.96
T_5	272.3	461.1	378.6	42.02	72.79	53.00	117.64	135.71	123.62	28.14	58.49	38.60
T_6	288.1	476.2	386.1	44.05	73.48	54.53	118.48	136.93	124.46	30.06	60.39	40.26
T_7	297.5	495.8	397.2	45.16	74.36	55.15	119.16	138.47	126.31	31.81	62.38	41.24
T_8	321.7	515.6	426.1	46.19	75.74	56.12	122.62	140.83	128.12	32.61	63.36	42.18
T_9	343.6	532.7	447.8	47.82	76.15	57.05	123.46	141.68	129.05	34.17	64.50	43.21
T_{10}	357.4	547.9	457.2	49.32	78.71	59.32	125.56	143.96	131.31	35.61	65.70	45.34
T_{11}	367.7	552.6	465.1	51.61	80.34	61.53	126.50	144.90	132.05	36.01	67.47	46.61
T_{12}	381.9	573.3	487.6	53.31	82.02	63.15	129.23	147.02	135.32	38.46	68.65	48.14
T_{13}	390.4	583.6	499.6	58.15	90.18	68.35	130.52	148.69	136.81	40.04	72.72	50.06
SEm±	3.445	3.268	2.387	1.361	1.666	1.204	1.296	1.361	1.255	0.582	0.517	1.389
CD ($p\leq 0.05$)	10.114	9.596	7.008	3.996	4.892	3.536	3.806	3.996	3.686	1.709	1.519	4.079
CV (%)	1.945	1.141	1.012	5.210	3.838	3.744	1.861	1.707	1.721	3.193	1.439	5.802

4. CONCLUSION

Zinc and silica solubilizing bacteria and their consortia showed influence on zinc and silica content in plant and grain, soil enzyme activity (dehydrogenase, acid and alkaline phosphatase and urease activity), yield and yield attributes on rice under field conditions at different crop growth stages as compared to the individual microorganisms by having directly effect on the availability of the nutrients besides crop growth, development, yield and yield attributes.

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