



Optimizing Soil Nutrient Bioavailability in Cotton through Potassium Solubilizing Microbial Interventions

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Authors' contributions

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

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ABSTRACT

Cotton crop was evaluated during the kharif season of 2022 to assess the response to various potassium solubilizers in combination with the recommended dose of fertilizers (RDF) on changes in macro and micro soil nutrients. The field experiment was conducted on Vertisol at the Research Farm, ICAR-All India Network Project on Soil Biodiversity and Biofertilizer, Department of Soil

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Science and Agricultural Chemistry, Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani. The study involved ten treatments replicated thrice in a randomized block design, comprising eight potassium solubilizing bacteria KSB-W1 (*Bacillus spp.*), KSB-PD-3-A (*Bacillus spp.*), KSB-NP-3 (*Bacillus spp.*), KSB-PD-3-A (*Bacillus spp.*), KSB-M-1 (*Pseudomonas spp.*), KSB-M-2 (*Pseudomonas spp.*), KSB-M-3 (*Sinorhizobium metallidans*), *Fraturia auruntia*, and *Pseudomonas striata* applied along with RDF. Cotton seeds were treated with Azatophos, and RDF was applied at sowing, while microbial cultures were applied 15 days after sowing (DAS). Overall, the results indicated that the treatment combinations of RDF + *Fraturia auruntia* and RDF + *Pseudomonas striata* significantly improved the availability of macro-nutrients (N, P₂O₅, K₂O) and micro-nutrients (DTPA-extractable Zn, Fe, Mn, and Cu) in the soil, showing their potential in enhancing soil fertility and nutrient uptake in cotton cultivation.

Keywords: Cotton; Potassium solubilizers; RDF; soil nutrients; *Fraturia auruntia*.

1. INTRODUCTION

“Cotton (*Gossypium hirsutum* L.) is one of the most important commercial cash crop and important fiber crop of global significance cultivated in more than seventy countries” (Bitew & Abate, 2024). “It is an important raw material of economy in terms of both employment generation, foreign exchange and hence it is popularly known as “White gold or friendly fiber” (Uddin & Rahaman, 2024). Cotton is one of the principal crops of India and plays a vital role in the country's economic growth by providing substantial employment and making significant contributions to export earnings (Yadav & Chattopadhyay, 2024). The genetically modified *Bt* cotton, containing the cry gene confer resistance to bollworms was first adopted as hybrid in 2002 in India (Nagaraj et al. 2024). “India, the largest cotton grower in the world has recorded spectacular success with *Bt* cotton for the past twenty years. *Bt* cotton contributed to increased productivity and reduced requirements for pesticides while, contributing to better and most sustainable environment in the face of climate change” (Sudha et al. 2014).

“Potassium (K) is the third most major essential nutrients for proper growth of plants and development. Potassium is most abundantly absorbed as cation in higher plants. It plays an important role in the growth and development of plant. It is involved in activation of more than 60 different enzymes responsible for various plant processes including photosynthesis, starch synthesis, nitrate reduction, metabolic reactions, and sugar degradation” (Almeida et al. 2015a, b; Cecilio Filho et al. 2015; Gallegos-Cedillo et al. 2016; Su et al. 2022). “In addition to plant metabolism, K also improves crop's quality because it facilitates grain filling and kernel

development, increases straw strength, and helps the plant to detoxify reactive oxygen species and provide resistance to pathogens as well as abiotic stresses” (Lian et al. 2002; Ashfaq et al. 2020; Johnson et al. 2022; Olaniyan et al. 2022). “its deficiency limits crop quality and yield. In soil, a distribution of different pools of K (water-soluble, exchangeable and non-exchangeable, and mineral forms) differs from soil to soil due to soil mineral compositions. The various pools of K in soil exist in dynamic equilibrium. The plant-available portion of K in the soil is typically low compared to the plant requirement, unavailable minerals forms such as feldspar, orthoclase and the micas are relatively resistant to decomposition and constitute about 90-98 % of the total K in most soils. Therefore, minerals forms provide relatively minor quantities of K to growing crop plants. The reduction of available potassium (both solution and exchangeable forms) in soil, caused by plant absorption and microbial actions, results in the conversion of potassium from non-exchangeable to exchangeable forms” (Sparks 1987).

“The available K (solution and exchangeable) pool needs to be recharged continuously to maintain the supply of K for optimum crop growth. The optimum amount of plant-available K in the soil can be maintained either by utilizing reserve-K (non-exchangeable and mineral K) or by the external supply of K-fertilizers” (Wang et al. 2000). “The fixed form of K in minerals is solubilized by some microorganisms, which then enhance acquisition of K by crop plants. Recently, many soils have become deficit in K due to excessive utilization by crops in intensive farming practices. Severe losses in terms of plant yield and quality may already occur prior to the appearance of visible symptoms of K deficiency” (Khanwilkar and Ramteke 1993; Johnson et al. 2022).

Beneficial soil microorganisms, such as saprophytic bacteria, fungal strains, and actinomycetes, have been reported to solubilize insoluble potassium (K) from soils through various mechanism such as decomposition, mineralization and the release of nutrients. (Zhao et al., 2016). "Among these microorganisms, potassium-solubilizing bacteria (KSB) have gained the attention of agriculturists as a soil inoculant to promote plant growth and yield. Potassium-solubilizing bacteria (KSB) are highly effective in releasing potassium from inorganic and insoluble pools of total soil potassium (K) through solubilization processes" (Archana et al. 2013, Meena et al. 2014 and Parmer and Sindhu 2013). On the basis of that a field experiment was conducted in 2022 at Vasant Rao Naik Krishi Vidyapeeth, Parbhani, to elucidate the solubilization potential of promising potassium-mobilizing bacteria and its effect on availability of nutrient in soil at harvest stage of *Bt* cotton.

2. MATERIALS AND METHODS

A field experiment was carried out at research farm, All India Network Project on Soil Biodiversity-Biofertilizers, Vasant Rao Naik Krishi Vidyapeeth, Parbhani to investigate the effect of potassium solubilizing bacteria on growth and yield components of *Bt* cotton variety Ajeet 199. The bacterial strains, (KSB-W1 (*Bacillus spp.*), KSB-PD-3-A, (*Bacillus spp.*), KSB-NP-3 (*Bacillus spp.*), KSB-M-1 (*Pseudomonas spp.*), KSB-M-2 (*Pseudomonas spp.*), KSB-M-3 (*Sinorhizobium metallidans*), *Frateuria aurantia*, *Pseudomonas striata* were selected for field experiment. The experimental soil is vertisol classified as *Typic Halpusters*. The properties of the soil used in the experiments were clayey in texture, moderately alkaline in reaction; pH (1:2.5 w/v water) 7.78; total soluble salt concentration (1:2.5 w/v water) 0.18 dSm⁻¹; organic carbon 5.13 g kg⁻¹; calcium carbonate 38.75 g kg⁻¹; available N 150.52 kg ha⁻¹; available P₂O₅ 14.70 kg ha⁻¹, available K₂O 488.40 kg ha⁻¹; DTPA extractable zinc 0.57 mg kg⁻¹; DTPA extractable iron 4.27 mg kg⁻¹; DTPA extractable copper 2.19 mg kg⁻¹ and DTPA extractable manganese was 8.24 mg kg⁻¹.

The experiment was laid out in randomized block design with 10 treatments replicated viz., T₁: Absolute control T₂: Only RDF (120: 60: 60 NPK kg ha⁻¹) T₃: RDF + KSB – W1 (*Bacillus spp.*) T₄: RDF + KSB – PD – 3 – A (*Bacillus spp.*) T₅: RDF + KSB – NP – 3 (*Bacillus spp.*) T₆: RDF + KSB – M – 1 (*Pseudomonas spp.*) T₇: RDF + KSB – M – 2 (*Pseudomonas spp.*) T₈: RDF + KSB – M – 3

(*Sinorhizobium metallidans*) T₉ RDF + *Frateuria aurantia* and T₁₀: RDF + *Pseudomonas striata*. The microbial inoculant application was made after germinating the cotton seedlings (15 DAS) liquid broth of isolates (10⁻⁸ CFU ml⁻¹) diluted in water was applied @ 5 L ha⁻¹ through drenching. The recommended dose of phosphorus and potassium along with half dose of N were applied at the time of sowing and half dose of N after one month of sowing. The inorganic sources of fertilizers urea, single super phosphate (SSP) and muriate of potash (MOP) were used for experiment. The soil samples analysed after harvest of crop and analysed for various soil properties using standard procedures. Soil available N were analysing by alkaline permanganate method (Subbiah and Asija 1956), available P (Olsen et al.1954), available K (ammonium acetate extract) and DTPA extractable Zn, Fe, Cu and Mn were estimated by Atomic Absorption Spectrophotometer (AAS). The results obtained were statistically analysed by simple tabular analysis and appropriately interpreted as per the methods described by Panse and Sukhatme (1985). Appropriate standard error (S.E.) and critical differences (C.D.) at 5 per cent levels were worked out for interpretation of result (A.O.A.C. 1990).

3. RESULTS AND DISCUSSION

Through the results of the 2022 field experiment during kharif, we studied how combinations of various potassium solubilizing bacteria (KSB) influenced soil and the effectiveness of RDF when cotton was cultivated. To measure how much microbial treatments influence nutrient availability in Vertisol, a randomized block design was used to compare several microbial treatments. Table 1 and Fig. 1 below present the influence of microbial inoculants on soil available macro nutrients following *Bt* cotton cultivation, while Table 2 and Fig. 2 below discuss their effects on readily available micronutrients (mg kg⁻¹) for the same *Bt* cotton plants.

3.1 Available Nitrogen (N)

Distinct differences in available N with values lying between 139.96 to 193.29 kg ha⁻¹ were observed among the treatments. The available N was the highest in treatment T₉ (193.29 kg ha⁻¹) received RDF + *Frateuria aurantia* which was found to be significantly higher than the rest of treatments at 5 per cent significance level and treatment T₁₀ (185.99 kg ha⁻¹) received RDF + *Pseudomonas striata* found at par with treatment

T₉. On the other hand, the control treatment T₁ (absolute control) recorded the lowest available nitrogen (139.96 kg ha⁻¹). This indicates the importance of microbial inoculants and RDF in improving soil fertility over the unamended control. Bagyalakshmi et al. (2012) they reported that soil from the potassium solubilizing microbe's inoculated treatment shows highest nitrogen content over control. The increase in available N may be due to dual inoculation of bacterial cultures helping in multiplication of soil microbes and ultimately enhancing the conversion of organically bound N to mineral form (Singh et al. 2016).

3.2 Available Phosphorous (P)

In case of available phosphorous the values were varied from 14.61 to 22.04 kg ha⁻¹ under the influence of potassium solubilizing bacterial inoculants. The maximum P availability was found in treatment T₁₀ (22.04 kg ha⁻¹) receiving RDF + *Pseudomonas striata* which significantly superior over rest of treatments and found closely at par with T₉ (20.95 kg ha⁻¹) received RDF + *Frateuria aurantia* and treatment T₆ RDF + KSB – M – 1 (*Pseudomonas spp.*). While, lowest P availability recorded in treatment T₁ (14.61 kg ha⁻¹) absolute control. The improvement in available phosphorus across treatments, especially in T₁₀ and T₉, can be attributed to the ability of microbial inoculants such as *Pseudomonas striata* and *Frateuria aurantia* to produce organic acids, phosphatases and chelating agents that solubilize unavailable phosphorus in the soil. "This build up P in soil is

attributed to solubilization of native P through greater release of organic acids under co-inoculation of different bacterial cultures with *Rhizobium sp.*" (Shashidhar et al. 2009).

3.3 Available Potassium (K)

Regarding to available K, all inoculated treatments show superior values over uninoculated control values were varied from 441 to 587 kg ha⁻¹. The highest available K was found under the influence of inoculation of *Frateuria aurantia* with RDF (T₉- 587 kg ha⁻¹) which found significantly superior over other treatments and found at par with treatment T₁₀ (578 kg ha⁻¹) receiving RDF + *Pseudomonas striata*. The lowest potassium availability was recorded in T₁ (absolute control) 441 kg ha⁻¹. All potassium solubilizing bacterial strains inoculated treatment showing increment in soil available potassium as compared to uninoculated treatment. Zhang and Kong (2014) concluded that inoculation with KSB decreased soil pH value and increased available K content in soil. Bashir et al. (2017) emphasized the importance of potassium-solubilizing microorganisms (KSMs) as natural bio-agents capable of converting fixed forms of potassium into plant-available potassium. They achieve this through various mechanisms such as acidolysis, chelation, exchange reactions, complex lysis, and the production of organic acids. KSMs hold significant potential in enhancing potassium availability to plants by solubilizing potassium from insoluble sources like feldspar and mica through organic acid production and other enzymatic processes.

Table 1. Effect of potassium mobilizing bacterial isolates on soil available macro nutrients under *Bt* cotton

Treatments	Available nutrients (Kg ha ⁻¹)		
	Avail. N	Avail. P ₂ O ₅	Avail. K ₂ O
T ₁ : Absolute control	139.96	14.61	441
T ₂ : Only RDF (120: 60: 60 NPK kg ha ⁻¹)	159.14	16.42	495
T ₃ : RDF + KSB – W1 (<i>Bacillus spp.</i>)	172.96	18.91	542
T ₄ : RDF + KSB – PD – 3 – A (<i>Bacillus spp.</i>)	161.34	17.51	541
T ₅ : RDF + KSB – NP – 3 (<i>Bacillus spp.</i>)	167.90	16.75	540
T ₆ : RDF + KSB – M – 1 (<i>Pseudomonas spp.</i>)	176.21	19.78	557
T ₇ : RDF + KSB – M – 2 (<i>Pseudomonas spp.</i>)	173.30	19.20	554
T ₈ : RDF + KSB – M – 3 (<i>Sinorhizobium metallidans</i>)	168.39	18.05	534
T ₉ : RDF + <i>Frateuria aurantia</i>	193.29	20.95	587
T ₁₀ : RDF + <i>Pseudomonas striata</i>	185.99	22.04	578
S.Em. ±	3.37	0.92	9.08
CD @ 5 %	10.02	2.72	26.97

Table 2. Effect of potassium mobilizing bacterial isolates on soil DTPA micronutrient (mg kg⁻¹) under *Bt* cotton

Treatments	DTPA micronutrient (mg kg ⁻¹)			
	DTPA Zn	DTPA Fe	DTPA Cu	DTPA Mn
T ₁ : Absolute control	0.420	4.14	2.13	11.49
T ₂ : Only RDF (120: 60: 60 NPK kg ha ⁻¹)	0.540	4.71	2.49	12.25
T ₃ : RDF + KSB – W1 (<i>Bacillus spp.</i>)	0.637	4.76	2.64	13.1
T ₄ : RDF + KSB – PD – 3 – A (<i>Bacillus spp.</i>)	0.620	4.81	2.60	12.73
T ₅ : RDF + KSB – NP – 3 (<i>Bacillus spp.</i>)	0.590	4.79	2.60	12.39
T ₆ : RDF + KSB – M – 1 (<i>Pseudomonas spp.</i>)	0.620	4.92	2.64	12.56
T ₇ : RDF + KSB – M – 2 (<i>Pseudomonas spp.</i>)	0.629	4.90	2.59	12.42
T ₈ : RDF + KSB – M – 3 (<i>Sinorhizobium metallidans</i>)	0.586	4.82	2.54	12.37
T ₉ : RDF + <i>Frateuria aurantia</i>	0.679	5.07	3.05	13.52
T ₁₀ : RDF + <i>Pseudomonas striata</i>	0.653	5.09	2.90	13.47
S.Em. ±	0.04	0.06	0.10	0.18
CD @ 5 %	0.13	0.19	0.28	0.53

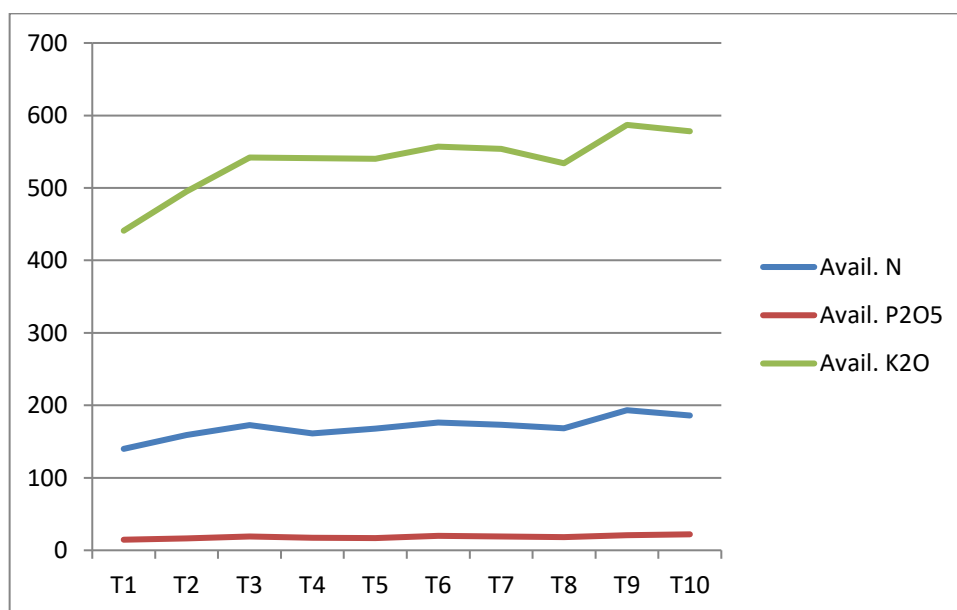


Fig. 1. Effect of potassium mobilizing bacterial isolates on soil available macro nutrients

3.4 Effect on DTPA Extractable Micronutrients

The scrutiny of result presented in Table 2 and Fig.2 reveals that the available micronutrients (DTPA extractable) in soil after harvest of cotton crop were influenced significantly by inoculation of different potassium solubilizing bacterial inoculants.

3.5 DTPA Extractable Zinc (Zn)

The availability of Zn significantly influenced by different potassium solubilizing bacterial

inoculants and varies from 0.420 to 0.679 mg kg⁻¹. Significantly highest available Zn content in soil was recorded in treatment T₉ (0.679 mg kg⁻¹) receiving RDF + *Frateuria aurantia* found at par with all inoculated treatments. Whereas, minimum DTPA Zn recorded in treatment T₁ absolute control (0.420 mg kg⁻¹). Our findings similar with results reported by Jayant Raman (2012) recorded highest availability of zinc in soil was obtained with the inoculation of treatment combination of *Pseudomonas striata* + *Trichoderma viride* and *Azotobacter chroococcum*.

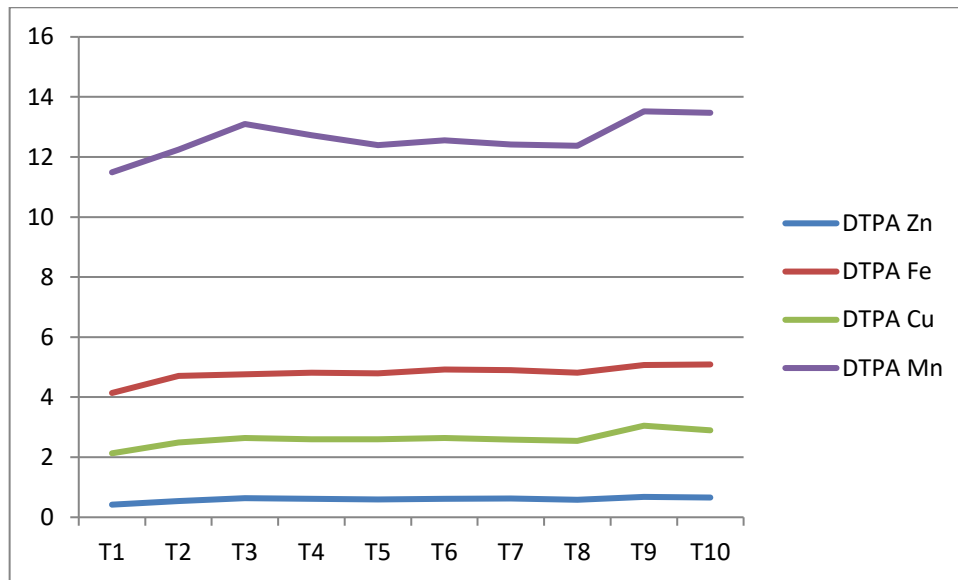


Fig. 2. Effect of potassium mobilizing bacterial isolates on soil DTPA micronutrient (mg kg⁻¹)

3.6 DTPA Extractable Iron (Fe)

In case of Fe availability, the values varied from 4.14 to 5.09 mg kg⁻¹ due to influence of inoculation of bacterial cultures with RDF. The treatment T₁₀ (5.09 mg kg⁻¹) receiving inoculation of *Pseudomonas striata* with RDF found significant over rest of treatments and found at par with treatment T₉ (5.07 mg kg⁻¹) receiving RDF + *Frateuria aurantia*, T₆ RDF + KSB – M – 1 (*Pseudomonas spp.*) and T₇ RDF + KSB – M – 2 (*Pseudomonas spp.*). Whereas lowest DTPA Fe content in soil found in treatment T₁ absolute control (Parmar and Sindhu 2013).

3.7 DTPA Extractable Copper (Cu)

The availability of Cu was influenced by different potassium solubilizing bacterial inoculants and varies from 2.13 to 3.05 mg kg⁻¹. Significantly highest available Cu content in soil was recorded in treatment T₉ (3.05 mg kg⁻¹) receiving RDF + *Frateuria aurantia* found at par with treatment T₁₀ RDF + *Pseudomonas striata* (2.90 mg kg⁻¹) and lowest DTPA Cu content (2.13 mg kg⁻¹) found in treatment T₁ absolute control. Adak et al. (2014) reported DTPA Cu in soil increased significantly with the application of microbial inoculants.

3.8 DTPA Extractable Manganese (Mn)

Regarding to Mn the availability range varied from 11.49 to 13.52 mg kg⁻¹ and treatment T₉ (13.52 mg kg⁻¹) receiving receiving RDF +

Frateuria aurantia found at par with treatment T₁₀ RDF + *Pseudomonas striata* (13.47 mg kg⁻¹). The improvement in available manganese (Mn) due to potassium-solubilizing bacteria (KSB) inoculation can be attributed to several factors. KSB produce organic acids that solubilize insoluble Mn forms, enhancing its availability. They also boost microbial activity, which supports the biogeochemical transformation of Mn into more accessible forms. KSB interact with soil minerals, releasing bound Mn, and their secreted enzymes help mobilize nutrients. Gyneshwar et al. (2002) reported "increased availability of trace elements by micro-organisms through production of growth promoting substances". "The availability of micronutrient (Zn, Fe, Cu and Mn) is might be due co-inoculation of bacterial cultures helps in mineralization which leads to organic forms into inorganic forms of nutrient hence its availability increases" (Singh et al., 2016).

4. CONCLUSION

The study has revealed that adding potassium solubilizing bacteria (KSB) to the soil greatly improves access to both major nutrients (N, P, K) and minor nutrients (Zn, Fe, Cu, Mn) when compared to the uninoculated control. RDF in combination with *Frateuria aurantia* was the treatment that provided the highest nutrient levels and RDF combined with *Pseudomonas striata* also performed well. From these findings, it is apparent that potassium-solubilizing bacteria are important for providing more potassium and

also improving the overall balance of important nutrients in soil. Farming communities see this development as a good and reliable approach to handling nutrients. KSB, for example, *Frateuria aurantia* and *Pseudomonas striata*, can be used in recommended quantities with fertilizer which improves soil fertility, lowers chemical use and keeps more nutrients available to plants. Adopting bio-inoculants in integrated nutrient management increases crop yields, promotes soil health and helps cotton-based farming systems remain sustainable for the long run. Microbial inputs are suggested to farmers as budget-friendly and environmentally safe methods to increase how effectively nutrients are used.

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 the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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