Journal of Advances in Biology & Biotechnology

Volume 27, Issue 8, Page 748-757, 2024; Article no.JABB.119784
ISSN: 2394-1081

Impact of Zinc and Silica Solubilizing Bacterial Consortia on Soil Nutrient Availability and Direct Sown Paddy

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/jabb/2024/v27i81193

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/119784

Original Research Article

Received: 21/05/2024
Accepted: 23/07/2024
Published: 31/07/2024

ABSTRACT

Effect of zinc and silica solubilizing bacteria and their consortia on paddy was studied under field conditions at Agricultural Research Station, Janagamaheswarapuram, Andhra Pradesh. Thirteen treatments were assessed for availability of nutrients *viz*., Nitrogen, Phosphorus, Potassium, Zinc and Silica in soil and concentration of Nitrogen, Phosphorus and Potassium in plant at 45, 90 and 120 days after sowing (DAS).Significantly highest nitrogen (198.9, 262.3 and 240.2 kg ha^{-1}), available phosphorus (36.7, 64.7 and 40.6 kg ha^{-1}), potassium (221.4, 349.6 and 263.5 kg ha^{-1}), zinc (0.86, 1.14 and 0.98 ppm) and silica (66.8, 98.9 and 84.8 ppm) were recorded in T_{13} (RDF + ZnKJJ-4 & ZnPGG-1 + SiKPP-1 & SiPYY-3) at 45, 90 and 120DAS, respectively. In the plant,

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***Cite as:** Babu, S. Vinod, A. Vijaya Gopal, N. Trimurtulu, G. Kishore Babu, and S. L. Bhattiprolu. 2024. "Impact of Zinc and Silica Solubilizing Bacterial Consortia on Soil Nutrient Availability and Direct Sown Paddy". Journal of Advances in Biology & Biotechnology 27 (8):748-57. https://doi.org/10.9734/jabb/2024/v27i81193.*

nitrogen (0.89, 1.10 and 0.98 %), phosphorus (0.46, 0.67 and 0.58 %) and potassium (1.87, 2.29 and 1.98 %) were significantly highest at 45, 90 and 120DAS, respectively, in T_{13}. There was increase in the available nutrient content upto90 DAS which then decreased at 120DAS. It is inferred that consortia of two zinc solubilizing and two silica solubilizing microorganisms (T_{13}) is useful for increased availability of Nitrogen, Phosphorus, Potassium, Zinc and Silica in soil and increased uptake of NPK by rice plant, which in turn reduce exogenous chemical fertilizers.

Keywords: Paddy; zinc solubilizing bacteria; silica solubilizing bacteria; Zinc; silica bacterial consortia; nutrients.

1. INTRODUCTION

India is one of the leading producers of rice crop. Rice is the basic food crop and being a tropical plant, it flourishes comfortably in a hot and humid climate. Rice is mainly grown in rain-fed areas that receive heavy annual rainfall. That is why it is fundamentally a *kharif* crop in India. Plants need several macro and micro nutrients for their growth and development. Nitrogen, phosphorus and potassium (NPK) are the primary nutrients in commercial fertilizers. Each of these fundamental nutrients plays a key role in plant nutrition. Nitrogen is considered to be the most important nutrient, and plants absorb more nitrogen than any other element. Nitrogen is essential in making plants healthy as they develop and nutritious to eat after they're harvested. Phosphorus, is linked to a plant's ability to use and store energy, including the process of photosynthesis. It's also needed to help plants grow and develop normally. Potassium is the third key nutrient of commercial fertilizers. It helps strengthen plants' abilities to resist disease and plays an important role in increasing crop yields and overall quality. In rice zinc (Zn) is one of the most important micronutrients necessary for the normal healthy growth and reproduction of plants. Silica is useful for proper cuticle development and grain formation in rice [1]. Zinc Solubilizing Bacteria (ZnSB) and Silica Solubilizing Bacteria (SiSB) and their consortia improved the bioavailable fraction of N, P, K, Zn and Si to host plant for enlightening the crop growth, yield and quality [2]. It will directly effect on the crop nutrient content and yield parameters. Inoculation of rice with silica solubilizing bacteria enhanced available silica in soil and silica content in plant and improved rice yield. Dissolution of silicate results in rendering phosphorus available for plant absorption as silica competes with phosphorus fixation sites; silica acts like auxiliary for phosphorus in plants [3].The development and efficiency of commercial microbial inoculants such as AMF, biofertilizers, and microbe-based decomposers offer farmers the potential to reduce synthetic farm inputs (fertilizers and pesticides) and stimulate the opportunity of integrated nutrient and pest management practices for sustainable agriculture [4]. Hence, an experiment was conducted to study the availability of nutrients in soil and uptake by rice plants by inoculating selected zinc and silica solubilizing isolates and their combinations under field conditions.

2. MATERIALS AND METHODS

Paddy variety, MTU-7029 (Swarna) was sown in black soil by adopting 20cm X 10 cm spacing at ARS, Jangamaheswarapuram. 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. Along NPK extra 25 kg ha^{-1} zinc sulphate, 120-200 kg ha^{-1} calcium silicate was applied in the zinc and silica nutrient imposed treatments *i.e.,* T_3 and T_4.

Thirteen treatments, replicated thrice, were imposed incompletely randomized design as detailed below.

Treatment details:

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 (Zinc isolate from Kurnool Dist., Jupadu bunglow Mandal and Jupadu bunglow village soil sample - 4)

T_6: RDF + ZnPGG-1(Zinc isolate from Prakasham Dist., Giddaluru Mandal and Giddaluru Village soil sample - 1)

T_7: RDF + SiKPP-1(Silica isolate from Kurnool Dist., Pamulapadu Mandal and Pamulapadu Village soil sample - 1)

T_8: RDF + SiPYY-3 (Silica isolate from Prakasham Dist., Yerragondapalem Mandal and Yerragondapalem Village - 3)
T_9: RDF + ZnKJJ-4 &ZnPGG-1
T_{10}: RDF + SiKPP-1 &SiPYY-3
T_{11}: RDF + ZnKJJ-4+ SiKPP-1
T_{12}: RDF + ZnPGG-1+ SiPYY-3
T_{13}: RDF + ZnKJJ-4 &ZnPGG-1 + SiKPP-1 &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 Estimation of Nutrient (N, P, K, Zn and Si) Content in Soil Samples

2.1.1 Soil sample collection and processing

Soil samples collected at 45, 90 and 120 DAS, from all the 13 treatments were dried under shade, gently ground with wooden hammer, sieved through 2 mm sieve and stored in labelled new polythene lined cloth bags for analysis.

2.1.2 Available nutrients (nitrogen, phosphorus, potassium, zinc and silica) in soil

Processed soil samples were used for analysing available nutrients (Nitrogen, phosphorus, potassium, zinc and silica) in soil and nutrient (N, P and K) content in plant samples by adopting standard procedures (Table 1). Concentration of macronutrients was expressed as % and micro nutrients in ppm.

2.2 Estimation of Nutrient (N, P and K) Content in Plant Samples

2.2.1 Collection, preparation and analysis of plant samples

The plant samples were collected at 45 DAS, 90 DAS and 120 DAS, washed thoroughly with distilled water and dried under shade. Then, they were dried in hot air oven at 65˚C till a constant weight was obtained. Dried plant samples were ground in a wooden pestle and mortar and stored in polythene bags for further chemical analysis. N, P, K, Zn and Si contents were estimated by following standard methods.

2.2.2 Digestion of plant sample

Powdered whole plant samples were separately treated with concentrated HNO_3 overnight for pre digestion. Then, the pre-digested samples were treated with diacid mixture [HNO_3:$HClO_4$ (9:4 ratio)] and digested on sand bath at low temperature till colourless white precipitate was obtained. The residue was dissolved in 6N HCl, filtered, made to known volume by using 6N HCl. This was used for further nutrient analysis (Table 1).

Content of N, P and K were calculated as given below.

$$\% \text{ N in plant sample} = \frac{\text{T.Vx } 0.00028 \text{ x } 100}{0.1}$$

$$= 0.28 \text{ x T.V wherein}$$

Weight of sample = 0.1g
Normality of H_2SO_4 = 0.02

Titration value (TV) = Sample titration value – Blank titration value

Final volume (50 ml) ×100×100

$$\%\, P \ in\ plant\ sample\ =$$

$$sample\ conc.in\ ppm\ \times \frac{Final\ volume\ (50\ ml)\ \times 100 \times 100}{Wt\ of\ sample\ (1g) \times aliquot\ (5ml)\ \times\ 10^6}$$

$$\%\, K\ in\ plant\ sample\ = \frac{100 \times 100}{Wt.of\ sample\ (1g) \times 10^6}$$

$$= R \times 0.01$$

Where R = concentration of K in ppm obtained from standard curve

Table 1. Methodology adopted for estimation of available nutrients and content of N, P and K in plant

Nutrient	Method Adopted	Reference
Available N in soil	Alkaline permanganate method	[5]
Available P in soil	Olsen’s method	[6]
Available K in soil	Neutral 1 N Ammonium acetate method	[7]
Available Zn in soil	DTPA extraction method followed by determination AAS/ICP	[8]
Available Si in soil	acetic acid extractant method	[9]
N content in plant	Kelplus method	[10]
P content in plant	Vanadomolybdo-phosphoric acid yellow colour method	[11]
K content in plant	Neutral 1 N Ammonium acetate method	[7]

3. RESULTS AND DISCUSSION

Rhizosphere management, through use of beneficial microbes helps to enhance nutrient availability in soil for the better plant growth via solubilization of zinc, potassium and phosphate, nitrogen fixation and phytohormones production [12]. The results of application of selected zinc and silica solubilizing isolates and their combinations on the direct sown paddy crop are reported as detailed below.

3.1 Influence of Zinc and Silica Solubilizing Bacterial Consortia on Available Nutrients in the Soil

3.1.1 Available nitrogen in soil

Available nitrogen content was 142.03 kg ha^{-1} (Table 2) in the initial soil sample. At 45 DAS all the treatments showed increased available nitrogen content compared to initial stage (Table 3). Highest available nitrogen was recorded in T_{13}, RDF + ZnKJJ-4 & ZnPGG-1 + SiKPP-1 & SiPYY-3 (198.9 kg ha^{-1}) followed by T_{12} (RDF + ZnPGG-1 + SiPYY-3) *i.e.,* 196.7 kgha^{-1},which were on par. Available nitrogen content further increased with highest recorded in T_{13} (262.7 kg ha^{-1}) at 90DAS, followed by T_{12} (258.7 kg ha^{-1}) and both were on par. At 120 DAS available nitrogen content decreased to 240.2 kg ha^{-1} in T_{13} followed by T_{12} (238.5 kg ha^{-1}) and T_{11} (237.2 kg ha^{-1}) and were superior to other treatments (Table 3).

Similar findings were obtained by [13] where biofertilizers and the recommended dose of fertilizers expanded the soil available nitrogen (63 %). The most effective treatment, was ZSB + PSB + KRB + RDF[14]which reported increased available nitrogen with the applied fertilizers and biofertilizers.

It was reported that application of Si alleviates the nitrogen deficiency in different crops by improving the nitrogen acquisition through root system [15]. Under limited availability of N, application of silicic acid has increased the uptake and accumulation of plant N [16] and [17] in rice [18] and [19].

3.1.2 Available phosphorus in soil

Phosphorus helps a plant convert other nutrients into usable building blocks to grow. Available phosphorus content was initially 26.28 kg ha^{-1} (Table 2). At 45 DAS all the treatments exhibited increased available content of phosphorus than initial (Table 3). The highest phosphorus availability was registered in T_{13}, RDF + ZnKJJ-4 & ZnPGG-1 + SiKPP-1 & SiPYY-3 (36.7 kg ha^{-1}) followed by T_{12} (RDF + ZnPGG-1 + SiPYY-3) *i.e.,* 35.4 kg $ha^{-1}$and were on par. At 90 DAS also increased available phosphorus was observed in T_{13} (64.7 kg ha^{-1}), on par with T_{11} (RDF + ZnKJJ-4 + SiKPP-1) *i.e.,* 62.4 kg $ha^{-1}$and T_{12} (RDF + ZnPGG-1 + SiPYY-3) (59.6 kg ha^{-1}). At 120 DAS available phosphorus content decreased to 40.6 kg ha^{-1} in T_{13} and found superior to T_{12} (38.5 kg ha^{-1}) (Table 3). An increasing trend until 90 DAS followed by decreasing trend by 120 DAS though more than 45 DAS was observed in general for all the available major nutrients.

Present results indicates that available phosphorus content increased slightly and depleted gradually in all the treatments with insufficient dose of phosphatic fertilizers. Inoculated zinc and silica microbial consortium stimulated root length development under reduced phosphorus supply with stabilized ammonium by 52 %. This was accompanied by the increased auxin production capacity of rhizosphere bacteria [20].

3.1.3 Available potassium in soil

Potassium has significant role in the regulation of water in plants (osmoregulation). Potassium influences both uptake of water through plant roots and its loss through the stomata. Available potassium content was 202.14 kg ha^{-1} (Table 2) in the initial soil sample. At 45 DAS all the treatments showed increased potassium compared to initial stage (Table 3). The highest available potassium was recorded in T_{13}, RDF + ZnKJJ-4 & ZnPGG-1 + SiKPP-1 & SiPYY-3 (221.4 kg ha^{-1}) followed by T_{12} (RDF + ZnPGG-1 + SiPYY-3) *i.e.,* 220.9 kg ha^{-1} and T_{11} (220.6 kg ha^{-1}) and were on par. At 90 DAS, all the treatments showed increased potassium availability than 45 DAS; significantly highest available potassium was recorded in T_{13} (349.6 kg ha^{-1}). At 120 DAS amount of available potassium decreased to 263.5 kg ha^{-1}in T_{13} but significantly higher than other treatments (Table 3).

Similar observations was made by earlier works [21] who reported increased chlorophyll content by inoculated bacteria, soluble and rock potassium. Many microorganisms like zinc and silica solubilizers in the soil, apart from zinc and silica, they can solubilize ‘unavailable’ forms of K bearing minerals, such as micas, illite and orthoclases by excreting organic acids which either directly dissolve rock K or chelate silicon ions to bring the K into solution [22]. Silicon (Si) removes K deficiency symptoms during salt stress and promoted the K absorption by roots in many crops including rice [23]

3.1.4 Available zinc in soil

Available zinc content was 0.48 ppm (Table 2) in the initial soil sample. At 45 DAS all the treatments showed increased available zinc content compared to initial. Highest available zinc was recorded in T_{13}, RDF + ZnKJJ-4 & ZnPGG-1 + SiKPP-1 & SiPYY-3 (0.86 ppm), followed by T_{12} (RDF + ZnPGG-1 + SiPYY-3) *i.e.,* 0.83 ppm. Available zinc content further increased in all the treatments at 90DAS. Higher available zinc content was recorded in T_{13} (1.14 ppm) at 90 DAS. At 120 DAS available zinc content was decreased among the treatments over 90 DAS and significantly highest zinc availability was recorded in T_{13} (0.98 ppm), followed by T_{12} (0.96 ppm) (Table 4).

The above results were in agreement with [24] where growth and yield parameters of paddy showed a significant increase in the treatment that received combination of MZSB 6, MZSB 8 and 75% recommended dose of fertilizer (RDF) as compared to control and other treatments. Zn-solubilizing microbes in the soils of many crops were tested as plant growth-promoting factors [24,25].

3.1.5 Available silica in soil

Available silica content was 46.0 ppm in the initial soil sample (Table 2). At 45 DAS all the treatments showed increased available silica content compared to initial stage (Table 4). Highest available silica was recorded in T_{13}, RDF + ZnKJJ-4 & ZnPGG-1 + SiKPP-1 & SiPYY-3 (66.8 ppm) followed by T_{12} (RDF + ZnPGG-1 + SiPYY-3) and T_{11} (RDF + ZnKJJ-4 + SiKPP-1) *i.e.,* 65.9 and 65.7 ppm and found on par. All the treatments at 90 DAS showed increased available silica content than initial and 45 DAS, T_{13} recorded highest (98.90 ppm), followed by T_{12} and T_{11} (97.7 and 97.3 ppm) and were on par. At 120 DAS available silica content decreased among the treatments over 90 DAS and significantly highest silica availability was recorded in T_{13} (84.8 ppm), T_{12} and T_{11} recorded 82.6 and 82.4 ppm, respectively (Table 4).

Available silica was observed highest in T_{13}. Similar results were observed with [26] where application of silica solubilizing bacteria increased availability of silica in soil by 12.45 - 60.15 % more over the control. It might be due to the silica solubilizing microorganisms present in the soil influenced the available silica content in soil by additional application externally. Pedda et al. [27] found that maximum grain yield (3622 kg/ha) was obtained with the application of SSB + FYM followed by FYM (farmyard manure) and SSB alone. Rhizobacteria strain CS4-2 (*Burkholderia eburnean*) showed the ability to solubilize and mobilize the silica and enhance Si-uptake in rice that improved plant-growth relevant to control or uninoculated [28].

3.2 Influence of Zinc and Silica Solubilizing Bacterial Consortia on Nutrient Concentration in Plants

3.2.1 Percent nitrogen in plant

Percent nitrogen in plant was influenced by the zinc and silica solubilizing bacterial isolates and their consortia by easy availability of the nutrients. Percent N significantly differed among the treatments. Highest nitrogen concentration of 0.87 %, 1.10 % and 0.98 % was recorded inT_{13} (RDF + ZnKJJ-4 & ZnPGG-1 + SiKPP-1 & SiPYY-3) followed by T_{12} (0.87 %, 1.08% and 0.95%) at 45, 90 and 120DAS, respectively, and 0.95% in T11 at 120DAS, which were on par. Control recorded the least nitrogen of 0.81% (Table 5).

Table 2. Initial Physico-chemical and microbiological properties of experimental field soil

Soil and microbial properties	Field
Available N (kg ha^{-1})	142.03
Available P (kg ha^{-1})	26.28
Available K (kg ha^{-1})	202.14
Available Zn (ppm)	0.48
Available Si (ppm)	46.0
Total Bacteria (Log CFU g^{-1} of soil)	8.44
Fungi (Log CFU g^{-1} of soil)	4.24
Actinomycetes (Log CFU g^{-1} of soil)	5.44
ZnSB (Log CFU g^{-1} of soil)	3.78
SiSB(Log CFU g^{-1} of soil)	3.46

Table 3. Influence of zinc and silica solubilizing bacterial consortia on available soil nutrients, (N, P and K, kg ha^{-1}) in direct sown paddy

Treatments	Available nitrogen (kg ha^{-1})			Available phosphorus (kg ha^{-1})			Available potassium (kg ha^{-1})		
	45 DAS	**90 DAS**	**120 DAS**	**45 DAS**	**90 DAS**	**120 DAS**	**45 DAS**	**90 DAS**	**120 DAS**
T_1	179.1	218.1	208.2	26.9	48.8	28.7	212.4	330.1	251.4
T_2	181.4	224.9	212.6	28.4	50.1	30.2	213.6	331.8	252.9
T_3	180.7	220.5	210.8	30.5	51.0	31.4	213.4	332.2	253.3
T_4	184.1	230.3	218.6	29.5	52.1	30.6	215.4	333.4	254.2
T_5	182.8	228.5	214.4	30.6	54.0	31.5	215.7	333.5	254.5
T_6	186.6	232.2	221.1	28.8	52.4	30.7	215.8	333.7	255.5
T_7	190.2	248.5	233.2	30.9	56.6	31.8	216.6	334.6	256.1
T_8	190.8	247.1	230.2	31.7	58.5	32.7	217.4	335.7	256.7
T_9	191.5	248.3	232.4	31.0	55.7	32.2	218.1	336.2	257.1
T_{10}	192.3	250.5	235.6	32.9	58.5	35.3	218.8	338.6	258.4
T_{11}	194.2	254.8	237.2	33.3	62.4	36.4	220.6	340.8	260.0
T_{12}	196.7	258.7	238.5	35.4	59.6	38.5	220.9	341.4	261.8
T_{13}	198.9	262.3	240.2	36.7	64.7	40.6	221.4	349.6	263.5
SE(m)	2.32	2.50	2.14	1.23	2.04	2.02	1.15	2.12	1.01
CD(*p*=0.05)	6.97	7.35	6.43	3.70	6.12	6.06	3.44	6.37	3.04
CV	3.14	1.80	2.43	4.14	6.34	5.23	3.48	4.13	2.15

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 & ZnPGG-1, T_{10}: RDF + SiKPP-1 & SiPYY-3, T_{11}: RDF + ZnKJJ-4 + SiKPP-1, T_{12}: RDF + ZnPGG-1 + SiPYY-3, T_{13}: RDF + ZnKJJ-4 & ZnPGG-1 + SiKPP-1 & SiPYY-3

Table 4. Influence of zinc and silica solubilizing bacterial consortia on available soil micro nutrients, Zn and Si (ppm) in direct sown paddy

Treatments	Available Zinc (ppm)			Available Silica (ppm)		
	45 DAS	90 DAS	120 DAS	45 DAS	90 DAS	120 DAS
T_1	0.60	0.91	0.69	57.2	90.1	72.1
T_2	0.61	0.94	0.74	58.4	91.2	74.2
T_3	0.69	0.98	0.79	59.6	92.2	75.2
T_4	0.68	0.97	0.76	60.8	93.3	76.4
T_5	0.67	0.96	0.78	62.2	94.5	78.3
T_6	0.69	0.99	0.79	60.4	93.1	77.2
T_7	0.74	1.02	0.81	62.3	94.7	79.7
T_8	0.76	1.05	0.84	63.4	95.2	80.4
T_9	0.77	1.08	0.86	63.7	95.6	80.6
T_{10}	0.78	1.09	0.88	64.6	96.4	81.2
T_{11}	0.81	1.10	0.93	65.7	97.3	82.4
T_{12}	0.83	1.11	0.96	65.9	97.7	82.6
T_{13}	0.86	1.14	0.98	66.8	98.9	84.8
SE(m)	0.00	0.01	0.01	0.63	0.43	0.54
CD(*p*=0.05)	0.01	0.03	0.02	1.84	1.28	1.62
CV	1.43	1.67	1.35	1.74	1.37	1.42

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 & ZnPGG-1, T_{10}: RDF + SiKPP-1 & SiPYY-3, T_{11}: RDF + ZnKJJ-4 + SiKPP-1, T_{12}: RDF + ZnPGG-1 + SiPYY-3, T_{13}: RDF + ZnKJJ-4 & ZnPGG-1 + SiKPP-1 & SiPYY-3

Table 5. Influence of zinc and silica solubilizing bacterial consortia on N, P and K concentration (%) in direct sown paddy plants

Treatments	Nitrogen (%)			Phosphorus (%)			Potassium (%)		
	45 DAS	90 DAS	120 DAS	45 DAS	90 DAS	120 DAS	45 DAS	90 DAS	120 DAS
T_1	0.70	0.93	0.81	0.32	0.53	0.38	1.71	2.10	1.84
T_2	0.71	0.95	0.83	0.35	0.54	0.41	1.73	2.14	1.86
T_3	0.73	0.97	0.84	0.36	0.55	0.44	1.74	2.16	1.85
T_4	0.76	0.98	0.86	0.37	0.56	0.46	1.76	2.17	1.88
T_5	0.77	0.99	0.87	0.38	0.57	0.45	1.78	2.19	1.89
T_6	0.81	1.02	0.93	0.37	0.58	0.47	1.80	2.20	1.90
T_7	0.82	1.03	0.92	0.38	0.60	0.51	1.82	2.23	1.93
T_8	0.83	1.05	0.90	0.40	0.61	0.52	1.81	2.22	1.92
T_9	0.85	1.06	0.93	0.41	0.62	0.54	1.83	2.24	1.94
T_{10}	0.86	1.07	0.94	0.42	0.62	0.53	1.85	2.26	1.96
T_{11}	0.85	1.06	0.95	0.43	0.63	0.55	1.84	2.25	1.95
T_{12}	0.87	1.08	0.96	0.44	0.64	0.56	1.85	2.28	1.96
T_{13}	0.89	1.10	0.98	0.46	0.67	0.58	1.87	2.29	1.98
SE(m)	0.01	0.01	0.01	0.00	0.00	0.01	0.02	0.01	0.01
CD(*p*=0.05)	0.02	0.02	0.02	0.06	0.01	0.02	0.05	0.02	0.02
CV	1.15	2.18	1.47	1.85	2.18	1.28	2.55	1.25	1.47

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 & ZnPGG-1, T_{10}: RDF + SiKPP-1 & SiPYY-3, T_{11}: RDF + ZnKJJ-4 + SiKPP-1, T_{12}: RDF + ZnPGG-1 + SiPYY-3, T_{13}: RDF + ZnKJJ-4 & ZnPGG-1 + SiKPP-1 & SiPYY-3

Growth enhancement of inoculated plants could be due to the higher N accumulation by bacterial N_2 fixation and better root growth, which might have promoted the greater uptake of water and nutrients. Similar results were found by [29] where addition of SSB-enriched biofertilizer to clay substrate significantly increased the content of total nitrogen, phosphorus and potassium in the leaves of *Brassica juncea*. They concluded that SSB-enriched biofertilizer improved the photosynthetic function of *B.juncea.*

3.2.2 Percent phosphorus in plant

Zinc and silica solubilizing bacterial isolates have the ability to solubilize P to some extent, these microorganisms help for the growth and development of the crop and also elevated crop tolerance under water deficit condition. At 45 DAS significant concentration of plant phosphorus was found in T_{13}: RDF + ZnKJJ-4 & ZnPGG-1 + SiKPP-1 &SiPYY-3 (0.46 %), followed by T_{12} (RDF + ZnPGG-1 + SiPYY-3) *i.e.,* 0.44 %. At 90 DAS significantly higher plant phosphorus concentration was recorded in T_{13} (0.67 %). At 120 DAS highest phosphorus concentration was obtained in T_{13} (0.58 %), followed by T_{12} (0.56 %) and T_{11} (0.55 %) and statistically they were on par (Table 5).

Phosphorus (%) was highest in T_{13} treatment at all the intervals studied. Similar findings were observed by [30] where zinc solubilizing bacterial isolates *i.e., Pseudomonas striata* along with *Pseudomonas florescence* strains showed phosphate solubilizing ability apart from zinc, resulted in significant increase in percent of phosphorus in plant compared to individual inoculations in paddy.Plant growth and development improved by Si application under P stress. Low concentration of Mn and Fe might be responsible for increase of P availability in plant under P-deficient conditions [31,32].

3.2.3 Percent potassium in plant

Osmoregulation is maintained by the potassium concentration in the plant. More the concentration of potassium,higher the osmoregulation, and helps the plant during transpiration. At 45 DAS and 90 DAS higher plant potassium concentration was obtained in T_{13}: RDF + ZnKJJ-4 & ZnPGG-1 + SiKPP-1 & SiPYY-3 (1.87 % and 2.29 %), followed by T_{12}: RDF + ZnPGG-1 + SiPYY-3 (1.85 % and 2.28 %), respectively. At 120 DAS significant maximum potassium concentration was recorded in T_{13} (1.98 %), followed by T_{10} (RDF + SiKPP-1 & SiPYY-3) and T_{12} (RDF + ZnPGG-1 + SiPYY-3) *i.e.,* 1.96 % (Table 5).

Present results revealed that a higher value of potassium concentration was noticed in treatments those received potassium along with N or P or combinations at all the growth stages. The concentration of potassium decreased slowly from 90 to 120 DAS. Besides silicon, silicate minerals contain potassium, calcium, magnesium, iron and zinc and therefore inoculation of Silica solubilizing bacteria (SiSB) to soil benefit the crop by releasing several of these nutrients [33]. By the action of SSB potassium availability was more in soil that showed direct impact on the percent potassium in the plant.

Highest availabilityof nutrients at 90DAS in soil or rice plant was attributed to panicle initiation stage which later declined as maturity occurs with transfer of source to sink.

4. CONCLUSION

Nitrogen, phosphorus and potassium are essential for crop growth and development in paddy whereas zinc and silica nutrients improve the grain quality and quantity. Zinc and silica solubilizing bacteria and their consortia showed significant effect on available nitrogen, phosphorus, potassium, zinc and silica in soil as well as nitrogen, phosphorus and potassium concentration in plant compared to individual zinc and silica solubilizing microorganisms. It is concluded that exogenous application of bacterial consortia can be exploited to improve the nutrient status and availability in direct sown paddy.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
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