E-ISSN: 2618-0618
P-ISSN: 2618-060X

NAAS Rating (2026): 5.20
www.agronomyjournals.com
2026; SP-9(1): 25-29
Received: 02-11-2025
Accepted: 08-12-2025

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Potassium-solubilising bacteria: A sustainable approach for enhancing global potassium nutrition in agriculture

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DOI: https://www.doi.org/10.33545/2618060X.2026.v9.i1Sa.4596

Abstract
Potassium (K) is the third most essential macronutrient after nitrogen and phosphorus. It is vital for plant metabolism, yield, and stress tolerance. In India, the absence of indigenous potash reserves and a heavy reliance on expensive imports have resulted in significant potassium depletion in soils. Additionally, the high cost of potash fertilizers discourages farmers from applying the necessary amounts, leading to nutrient deficiency. This paper provides a comprehensive overview of potassium dynamics in soil, current constraints on potash fertilizers in India, and the global potash market situation. It also highlights the role and mechanisms of potassium-solubilising bacteria (KSB) in transforming insoluble mineral potassium into plant-available forms through processes such as organic acid production, chelation, and enzymatic action. The paper stresses the importance of incorporating KSB as a biofertilizer to improve nutrient-use efficiency, enhance soil fertility, and promote sustainable crop production. Future prospects include developing effective microbial consortia, standardising field applications, and utilising genomics-based approaches for large-scale use of KSB, aiming to reduce dependency on potash fertilizers and encourage sustainable agriculture.

Keywords: Biofertilizers, potassium mobilisation, potassium solubilising bacteria, soil fertility, and sustainable agriculture

Introduction

Potassium (K) is one of the three major macronutrients essential for plant growth, next only to nitrogen (N) and phosphorus (P). It plays a vital role in enzyme activation, photosynthesis, starch and protein synthesis, assimilate translocation, osmotic regulation, and stress tolerance Adequate potassium nutrition improves crop yield and quality while enhancing plant resilience to abiotic and biotic stresses like pest and disease attack (Çolpan, E *et al*., 2013) [6].

Although potassium constitutes about 0.04-3% of the Earth's crust (Sparks and Huang, 1985) [28], only 1-2% of this is plant-available, with most being locked in primary silicate minerals such as mica, illite, and feldspar (Meena *et al*., 2014) [20]. With intensive farming and chemical fertilizer dependence, the natural potassium pool has been severely depleted in several agro-ecosystems worldwide, including India.

Potash Fertiliser Constraints in India

India is the fourth-largest consumer of potash fertilizers, yet it lacks any commercially viable potash reserves. The country imports nearly 100% of its demand for muriate of potash (MOP), which amounts to approximately 3.5 to 4.0 million tonnes annually. The primary sources of these imports are Canada, Belarus, Russia, and Jordan (FAI, 2023) [11]. This reliance on imports creates a significant foreign exchange burden, exceeding ₹10,000 crore each year. The uneven consumption of fertilizers is evident in the national nitrogen, phosphorus, and potassium (N:P:K) ratio, which stands at 6.7:2.7:1. This imbalance has led to severe potassium depletion in soils (Annual report 2023-24). National surveys indicate that over 40% of agricultural soils in India are deficient in potassium (Meena *et al*., 2014) [20]. Furthermore, rising potash prices, global geopolitical conflicts (such as the Russia-Ukraine war), and erratic supply have rendered fertilizers increasingly unaffordable for smallholder farmers (FAO, 2022; World Bank, 2023) [12, 35].

Global Scenario and Market Dependence

Globally, potash production is concentrated in five countries — Canada, Russia, Belarus, China, and Germany — accounting for over 90% of total production (USGS, 2024) [30]. This uneven distribution has led to price volatility and trade vulnerability. The Russia-Ukraine conflict and sanctions on Belarus have severely disrupted supply chains, affecting potash importers like India, Brazil, and Indonesia (FAO, 2022; World Bank, 2023) [12, 35].

Such global uncertainties emphasize the urgency for biological substitutes. Potassium-solubilizing microorganisms (KSMs) — especially bacteria like *Bacillus mucilaginosus*, *Frateuria aurantia*, and *Paenibacillus glucanolyticus* — can release K^+ ions from insoluble minerals through acidolysis, complexation, and chelation. Their use offers resilience against market fluctuations and fosters local nutrient self-sufficiency.

Importance of Organic and Microbial Fertilizers

Excessive use of chemical fertilizers can lead to soil acidification, loss of organic matter, and an imbalance in soil microorganisms (Parmar and Sindhu, 2013) [24]. To restore soil fertility, biofertilizers have emerged as sustainable alternatives. These products contain beneficial microorganisms that help solubilize and mobilize essential nutrients while improving soil structure and enhancing microbial biodiversity (Meena *et al*., 2016) [21].

In India, the promotion of organic and microbial fertilisers aligns with government initiatives such as the Paramparagat Krishi Vikas Yojana (PKVY) and the National Mission on Sustainable Agriculture (NMSA) (DACFW, 2023) [7]. Products like Multiplex Shakti and Nalpak exemplify integrated microbial formulations that provide nitrogen fixation, phosphate solubilization, and potassium mobilization. These fertilisers improve soil biological activity and reduce the dependence on costly imported fertilisers based on the useful results obtained by the farmer through of India sunce more than a decade.

We have observed a growing demand across India for these products, especially for high potash-demanding crops such as sugarcane, bananas, tea, and potatoes.

Indian Context and Need for Farmer Awareness

Despite proven efficiency, adoption of KSB-based biofertilizers remains limited due to low awareness and inconsistent field results. However, demonstration trials in India on crops like rice, banana, potato, and tea have shown that combining *Frateuria aurantia,* 1×10^8 CFU/ml with reduced potash application can maintain yields while cutting fertilizer costs by up to 50-60% (Vasant, M.U.P., (2021) [32].

Given India's growing focus on "Atmanirbhar Krishi (self-reliant agriculture)," scaling up microbial potassium fertilizers can strengthen soil health, minimize imports, and enhance sustainability.

Role of Microorganisms in Potassium Solubilization

Soil microorganisms significantly influence nutrient cycling, decomposition, mineralization, and nutrient release (Parmar and Sindhu, 2013) [24]. Certain bacteria, fungi, and actinomycetes can solubilize insoluble potassium minerals through various biochemical mechanisms such as acidolysis, chelation, complexolysis, polysaccharide formation, and exchange reactions (Vandevivere *et al*., 1994) [31]. These potassium-solubilizing bacteria (KSB) or potassium-solubilizing microorganisms (KSM) release organic acids—citric, oxalic, gluconic, and tartaric—that lower the pH and liberate potassium ions for plant absorption (Groudev, 1987) [13].

Common Potassium Solubilizing Bacteria

The most prominent KSB species include *Bacillus mucilaginosus*, *Bacillus edaphicus*, *Bacillus circulans*, *Paenibacillus glucanolyticus*, *Pseudomonas sp.*, *Burkholderia sp.*, *Enterobacter hormaechei*, *Frateuria aurantia*, and *Acidithiobacillus ferrooxidans* (Basak and Biswas, 2010; Meena *et al*., 2014) [4, 20]. Among these, *Bacillus mucilaginosus* and *B. edaphicus* are particularly effective in solubilizing potassium from mica and feldspar minerals.

Mechanisms of Potassium Solubilization

Microorganisms solubilize potassium through several biochemical processes, primarily involving the release of organic acids, chelation, oxidation reactions, and biofilm formation.

In the acidolysis mechanism, microorganisms directly dissolve mineral potassium by releasing protons that displace potassium ions from mineral lattices. The secretion of organic acids such as citric, oxalic, malic, and gluconic acids lowers the pH of the surrounding environment, which further promotes the dissolution of mineral-bound potassium (Meena *et al*., 2015).

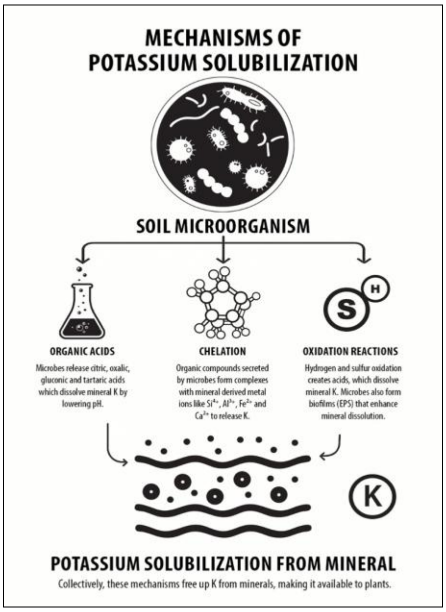
Additionally, microbial oxidation of ammonia and hydrogen sulfide generates nitric and sulfuric acids, respectively, which contribute to potassium solubilization (Huang *et al*., 2013) [15].

Another important mechanism is chelation, in which organic compounds secreted by microbe's form complexes with metal ions like Si^{4+}, Al^{3+}, Fe^{2+}, and Ca^{2+}, thereby freeing up potassium ions from the mineral matrix (Štyriaková *et al*., 2003) [29].

Microorganisms also produce exo-polysaccharides (EPS) that enhance mineral dissolution by facilitating microbial attachment to mineral surfaces and forming a conducive microenvironment for potassium release (Welch and Vandevivere, *et al*., 1994) [34].

Furthermore, biofilm formation increases the residence time of microbial cells on mineral surfaces, improving potassium extraction efficiency (Meena *et al*., 2014) [20]. The production of indole acetic acid (IAA) and other phytohormones by these bacteria enhances root-microbe interaction, promoting nutrient uptake and overall plant growth (Etesami *et al*., 2015) [10].

Collectively, these mechanisms enable potassium-solubilizing bacteria to convert unavailable mineral potassium into soluble, plant-accessible forms, enhancing nutrient cycling and soil fertility.



Crop-wise Application of Potassium Solubilising Bacteria (KSB)

Crop-wise Application and Benefits of Potassium Solubilising Bacteria (KSB)				
SL No.	**Crop**	**Scientific Name**	**Key Findings / Observations**	**References**
1	Paddy	*Oryza sativa* L.	• Increased plant height (4.09-10.8%), stem diameter (4.07-10.4%), root length (8.0-13.1%), leaf area (19.8-21.4%), and dry biomass (7.53-15.7%). • Combined with 50% recommended K fertilizer, improved grain yield, biological yield, and dry matter translocation. • Native KSB effective under flooded irrigation to reduce chemical fertilizer use.	Bakhshandeh *et al.*, 2017 [3]; Yaghoubi Khanghahi *et al.*, 2019 [36]
2	Wheat	*Triticum aestivum* L.	• Improved grain yield (5046 kg ha^{-1}), spike length, and total biomass. • Enhanced nutrient uptake efficiency and soil fertility.	Sheng, 2005 [27]; Singh *et al.*, 2000
3	Maize	*Zea mays* L.	• KSB + mineral K fertilizers enhanced yield, nutrient uptake, and soil health. • Improved fertilizer use efficiency and long-term soil fertility.	Goswami, 2020; Imran *et al.*, 2020
4	Garlic	*Allium sativum* L.	• 75% K_2SO_4 + Bacillus mucilaginosus HQ013329 improved bulb storage ability. • Reduced weight loss and maintained bulb quality during storage.	Mounir, A.M. *et al.*, 2020 [22]
5	Onion	*Allium cepa* L.	• Seedling dipping @10 ml/L for 30 min with 50-100% K_2O ha^{-1} enhanced plant height, leaf number, and root length. • Increased dry weight of bulbs/leaves, nutrient uptake (N, P, K), and yield.	Mansoor, M.N.J., 2015 [19]
6	Potato	*Solanum tuberosum* L.	• Bacillus cereus + Frateuria aurantia increased plant height (15%), branches (27%), shoot dry weight (26%). • Soil available K ↑ 42%, tuber K uptake ↑ 62%, tuber yield ↑ 21%. • Application @1 L/80 kg FYM ha^{-1} + 75% K improved yield and soil fertility. Application @1 L/80 kg FYM ha^{-1} + 75% K improved yield and soil fertility.	Badoni *et al.*
7	Sweet Potato	*Ipomoea batatas* L.	• 100 kg potash sulphate + 453 kg feldspar rock + KSB inoculation enhanced growth, yield, and quality. • Improved chemical composition and storability compared to 200 kg commercial K fertilizer.	Shams, A.S. & Fekry, W.A., 2014 [26]
8	Tomato	*Solanum lycopersicum* L.	• Improved plant height, leaf area, total root length, root/shoot ratio, and tissue K content. • Effective under Alfisol and Vertisol conditions.	Lynn, T.M. *et al.*, 2013 [17]
9	Chilli	*Capsicum annuum* L.	• NPK microbial consortium increased shoot/root biomass, leaf and fruit number. • Enhanced chlorophyll, sugars, phenolics, and flavonoids. • Improved physiological performance.	Devi, R. *et al.*, 2022 [8]
10	Cauliflower	*Brassica oleracea var. botrytis* L.	• Combined PSB + KSB + RDF improved leaf number, leaf area, shoot length, and biomass. • Enhanced chlorophyll, protein, carbohydrate, and ascorbic acid levels.	Kumari, S. *et al.*, 2017 [16]
11	Cucumber	*Cucumis sativus* L.	• PSB + KSB increased N, P, K uptake. • Produced IAA and siderophores enhancing plant growth and development.	Han, H.S. & Lee, K.D., 2006
12	Beetroot	*Beta vulgaris* L.	• Increased shoot/root dry biomass, soil P and K content. • Provided protection (100% & 75%) against Fusarium root rot pathogens.	Aallam, Y. *et al.*, 2022 [1]
13	Lettuce	*Lactuca sativa* L.	• PSB + KMB + KSB co-inoculation improved biomass, leaf number, and nutrient content. • Increased root/shoot length, fresh and dry weights.	Biswas, S. & Shivaprakash, M.K., 2022 [5]
14	Brinjal	*Solanum melongena* L.	• Improved plant growth, nutrient uptake, and yield with KSB inoculation.	Thuvaraka *et al.*, 2023
15	Okra	*Abelmoschus esculentus* L.	• Enhanced plant growth, nutrient uptake, and yield following KSB application.	Okra, 2013
16	Grapes	*Vitis vinifera* L.	• Improved yield and fruit quality (phenols, reducing sugars, tannins). • Enhanced storage quality.	Swaminathan *et al.*, 2021
17	Banana	*Musa paradisiaca* L.	• KSB improved plant growth, nutrient uptake, and fruit yield.	Nowembabazi *et al.*, 2021 [23]
18	Watermelon	*Citrullus lanatus* L.	• Increased germination (68%), radical/plumule length. • Fruit weight ↑ 31.34%, total sugar ↑ 24.55%, yield ↑ 10%.	Mali, S.D. *et al.*, 2022 [18]
19	Apple	*Malus domestica* Borkh.	• Promoted seedling growth via phytohormone stimulation. • Enhanced K solubility and nutrient uptake. • Improved yield and plant vigor.	Zhuang, L.I. & Cheng, C.G., 2020 [37]; Ahmad & Zargar, 2017
20	Mango	*Mangifera indica* L.	• Increased available N (10%), P (7%), K (18%), enzyme activities (54-52%). • Fruit yield ↑ 23-27% across 3 seasons • Yield range: 9.14-17.14 t ha^{-1} with KSB + K fertilization.	Wang, J. *et al.*, 2022 [33]
21	Cotton	*Gossypium hirsutum* L.	• Increased seed cotton yield (2469.13 kg ha^{-1}) over control (2376.37 kg ha^{-1}).	Ciobanu, 1963
22	Groundnut	*Arachis hypogaea* L.	• KSB @3 L ha^{-1} improved plant height, nodules, pods, and oil/protein content. • Pod yield: 2490 kg ha^{-1}; Haulm yield: 2810 kg ha^{-1}. • Increased P content in pods and haulm.	Purohit, 2019 [25]
23	Black Pepper	*Piper nigrum* L.	• Increased tissue dry mass (37-68%) and K uptake (up to 184%) in wood ash-amended soils.	Sangeeth *et al.*, 2012
24	Tea	*Camellia sinensis* L.	• 75% K fertilizer + KSB maintained yields and tea quality. • Improved soil health and reduced dependency on chemical fertilizers. • Promoted eco-friendly tea cultivation.	Rallos, 2012

Challenges and Industrial Prospects

Despite the demonstrated benefits of KSB, their widespread application remains limited due to:

1. Slow and gradual effects on yield improvement.
2. Limited awareness among farmers and extension workers.
3. Inconsistent performance under field conditions.
4. Lack of efficient strain preservation and formulation technologies.
5. Insufficient commercial interest in microbial potassium fertilizers (Meena *et al*., 2016) [21].

To overcome these challenges, large-scale strain identification, formulation standardization, and field demonstration trials are necessary to integrate KSB biofertilizers into mainstream agriculture.

Conclusion

Potassium-solubilizing bacteria provide a sustainable and eco-friendly solution to India's increasing reliance on imported potash fertilizers. Indigenous biofertilizer formulations like Multiplex Shakti and Multiplex Nalpak show that microbial potassium mobilization can improve soil fertility, decrease dependency on fertilizer imports, and promote resilient agricultural practices. Strengthening research, enhancing formulation technology, and expanding field extension services will be essential for scaling this innovation to ensure national food security and soil health.

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