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Potassium solubilizing bacteria (KSB): Framework, stimulation of plant growth and future outlook: A review

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Abstract

Potassium (K) is an essential macronutrient required for the fundamental growth and physiological development of all plants and animals. It is absorbed by plant roots and circulates throughout the organism as the cation K⁺. Although global soil reserves of potassium are typically high, the vast majority exists as insoluble minerals, meaning plants can only access a very small fraction of this total. This limitation has made modern agriculture heavily dependent on expensive synthetic fertilizers, which can degrade soil health over time. Potassium-solubilizing bacteria (KSB) offer a powerful biological solution by converting these inaccessible mineral forms into usable nutrients. Diverse bacteria, including *Acidithiobacillus ferrooxidans*, *Paenibacillus* spp., and various *Bacillus* species, have demonstrated the ability to dissolve silicate minerals such as biotite, feldspar, and mica. These microbes utilize a suite of biological processes including the secretion of organic and inorganic acids, acidolysis, polysaccharides, chelation, and exchange processes to release K into the soil solution. Utilizing KSB in integrated nutrient management not only boosts soil K availability but also promotes sustainable farming by reducing the reliance on chemical inputs. This review explores the framework of KSB, the specific biochemical pathways they use to solubilize K, and their multi-functional role in promoting plant development and crop yield. By addressing current challenges and outlining future research directions, this article underscores the importance of KSB as a cornerstone for sustainable global food security.

Keywords: Biofertilizers, insoluble K minerals, synthetic potassium fertilisers, potassium solubilization, and sustainable agriculture

1. Introduction

Climate change, energy crises, land degradation, galloping population, and poor crop productivity due to nutrient mining threatens the sustainability of current agricultural production systems globally (Lal, 2015) [35]. It is projected that > 600 million people worldwide will face hunger in 2030, highlighting the immense challenge of achieving the zero-hunger target (SDG-2). Likewise, in India ~195 million people are undernourished and it ranks 111th out of 125 countries in the Global Hunger Index with a score of 28.7 in 2023 (www.globalhungerindex.org). Future agriculture must be intensive and sustainable in order to feed the growing global population (FAO, 2017) [18]. However, it is commonly understood that agriculture cannot sustainably produce food unless the nutrients that are taken out of the soil due to increased crop output are replenished (World Bank, 1994) [67]. Plant growth is poor in many agricultural soils because there is insufficient availability of one or more critical plant nutrients (Kumar, 2024) [33]. In order to overcome this issue and increase plant yields, farmers are now more reliant on synthetic fertilisers (Glick, 2012) [20].

Although chemical fertilisers aided in plant growth, they had little effect on the soil's characteristics. It is commonly known that the ecosystem affects when chemical fertilisers, primarily phosphorous, nitrogenous, and potassium fertilisers, are used continuously (Olaniyan *et al.*, 2022) [47]. In order to increase crop production, farmers are utilising highly analysed inorganic fertilisers; however, prolonged and unregulated use of these chemical fertilisers eventually degrades soil health (Hamid & Bashir, 2019) [23] and again the introduction of high-yielding wheat and rice varieties, along with increased use of nitrogen (N) and phosphorus (P),

caused crops to remove more K, and mining of the K capital continued without supplementing with K from other sources (Bijay-Singh & Yadvinder-Singh, 2003)^[8]. As a result, the soils' K reserves were depleted, making K application crucial to achieving high yield, high quality, and high profit in most soils and crops, especially in intensive agriculture (Dhillon *et al.*, 2019)^[15].

In accordance to plant physiologists, potassium is second only to nitrogen in terms of stimulating plant development. Potassium activates more than 60 enzymes and is directly or indirectly involved in all major plant growth processes i.e Promotes photosynthesis, Promotes the transport of photosynthates to storage organs of crops, Improves the quality of crops and prolongs their shelf-life (tobacco, fruit and fibre crops), Increases the ability of plants to withstand biotic and abiotic stresses such as attack of pests and diseases, drought and frost (Meena *et al.*, 2016)^[41]. Despite its importance, potassium deficiency limits crop productivity worldwide because most soil potassium exists in insoluble mineral forms inaccessible to plants (Mostofa *et al.*, 2022)^[43]. Even though soil K is abundant, only 2 to 3% of it is available to plants in free soluble form; the remaining 95% of soil potassium is thought to be bonded to other soil minerals (Etesami *et al.*, 2017)^[17].

In the soil, there are four forms of potassium and these include unavailable K (mineral K), available K (soluble K), non-exchangeable K (fixed or trapped K), and exchangeable K (ionic K). While the exchangeable K (ionic K) is easily absorbed by the plant's root system and replaces potassium on the exchange sites, the fixed K is a reserve supply of potassium. Furthermore, some are found in the soil microbial population's organic matter (Kour *et al.*, 2020)^[31]. Plants absorb potassium in diverse ways, and they require it more during the early stages of growth than they do nitrogen and phosphorus (Sattar *et al.*, 2019)^[56]. Soil temperature, soil moisture, and tillage system are the primary factors influencing its uptake (Mouhamad *et al.*, 2016)^[44]. Potassium solubilizing bacteria (KSB), including genera like *Bacillus* and *Pseudomonas*, offer a bio-based solution by releasing potassium from soil minerals through organic acid secretion and enzymatic activity (Dakshyani *et al.*, 2024; Etesami *et al.*, 2017)^[13, 17] and also, notable efficient KSB strains belong to genera such as *Bacillus*, *Paenibacillus*, *Azospirillum*, *Streptomyces*, and *Priestia* (Damathia *et al.*, 2025; Gupta *et al.*, 2020)^[14, 22]. Harnessing these well-characterized KSB strains in bio-inoculant formulations offers a practical and sustainable strategy to reduce chemical fertilizer use and improve nutrient cycling in agroecosystems (Sattar *et al.*, 2019)^[56].

2. Forms and availability of potassium in soils

Potassium in soils exists in four pools:

Soil solution K: 0.1 - 0.2% Soil solution K is the form that is directly taken up by plants and microbes and also is the form most subject to leaching in soils (Havlin *et al.*, 2013)^[24]. Levels of soil solution K are generally low, unless applications of K have been made to the soil (Sparks, 2000)^[61].

Exchangeable-K: 1 – 2% Exchangeable K is the portion of the soil K that is electrostatically bound as an outer-sphere complex to the surfaces of clay minerals and humic substances (Sparks, 1987)^[62]. It is readily exchanged with other cations and also is readily available to plants (Brady & Weil, 2017)^[9].

Non-exchangeable-K: 1-10% Non-exchangeable or fixed K differs from mineral K in that it is not bonded within the crystal structures of soil mineral particles. It is held between adjacent tetrahedral layers of dioctahedral and trioctahedral micas, vermiculites, and intergrade clay minerals such as chloritized vermiculite (Sparks, 1987)^[62]. Potassium becomes fixed because the binding forces between K and the clay surfaces are greater than the hydration forces between individual K⁺ ions. This results in a partial collapse of the crystal structures and the K⁺ ions are physically trapped to varying degrees, making K release a slow, diffusion-controlled process (Sparks & Huang, 1985)^[60]. Release of non-exchangeable K to the exchangeable form occurs when levels of exchangeable and soil solution K are decreased by crop removal and/or leaching and perhaps by large increases in microbial activity (Syers, 1998)^[63]. Non-exchangeable K is moderately to sparingly available to plants (Havlin *et al.*, 2013)^[24].

Mineral K: 90-98% Most of the total K in soils is in the mineral form, mainly as K-bearing primary minerals such as muscovite, biotite, and feldspars (Lalitha & Dhakshinamoorthy, 2014)^[36]. Mineral K comprised about 98% of the total K. Most of the mineral K is present as K feldspars in the sand fractions (Sparks, 2000)^[61]. Common soil K-bearing minerals, in the order of availability of their K to plants, are biotite, muscovite, orthoclase and microcline (Huang *et al.*, 1968)^[25]. Mineral K is generally assumed to be only slowly available to plants; however, the availability is dependent on the level of K in the other forms, and the degree of weathering of the feldspars and micas constituting the mineral K fraction (Islam *et al.*, 2023)^[28].

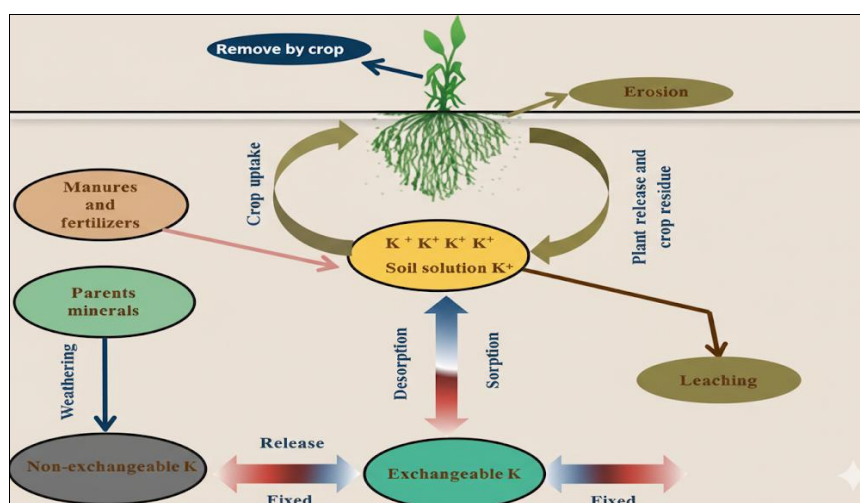


Fig.1: Forms and availability of potassium in soils

Framework of Potassium Solubilizing Bacteria

Potassium solubilizing bacteria (KSB) constitute an essential group of plant growth-promoting rhizobacteria (PGPR) that play a significant role in enhancing potassium (K) availability in soils, particularly in systems where K is locked in insoluble mineral forms (Etesami *et al.*, 2017; Olaniyan *et al.*, 2022)^[17, 47]. These bacteria have been extensively studied in recent years for their potential to sustainably improve crop nutrition and yield, especially under challenging agroecological conditions (Sattar *et al.*, 2019)^[56]. KSB are taxonomically diverse, predominantly belonging to genera such as *Bacillus*, *Pseudomonas*, *Paenibacillus*, *Enterobacter*, *Serratia*, and *Streptomyces*, identified by molecular and biochemical techniques (Gao *et al.*, 2025; Nawaz *et al.*, 2023)^[19, 46]. Their potassium solubilizing capabilities stem principally from their ability to secrete organic acids such as citric, lactic, acetic, and gluconic acids that acidify the soil microenvironment, facilitating the release of potassium ions from mineral complexes like feldspar and mica (Bahadur *et al.*, 2019)^[2].

These biochemical processes, including acidolysis and chelation, effectively convert fixed K forms into soluble forms that plants can absorb (Damathia *et al.*, 2025; PMC, 2024)^[14, 50]. Recent genomic studies have elucidated the genetic regulation underlying these mechanisms. For example, *Bacillus aryabhattai* SK1-7 showcases upregulated genes associated with organic acid production and extracellular polysaccharide synthesis when exposed to insoluble potassium compounds, thus enhancing mineral weathering and nutrient mobilization (Chen *et al.*, 2022)^[12]. These bacteria also produce plant growth promoting substances like indole-3-acetic acid (IAA), siderophores, and enzymes that support root development and nutrient uptake, further elevating plant vigor (Nawaz *et al.*, 2023)^[46]. Empirical trials demonstrate KSB effectiveness in diverse crops and stress-prone soils, including salt-affected areas, by improving potassium uptake, cytosolic K^+/Na^+ ratios, and overall yield (Nawaz *et al.*, 2023; Sharma *et al.*, 2024)^[46, 57]. Consequently, KSB are becoming integral components of integrated nutrient management strategies, reducing dependency on synthetic fertilizers and fostering sustainable intensification of agriculture (Jadhao *et al.*, 2025; Sivakumar *et al.*, 2024)^[29, 59].

3. Mechanisms of Potassium Solubilization

Potassium solubilizing bacteria (KSB) enhance potassium availability in soils primarily through three core mechanisms: acidification, chelation/polysaccharide production, and mineral weathering with enzyme activity.

Acidification: KSB secrete organic acids such as citric, malic, gluconic, formic, and acetic acids that lower the pH of the rhizosphere. This acidification facilitates the breakdown of potassium-bearing aluminosilicate minerals (e.g., feldspar, mica) by proton exchange and dissolution, releasing soluble potassium ions (K^+) accessible to plants (Bahadur *et al.*, 2019)^[2]. For example, *Bacillus aryabhattai* SK1-7 secretes high levels of malic, formic, and acetic acids under insoluble potassium culture, significantly enhancing potassium solubilization (Chen *et al.*, 2022)^[12].

Production of Chelators and Polysaccharides: KSB produce

extracellular polymeric substances (EPS), mainly composed of polysaccharides and proteins, which can bind to mineral particles, forming bacteria-mineral complexes (Sheng *et al.*, 2008; Bandara *et al.*, 2006)^[58, 3]. These complexes trap secondary metabolites and acidolytic compounds, modifying the microenvironment around minerals and increasing potassium release (Basak & Biswas, 2009)^[5]. Polysaccharide secretion has been observed to be significantly higher under insoluble potassium conditions, aiding in adhesion and mineral weathering (Zhang & Kong, 2014)^[71].

Mineral Weathering and Enzyme Activity: KSB facilitate potassium release through enzymatic processes and active absorption. Enzymes related to organic acid biosynthesis such as malate dehydrogenase (*mdh*), phosphoenolpyruvate carboxylase (*ppc*), and citrate synthase (*gltA*) are upregulated in potassium solubilizing strains, enhancing the breakdown of mineral structures (Chen *et al.*, 2022)^[12]. These processes work synergistically with acidification and polysaccharide production to gradually dissolve fixed potassium minerals. Quantitatively, KSB strains have demonstrated potassium solubilization indices ranging from 1.57 to 5.57, with released potassium concentrations reaching significant levels under optimal conditions, accompanied by pH reductions from neutral to around 4.4, confirming acidification's pivotal role (Bahadur *et al.*, 2019; Zhao *et al.*, 2024)^[2, 71].

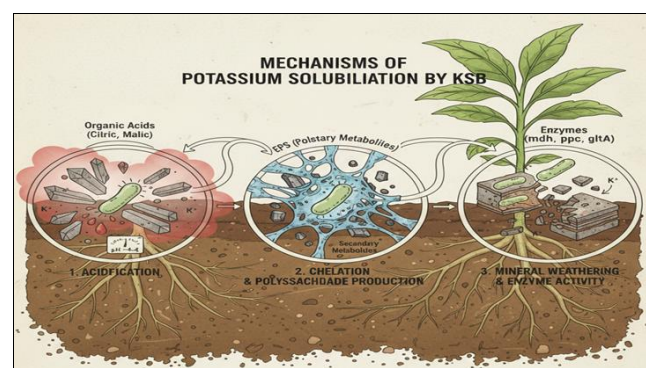


Fig 2: Mechanisms of Potassium Solubilization

The mechanism of microbial-mediated weathering, a process that significantly accelerates potassium release compared to the prolonged timescales of natural mineral weathering. As depicted, the colonization of potassium-bearing minerals specifically feldspar and illite by silicate bacteria leads to the formation of bacterium-mineral complexes. This interaction drives mineral dissolution and potassium solubilization through distinct metabolic activities. Specifically, the bacteria secrete metabolites that lower the pH of the surrounding rhizosphere, creating an acidic environment conducive to structural breakdown. Concurrently, the production of organic ligands facilitates the chelation and complexation of mineral ions. Through this oxidative activity and environmental acidification, the bacteria effectively degrade the mineral lattice, resulting in the release of free potassium ions (K^+) and thereby increasing their bioavailability for plant uptake (Rajawat *et al.*, 2019)^[55].

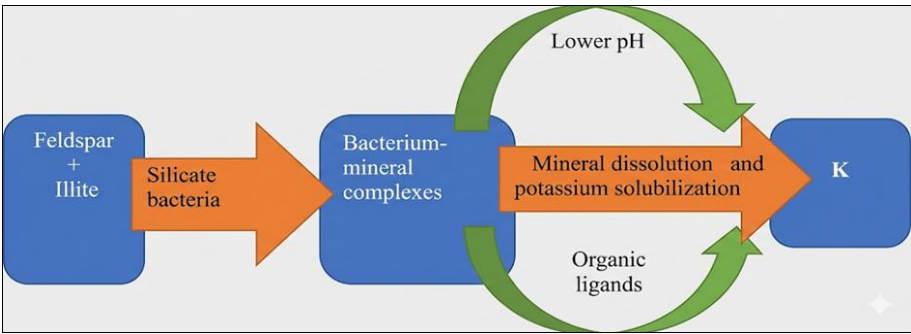


Fig 3: Microbial-mediated solubilization of potassium (K⁺) from feldspar and illite via pH reduction and organic ligand secretion.

4. KSB-Mediated Stimulation of Plant Growth

Potassium Solubilizing Bacteria (KSB) contribute significantly to plant growth stimulation through multiple mechanisms validated by extensive laboratory and field studies (Sattar *et al.*, 2019) [56]. These bacteria not only enhance potassium availability but also promote overall plant development, improve potassium use efficiency (KUE), and provide additional plant growth-promoting rhizobacteria (PGPR) benefits such as hormonal modulation and pathogen biocontrol (Etesami *et al.*, 2017; Yadav, 2022) [17, 68].



Fig 4: Seed treatment with KSB

Enhanced Seed Germination and Growth: KSB inoculation has been shown to improve seed germination rates and seedling vigor by supplying bioavailable potassium crucial during early developmental stages (Bahadur *et al.*, 2019) [2]. Potassium’s role in osmoregulation and enzyme activation is crucial for cell elongation and division, thereby stimulating root and shoot growth. For example, KSB strains such as *Serratia marcescens* HPY10 and AKY2 released potassium at concentrations exceeding 7 mg/L in culture media, correlating with increased root length and biomass in inoculated plants compared to controls (Bahadur *et al.*, 2019) [2]. Rice plants inoculated with a consortium of KSB strains (*Enterobacter hormaechei*, *Pseudomonas putida*) exhibited significantly enhanced root fresh weight, shoot length, and dry biomass under saline conditions, reflecting improved nutrient uptake and stress tolerance (Nawaz *et al.*, 2023) [46].

Yield Improvement and Potassium Use Efficiency (KUE): Field trials underline KSB’s efficacy in boosting crop yields by improving KUE the ratio of biomass produced per unit of potassium absorbed. In rice, inoculation with KSB led to grain yield increases up to 15–25% compared to uninoculated controls, mediated through sustained potassium availability even under potassium-deficient soils (Nawaz *et al.*, 2023; Bahadur *et al.*, 2019) [46, 2]. Besides solubilizing mineral potassium, these bacteria increase potassium assimilation efficiency by maintaining a favourable cytosolic K⁺/Na⁺ ratio, which is critical in salt-stressed environments (PMC, 2023) [49].

Table 1: Yield Improvement and Potassium Use Efficiency in various crops

Test Crop	Potassium Solubilizing Microorganism (KSM)	Effect Compared to Control	Reference
Maize (<i>Zea mays</i>)	<i>Cereibacter sphaeroides</i> , <i>Rhodopseudomonas</i> spp. (LPS-PNSB)	13.5% increase in yield (12.6 vs 11.1 t/ha) when combined with full K; allowed 100% reduction in chemical K while maintaining yield.	Do <i>et al.</i> , 2024 [16]
Banana (<i>Musa</i> spp.)	<i>Agrobacterium pusense</i> + <i>Bacillus paralicheniformis</i>	26.7% increase in yield (68.02 vs 53.65 t/ha); significantly improved bunch weight and fruit count.	Hussain & Sekhar, 2021 [27]; Pradhan <i>et al.</i> , 2025 [51]
Rice (<i>Oryza sativa</i>)	<i>Pantoea vagans</i> (Strain ZHS-1)	Significant increase in root activity and biomass; solubilized 20.3 mg/L of K from feldspar; enriched soil with K-solubilizing bacteria.	Tian <i>et al.</i> , 2024 [64]
Potato (<i>Solanum tuberosum</i>)	<i>Trichoderma harzianum</i> + 50% NPK	42.17% increase in total yield and 49.09% increase in commercial yield compared to control; reduced fertilizer need by 50%.	Malaver <i>et al.</i> , 2025 [65]
Wheat (<i>Triticum aestivum</i>)	<i>Siccibacter colletis</i>	Promoted growth, yield, and nutrient uptake; strain isolated from <i>Argania</i> rhizosphere showed high phosphate solubilization.	Kumar <i>et al.</i> , 2025 [32]
Cotton (<i>Gossypium</i> spp.)	<i>Pseudomonas aeruginosa</i> (Strain A10)	Significant increase in plant height and root growth; solubilized 21.8 ppm of K; maintained efficacy at pH 8–9.	Zhao <i>et al.</i> , 2024 [73]
Chinese Cabbage (<i>Brassica rapa</i>)	Biochar + Phosphogypsum (Soil Amendment)	10.13% increase in available soil Potassium; 14–16% increase in alkali-hydrolyzed nitrogen; significantly improved yield and quality.	Mu <i>et al.</i> , 2024 [45]
Sugar Beet (<i>Beta vulgaris</i>)	<i>Bacillus velezensis</i> (Strain KT27)	15.2% increase in root yield compared to untreated control; 60.2% inhibition of <i>Cercospora</i> leaf spot.	Wita <i>et al.</i> , 2025 [66]

Hormonal Modulation and Bio-Control of Pathogens: Many KSB strains exhibit PGPR traits including production of plant hormones like indole-3-acetic acid (IAA), gibberellins, and cytokinin’s, which regulate physiological processes such as root

elongation and nutrient transport (Bahadur *et al.*, 2019) ^[2]. This hormonal stimulation contributes to enhanced root surface area and nutrient absorption capacity. Moreover, production of antimicrobial compounds such as hydrogen cyanide (HCN), siderophores, and ammonia by KSB suppresses phytopathogens like *Fusarium oxysporum*, thereby reducing disease incidence and promoting healthier plants (Bahadur *et al.*, 2019; PMC, 2024) ^[2, 50]. Some strains also solubilize secondary nutrients like phosphate and zinc, adding synergistic benefits to plant nutrition (Bahadur *et al.*, 2019) ^[2]. KSB-mediated stimulation of plant growth integrates direct nutrient solubilization and hormonal regulation with indirect pathogen suppression, resulting in improved germination, growth, yield, and nutrient use efficiency. Their multifunctional role positions KSB as key biofertilizers for sustainable agriculture, especially in challenging environments with nutrient constraints or salinity stress.

5. Integration of KSB in Sustainable Agriculture

Potassium solubilizing bacteria (KSB) are increasingly recognized as key biological agents to address potassium (K) deficiency challenges in sustainable agricultural systems, particularly in salt-affected, low-K, and degraded soils where traditional fertilizer use is limited by cost, environmental risks, or inefficiencies (Chen *et al.*, 2023; Liu *et al.*, 2022) ^[11, 37]. Their integration into these systems offers comprehensive benefits by enhancing potassium bioavailability, improving soil health, and fostering plant resilience against abiotic stresses (Dakshyani *et al.*, 2024; Oyebamiji *et al.*, 2024) ^[13, 48]. In salt-affected soils, excessive sodium (Na⁺) ion concentration disrupts potassium uptake, causing ionic imbalances detrimental to plant growth and yield. KSB mitigate this stress by solubilizing fixed potassium from minerals and enhancing the cytosolic K⁺/Na⁺ ratio within plants, which is critical for maintaining cell turgor, enzyme function, and photosynthesis under salinity stress (Zhao *et al.*, 2024; Gupta *et al.*, 2023) ^[73, 21]. In recent greenhouse and field experiments, inoculation with KSB strains significantly improved crop growth, root architecture, biomass accumulation, and yield in saline-sodic soils, demonstrating practical applicability in salt-prone regions (Dakshyani *et al.*, 2024) ^[13]. Such inoculants also stimulate the expression of potassium transporters in roots, further optimizing

K uptake efficiency (Chen *et al.*, 2023) ^[11]. Degraded and potassium-deficient soils, commonly resulting from intensive cultivation, erosion, and poor nutrient cycling, benefit profoundly from KSB application. These bacteria secrete organic acids that acidify the rhizosphere and chelate metal ions, disrupting mineral lattices and converting insoluble potassium into soluble forms readily taken up by roots (Rajawat *et al.*, 2022; Meena *et al.*, 2016) ^[55, 41]. Alongside potassium solubilization, KSB enhance soil microbial diversity and enzymatic activities, promoting nutrient cycling and remediating soil health. Importantly, KSB exhibit compatibility with conservation agriculture practices such as minimum tillage and organic matter retention, underpinning resilient agroecosystem services (Kumawat *et al.*, 2023; Yadav, 2022) ^[34, 70]. KSB also synergize with other beneficial microbes, including phosphate solubilizing bacteria (PSB) and arbuscular mycorrhizal fungi (AMF), accelerating nutrient availability through complementary mechanisms. Such microbial consortia formulations enable efficient mobilization of multiple macro- and micronutrients, optimizing nutrient uptake and plant performance (Rai *et al.*, 2023; Berger *et al.*, 2015) ^[52, 7]. Organic amendments like compost, biochar, and green manures further aid KSB colonization and activity by providing carbon substrates and conducive microhabitats, improving their survival and function in field conditions (Hussain *et al.*, 2022; Brtnicky *et al.*, 2021) ^[26, 10]. Collectively, these integrated approaches reduce the need for excessive chemical fertilizers, lowering agricultural input costs and minimizing environmental contamination risks such as eutrophication and soil acidification. KSB application, therefore, aligns with sustainable intensification goals, enhancing food security while safeguarding ecosystem integrity (Etesami *et al.*, 2017) ^[17]. Thus, the integration of potassium solubilizing bacteria within salt-affected, low-potassium, and degraded soils, combined with conservation agriculture practices and synergistic microbial partnerships, presents a robust strategy for sustainable crop production.

6. Comparative Efficiency of Key KSB Strains

The following table synthesizes data on strain specificity, demonstrating how different bacteria are better suited for particular mineral types and environmental challenges.

Table 2: Comparative Efficiency of Key KSB Strains

Bacterial Genus/Strain	Target Mineral	Key Factors Influencing Efficiency	Impact on Crop Performance	Tested Crops	Reference
<i>Bacillus aryabhattai</i>	Insoluble K Compounds (Feldspar)	Upregulation of <i>mdh</i> , <i>ppc</i> , and <i>gltA</i> genes; high secretion of malic, formic, and acetic acids.	Enhanced mineral weathering and aggressive nutrient mobilization.	Wheat & Tobacco	Chen <i>et al.</i> , 2022 ^[12]
<i>Enterobacter hormaechei</i>	Mica and Feldspar in Saline Soil	Synergy with <i>Pseudomonas putida</i> ; restoration of cytosolic ion balance.	Improved root fresh weight and biomass under high salinity stress.	Rice (<i>Oryza sativa</i>)	Nawaz <i>et al.</i> , 2023 ^[46] ; PMC, 2023 ^[49]
<i>Paenibacillus</i> spp.	Silicate Minerals (Biotite/Mica)	High production of Extracellular Polymeric Substances (EPS) and polysaccharides.	Formation of bacteria-mineral complexes for sustained K release.	Cereal crops	Zhang & Kong, 2014 ^[70] ; Sheng <i>et al.</i> , 2008 ^[58]
<i>Serratia marcescens</i>	Fixed & Non-exchangeable K	Production of IAA (7 mg/L+), siderophores, and antimicrobial HCN.	Increased root surface area; suppression of <i>Fusarium</i> pathogens.	Maize & Wheat	Bahadur <i>et al.</i> , 2019 ^[2] ; Rajawat <i>et al.</i> , 2022 ^[55]
<i>Pseudomonas putida</i>	Mineral K (Muscovite)	Rapid rhizosphere colonization and acidification (pH reduction to 4.4).	Enhanced KUE; grain yield increases of 15–25%.	Rice & Cotton	Zhao <i>et al.</i> , 2024 ^[73] ; Nawaz <i>et al.</i> , 2023 ^[46]

Detailed Analysis of Comparative Factors

Genetic Superiority: Strains like *Bacillus aryabhattai* SK1-7 are highly valued in research because they possess a distinct genetic architecture that allows them to "sense" potassium

deficiency and trigger a metabolic shift toward acidogenesis. This sensing mechanism leads to the upregulation of critical genes involved in organic acid biosynthesis such as malate dehydrogenase (*mdh*), phosphoenolpyruvate carboxylase (*ppc*),

and citrate synthase (*gltA*) which are essential for the aggressive breakdown of mineral structures.

Environmental Specialization: While *Serratia* is excellent for overall plant vigor and biological control, *Enterobacter* and *Pseudomonas* strains are currently the "gold standard" for remediating salt-affected soils due to their ability to regulate Na⁺ exclusion in roots. These specific strains improve potassium assimilation and maintain a favorable cytosolic K⁺/Na⁺ ratio, which is critical for preserving cell turgor and photosynthesis under high salinity stress.

Physical Weathering: *Paenibacillus* stands out for its high production of biofilms and extracellular polymeric substances (EPS). Instead of just dissolving minerals via acid, it physically binds to mineral particles to form bacteria-mineral complexes, creating a localized "micro-reactor" where acidolytic compounds are trapped at high concentrations, thereby accelerating the release of potassium.

7. Knowledge Gaps and Challenges

Despite the promising potential of potassium solubilizing bacteria (KSB) for enhancing crop potassium nutrition and sustainable agriculture, several critical knowledge gaps and challenges remain to be addressed to advance their effective application. The diversity and functional specificity of KSB across different agroecosystems is not fully elucidated. Although multiple genera such as *Bacillus*, *Pseudomonas*, and *Paenibacillus* have been identified as KSB, their solubilization efficiency varies widely depending on strain, soil type, and environmental conditions (Etesami *et al.*, 2017^[17]). Understanding the ecology and adaptive traits of KSB in diverse soils, including their interaction with other soil microbes, is essential for developing tailored bioinoculants with consistent performance (Sattar *et al.*, 2019)^[56].

Mechanistic understanding at the molecular level remains incomplete. While organic acid secretion and extracellular polysaccharide production are established solubilization pathways, the regulatory networks that control gene expression and metabolic flux under field conditions require further study (Chen *et al.*, 2022; Zhang & Kong, 2014)^[12, 70]. Advances in genomics and transcriptomics should be harnessed to uncover key genes and signalling pathways to optimize strain selection and engineering (Zhao *et al.*, 2024)^[73].

There is a persistent challenge in formulation technology and field scalability. Many potent KSB strains identified under laboratory conditions fail to establish or maintain efficacy in open field environments due to abiotic stresses like temperature fluctuations, desiccation, UV exposure, and competition with native microbiota (Bargaz *et al.*, 2018; Yadav, 2022)^[4, 70]. Robust delivery systems, carrier materials, and inoculation methods need development to improve bacterial survival, colonization, and activity in diverse cropping systems. Standardized and long-term field trials are lacking. Most current evidence relies on pot experiments or short-term studies under controlled conditions. More extensive, multi-location, and multi-seasonal field evaluations measuring not only potassium solubilization but also crop yield, soil health, and environmental impact are essential for validating KSB biofertilizer technologies for practical adoption (Raimi *et al.*, 2017; Basu *et al.*, 2021)^[6, 53].

Regulatory frameworks and farmer awareness of microbial biofertilizers remain limited in many regions. Addressing issues of quality control, certification, and dissemination strategies

alongside socio-economic studies will facilitate wider acceptance and integration of KSB-based products into mainstream agriculture (Malusa & Vassilev, 2014; Atieno *et al.*, 2020)^[40, 1]. Thus, addressing these knowledge gaps requires multidisciplinary research combining microbial ecology, molecular biology, agronomy, and socio-economics to realize the full potential of potassium solubilizing bacteria in sustainable agriculture.

8. Future Prospects

Future prospects for potassium solubilizing bacteria (KSB) usher in an era of innovative biotechnological applications and integration with advanced agricultural practices to enhance Potassium Use Efficiency (KUE), crop productivity, and sustainability. Emerging trends focus on utilizing multi-strain consortia, genome editing, advanced formulation technologies, and principles of precision agriculture to overcome current limitations and maximize KSB effectiveness across diverse agroecosystems.

Multi-Strain Consortia: Instead of single-strain inoculants, using microbial consortia comprising complementary KSB and other beneficial microbes (such as phosphate solubilizing bacteria and nitrogen fixers) offers synergistic effects. Such consortia enhance the nutrient solubilization spectrum and confer broader stress tolerance, increasing the consistency of crop responses under variable field conditions. Recent studies demonstrate consortia incorporating *Enterobacter*, *Pseudomonas*, *Bacillus*, and *Paenibacillus* species significantly improving potassium assimilation, root growth, and yield in crops under salinity and nutrient-deficient conditions (Nawaz *et al.*, 2023; Yadav, 2022)^[46, 70].

Genome Editing and Synthetic Biology: Advanced genetic tools like CRISPR-Cas enable precise manipulation of KSB genomes to enhance potassium solubilization pathways, acid production, stress tolerance, and plant growth-promoting traits. Genome sequencing of efficient isolates has identified key genes involved in organic acid synthesis and extracellular polysaccharide production that can be targets for enhancement (Chen *et al.*, 2022; Zhang *et al.*, 2023)^[12, 70]. Synthetic biology can also assemble custom microbial consortia with designed metabolic networks optimized for soil environments and specific crop needs (Jaiswal *et al.*, 2022)^[30].

Advanced Formulations and Delivery Technologies: Development of robust bioformulations using carriers like biochar, alginate beads, or nano-encapsulation ensures prolonged viability, controlled release, and effective colonization of KSB in field soils. Co-application with organic amendments further improves their survival and activity. Innovative seed coatings and foliar delivery methods enable targeted application, reducing inoculum loss and environmental degradation risks (Basu *et al.*, 2021; Vishwakarma *et al.*, 2020)^[6, 63].

Integration with Precision Agriculture: Leveraging remote sensing, soil nutrient mapping, and data-driven decision support systems allow precise KSB inoculation tailored to site-specific soil potassium status and crop requirements. Variable-rate inoculation and real-time monitoring of nutrient dynamics enhance intervention efficiency, minimize wastage, and optimize yield outcomes (Lowenberg-DeBoer *et al.*, 2020; Rajawat *et al.*, 2022)^[38, 55].

Research Directions: Focus on understanding microbe-soil-plant interactions under diverse climatic and edaphic conditions, developing regulations and standards for microbial biofertilizers, and educating farmers about best practices will be crucial for technology adoption. Multi-location and long-term field trials must validate multi-strain consortia and engineered strains for efficacy and environmental safety (Sattar *et al.*, 2019; Malusa *et al.*, 2016) [56, 39].

9. Conclusion

Potassium solubilizing bacteria (KSB) emerge as transformative biofertilizers poised to revolutionize sustainable agriculture by unlocking the natural reservoir of soil potassium through sophisticated biochemical and molecular mechanisms. Their multi-functional role extends beyond nutrient solubilization, encompassing hormonal modulation, pathogen biocontrol, and synergy with other beneficial microbes, thereby fostering resilient and productive agroecosystems. The future of KSB technology lies in harnessing multi-strain microbial consortia, genome editing for trait enhancement, advanced bioformulations, and precision agriculture integration to tailor site-specific nutrient management. Addressing current bottlenecks such as strain stability, field efficacy, and regulatory frameworks through multidisciplinary innovation will propel KSB from promising laboratory agents to mainstream tools in combating soil fertility decline and ensuring global food security. This intersection of microbiology, biotechnology, and agronomy heralds a new paradigm of eco-friendly, cost-effective, and high-efficiency plant nutrition that aligns with the urgent need for climate-smart and regenerative farming paradigms.

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