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Biodiversity and functional role of Potassium Solubilizing Bacteria (KSB) in sustainable crop production: A review

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ABSTRACT

The Potassium (K) is a vital macronutrient required for plant growth, photosynthesis, enzyme activation, and overall crop productivity. Despite its abundance in soils, more than 90% of potassium is locked in insoluble mineral forms such as feldspar, mica, and illite, making it unavailable for plant uptake. Potassium Solubilizing Bacteria (KSB) represent an eco-friendly alternative to chemical fertilizers, capable of mobilizing mineral-bound potassium through the production of organic acids, chelating compounds, and exopolysaccharides. These microbes enhance soil fertility, promote plant growth, and improve nutrient uptake efficiency. This review explores the diversity of KSB, mechanisms of potassium solubilization, and their effects on crop yield and soil health. It also examines the synergistic effects of co-inoculation with phosphate solubilizing bacteria (PSB), the influence of environmental factors on KSB activity, and recent advances in formulation technologies for field application. Understanding the bioefficacy and adaptability of KSB is essential for developing sustainable, low-cost biofertilizers to address potassium deficiency in agricultural systems. The review concludes by identifying key challenges and future research directions to harness the full potential of KSB for global food security and environmentally sustainable farming practices.

KEY WORDS: *Potassium Solubilising Bacteria*; *Bacillus*; *Rhizosphere*; *Biofertilizer*

1. Introduction

Potassium (K) is a critical macronutrient that plays a pivotal role in numerous plant physiological processes, including enzyme activation, photosynthesis, osmoregulation, protein synthesis, and translocation of assimilates. It is the third most essential macronutrient for plants, following nitrogen and phosphorus (Cakmak, 2005). Despite the abundant presence of potassium in most soils—often exceeding 20,000 ppm—the majority of it is found in forms that are not directly available to plants. Only a small fraction of potassium (approximately 0.1–2%) is present in plant-available forms such as exchangeable or solution potassium in the soil water phase (George and Micheal, 2002). The bulk of potassium is trapped in mineral matrices like feldspar, mica, and illite, from which it is not readily accessible to plants (Buchholz and Brown, 1993). This limitation in potassium availability, coupled with the high cost of conventional potassium fertilizers such as muriate of potash (KCl), has sparked a growing interest in

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sustainable alternatives to traditional fertilizers, particularly in regions like India, where the domestic production of potassium falls short of agricultural demand (Mala, 2013).

In response to this challenge, Potassium Solubilizing Bacteria (KSB) have emerged as promising biological agents capable of converting insoluble forms of potassium into more accessible, plant-available forms. These microorganisms, primarily from genera such as *Bacillus*, *Paenibacillus*, *Pseudomonas*, and *Acidothiobacillus*, mobilize potassium through a variety of mechanisms, including acidolysis, complexolysis, and the production of organic acids like citric, tartaric, and oxalic acid (Sheng and Huang, 2002; Friedrich *et al*., 1991). In addition to solubilizing potassium, KSB enhance plant growth through the production of phytohormones such as indole-3-acetic acid (IAA), phosphate solubilization, and siderophore-mediated nutrient acquisition (Sheng and Huang, 2001; Hu and Boyer, 1996).

The integration of KSB into agricultural systems offers a range of agronomic and ecological benefits. Studies in both field and controlled environments have shown that inoculation with KSB strains such as *Bacillus edaphicus* and *Paenibacillus glucanolyticus* can enhance dry matter content, root and shoot elongation, and overall yield in crops such as cotton, black pepper, groundnut, and tea (Sheng, 2005; Sangeeth *et al*., 2012; Bagyalakshmi *et al*., 2012). For example, the inoculation of *Paenibacillus glucanolyticus* has been shown to significantly improve potassium uptake and biomass accumulation in black pepper grown in potassium-deficient soils treated with wood ash (Sangeeth *et al*., 2012). These benefits are particularly notable in soils with low available potassium, where KSB help to alleviate nutrient deficiencies and boost crop productivity.

In addition to the direct benefits of KSB inoculation, these bacteria exhibit synergistic effects when co-inoculated with other beneficial microorganisms, such as phosphate-solubilizing bacteria (PSB). Han *et al*. (2006) demonstrated that dual inoculation with KSB and PSB in pepper and cucumber plants resulted in greater nutrient uptake and biomass accumulation than single inoculations or conventional mineral applications. The synergistic interaction between KSB and other microbial species offers significant potential in integrated nutrient management (INM) strategies, reducing reliance on chemical fertilizers while maintaining or even enhancing crop productivity. This highlights the importance of microbial consortia in modern agricultural practices, where multiple microbial functions can be harnessed to improve soil health and plant nutrition.

Despite the promising potential of KSB, several biotic and abiotic factors can influence their effectiveness in field conditions. Soil pH, moisture, temperature, mineral composition, and the availability of organic carbon are among the key factors that can impact the performance of KSB in soil (Parmar and Sindhu, 2013). For instance, extreme pH values, both acidic and alkaline, can hinder microbial activity and potassium solubilization. Furthermore, the availability of organic carbon and other nutrients can affect the growth and activity of KSB, particularly in nutrient-deficient soils. Understanding these environmental variables is essential for optimizing the use of KSB as biofertilizers in diverse agroecosystems.

The formulation and field application of KSB biofertilizers present additional challenges. While microbial inoculants such as nitrogen-fixing rhizobia and arbuscular mycorrhizal fungi have been extensively studied and commercialized, KSB-based formulations are relatively underexplored. The formulation of KSB products must account for factors such as microbial stability, shelf-life, and cost-effectiveness. Advances in biotechnology and microbial ecology are being employed to develop stress-tolerant and multifunctional KSB strains, with a focus on improving their shelf-life, viability during storage, and efficacy under field conditions. Additionally, the development of suitable carrier materials and the integration of KSB into existing agricultural practices, such as combined use with other microbial inoculants or chemical fertilizers, remains a critical area of research.

Moreover, the commercialization of KSB biofertilizers is impeded by regulatory hurdles. The lack of standardized testing protocols, quality control measures, and certification processes in many regions has led to concerns about the consistency and effectiveness of KSB products available in the market. The absence of clear regulatory frameworks also complicates the widespread adoption of KSB-based products, as farmers may be hesitant to invest in biofertilizers that are not well-regulated or certified. Thus, there is a need for the development of robust regulatory mechanisms that ensure the quality and efficacy of KSB biofertilizers before they can be widely adopted.

Given the growing body of research on KSB, significant knowledge gaps remain in areas such as the molecular mechanisms of potassium solubilization, strain-specific interactions with host plants, and the long-term field performance of KSB under diverse agro-climatic conditions. Understanding these mechanisms will be crucial for improving the efficiency and stability of KSB-based biofertilizers. In particular, research into the genetic regulation of potassium solubilization processes, as well as the role of microbial communities in enhancing nutrient cycling, will open new avenues for optimizing KSB strains for different environmental conditions.

This review aims to provide a comprehensive overview of the current state of research on KSB, focusing on the taxonomy, mechanisms of potassium solubilization, their effects on plant growth and nutrient uptake, and their interactions with other soil microbes. It also evaluates the challenges related to the commercialization and formulation of KSB biofertilizers and discusses potential future directions for advancing KSB research. Through this review, we aim to consolidate the existing knowledge on KSB and highlight the key areas that require further investigation to maximize their potential as sustainable alternatives to chemical fertilizers.

2. Soil potassium status and its limitations

Potassium (K) is one of the most abundant mineral nutrients in soil and plays a fundamental role in plant physiology, including enzyme activation, photosynthesis, osmoregulation, translocation of assimilates, and resistance to abiotic stress (Cakmak, 2005). Despite its high total concentration in most agricultural soils, potassium is predominantly present in forms that are not directly available for plant uptake. More than 90% of the total soil potassium is structurally bound within silicate minerals such as feldspar, mica, and illite. These forms are highly stable and cannot be absorbed by plant roots without prior solubilization.

Soil potassium exists in four interrelated pools that vary in their plant availability. The largest portion is mineral or structural potassium, which is tightly bound in the crystal lattices of primary minerals. This fraction is virtually inert in the short term and requires extensive weathering to be released. A second fraction, termed non-exchangeable or fixed potassium, is held between layers of 2:1 clay minerals, particularly illite and vermiculite. This pool can contribute potassium to the soil solution over time, albeit slowly, and is influenced by soil moisture, cation exchange processes, and microbial activity. More readily available forms include exchangeable potassium, which is adsorbed onto the surfaces of clay particles and soil organic matter and can be rapidly taken up by plant roots. Finally, the smallest fraction, soil solution potassium, exists as free K^+ ions in the soil water and represents the form most directly accessible to plants (George and Micheal, 2002; Friedrich *et al*., 1991).

However, the availability of these pools is not static. A critical issue is potassium fixation, a phenomenon wherein K^+ ions added through fertilizers or released from non-exchangeable sources become trapped between clay layers, especially in soils rich in illite and vermiculite. This fixation limits the immediate bioavailability of potassium and often necessitates repeated fertilization to meet crop demands. Additionally, potassium is highly mobile in certain soil textures. In sandy or low cation-exchange-capacity soils, it is prone to leaching beyond the root zone, particularly under conditions of heavy rainfall or over-irrigation. Such losses reduce nutrient use efficiency and contribute to environmental degradation.

The extraction of potassium through crop harvest is another major depletion pathway. High-yielding and intensively cultivated systems remove substantial quantities of potassium from the soil annually, further widening the gap between natural potassium supply and crop requirement. This is especially problematic in developing countries where potassium fertilizers are either unaffordable or heavily reliant on imports, such as in India where more than 29,000 tonnes of potassium are imported annually (Mala, 2013).

Several environmental and soil factors modulate potassium availability. Soil pH, for instance, plays a key role; acidic conditions may enhance leaching, while high pH may reduce microbial-mediated solubilization. Soil moisture and temperature also influence potassium diffusion and uptake by affecting root metabolism and microbial activity. Texture and mineralogy determine potassium retention capacity, with clay-rich soils generally holding more potassium in exchangeable form than sandy soils. Biological factors, especially the composition and activity of rhizosphere microorganisms, contribute significantly to the release of potassium from mineral forms (Sheng and Huang, 2002).

Among these biological agents, potassium solubilizing bacteria (KSB) have shown promise in mobilizing unavailable potassium through mechanisms such as acidolysis, chelation, and polysaccharide production. Certain strains of *Bacillus mucilaginosus*, *Paenibacillus glucanolyticus*, and *Bacillus edaphicus* have been shown to effectively solubilize potassium-bearing minerals and improve K uptake in various crops. These microbial processes offer a natural and sustainable means of increasing potassium bioavailability, thereby reducing dependence on chemical fertilizers.

Despite these benefits, the consistent performance of KSB in field conditions remains influenced by soil heterogeneity, competition with native microflora, and formulation constraints. Therefore, a detailed understanding of the soil potassium pools, their dynamics, and the environmental context is crucial for optimizing the use of KSB in sustainable agricultural systems.

3. Mechanisms of potassium solubilization by Potassium Solubilizing Bacteria (KSB)

Potassium (K) is an essential macronutrient required for a variety of physiological processes in plants, including enzyme activation, protein synthesis, and osmoregulation. However, a large proportion of potassium in soils is present in mineral forms (e.g., feldspar, mica) that are insoluble and not readily available to plants. Potassium solubilizing bacteria (KSB) play a crucial role in enhancing the bioavailability of potassium by converting insoluble forms into soluble ones, thereby improving plant nutrition. Several mechanisms have been identified through which KSB solubilize potassium, including organic acid production, proton excretion, enzyme secretion, and ion exchange.

3.1 Organic acid production

One of the primary mechanisms through which KSB solubilize potassium is the production of organic acids. These acids lower the pH of the surrounding soil environment, leading to the dissolution of potassium-bearing minerals. The production of acids, such as citric acid, oxalic acid, lactic acid, and acetic acid, is widely recognized as a key factor in K solubilization (Saharan & Nehra, 2011). These organic acids are capable of chelating potassium ions and breaking the mineral structures that bind potassium, thus making it more accessible to plants.

The acidification of the soil through organic acid production can also enhance the solubility of other essential nutrients, such as phosphorus and calcium, further promoting plant growth (Khan *et al*., 2012). For instance, the bacterium *Bacillus mucilaginosus* is known to produce citric acid, which effectively solubilizes potassium from feldspar, a common potassium-containing mineral in soils (Swarup *et al*., 2013). Similarly, *Enterobacter* species have been shown to produce a combination of organic acids that facilitate the solubilization of potassium as well as other macro- and micronutrients.

3.2 Proton excretion

In addition to organic acid production, KSB also solubilize potassium through proton excretion. The secretion of protons (H+) by bacteria into the surrounding environment causes acidification, which helps in the breakdown of potassium-bearing minerals. The acidification process not only dissolves minerals but also enhances the release of potassium ions into the soil solution (Rodríguez *et al*., 2006). This mechanism is particularly important in alkaline soils where potassium availability is naturally limited due to the higher pH and reduced solubility of potassium minerals.

Bacteria such as *Bacillus* and *Pseudomonas* spp. are known for their ability to secrete protons, effectively lowering the pH of the rhizosphere.

The presence of protons in the soil promotes the dissociation of potassium from mineral particles, making it available for plant uptake (Gaur & Pathak, 2003).

3.3 Production of enzymes

KSB also produce enzymes that contribute to potassium solubilization. These enzymes include phosphatases, proteases, and cellulases, which can break down organic materials in the soil, releasing minerals including potassium. The enzymatic degradation of minerals in the soil matrix is an essential process for mineral weathering and the subsequent release of potassium (Kandeler *et al.*, 2000).

For example, *Bacillus* spp. and *Pseudomonas* spp. produce various extracellular enzymes that catalyze the release of potassium ions from insoluble mineral sources. Additionally, some KSB also secrete exopolysaccharides, which enhance mineral dissolution by forming a protective biofilm around the bacterial colony, thereby increasing the efficiency of potassium solubilization in the rhizosphere (Barka *et al.*, 2004).

3.4 Ion exchange and chelation

Potassium solubilization by KSB can also occur through ion exchange and chelation. KSB can exchange cations, such as calcium and magnesium, with potassium ions from the mineral surfaces. This ion exchange process effectively releases potassium into the soil solution, increasing its availability for plant uptake. In addition, KSB can produce chelating agents, which bind to potassium and release it from mineral particles. Chelation plays a vital role in the solubilization of potassium from complex minerals, especially in soils with high cation exchange capacity (CEC).

A study by Glick *et al*. (2007) demonstrated that *Pseudomonas putida* and other KSB can mobilize potassium through a combination of ion exchange and chelation. These bacteria have the ability to use organic compounds as chelating agents, which not only solubilize potassium but also enhance the uptake of other essential nutrients like phosphorus and magnesium.

3.5 Role of phytosiderophores and other metabolites

Some KSB, particularly those in the genus *Pseudomonas*, can produce metabolites known as phytosiderophores. These are compounds that specifically bind to metal ions, such as potassium, facilitating their transport into the plant roots (Loper and Buyer, 1991). Phytosiderophores play a crucial role in solubilizing potassium in soils where it is otherwise bound to mineral particles or organic matter, thus enhancing the bioavailability of potassium to plants.

In addition to phytosiderophores, KSB may secrete other secondary metabolites that can assist in potassium solubilization. These include siderophores for iron, which often work in tandem with potassium solubilization mechanisms, improving the overall nutrient availability in the rhizosphere (Bais *et al*., 2006).

3.6 Interactions with plant roots

The interaction between KSB and plant roots is another important factor in potassium solubilization. KSB can establish symbiotic or associative relationships with plant roots, leading to enhanced potassium uptake. In return for potassium and other nutrients, plants provide organic carbon sources to the bacteria. The rhizosphere is a dynamic environment where KSB can alter the soil chemistry, making potassium more available to plants. For example, the exudation of organic acids and enzymes by plant roots can stimulate KSB activity, thereby promoting the solubilization of potassium from minerals (Etesami and Beattie, 2018).

4. Effects of KSB on plant growth and nutrient uptake

4.1 Enhancement of potassium availability by KSB

Potassium (K) is essential for plant growth (Fig. 1), yet its availability in many agricultural soils is limited due to its fixation in mineral forms such as feldspars, micas, and illite, which plants cannot directly absorb. Potassium solubilizing bacteria (KSB) are recognized for their unique ability to mobilize these unavailable forms through biochemical mechanisms, thus enhancing the potassium nutrition of crops in a sustainable manner.

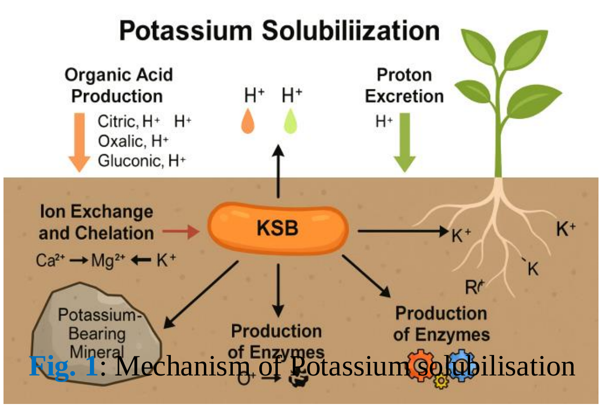

Fig. 1: Mechanism of Potassium solubilisation

One of the principal mechanisms by which KSB enhance potassium availability is through the production of organic acids such as citric, oxalic, gluconic, and malic acids. These acids lower the soil pH and chelate metal ions (like Al^{3+}, Fe^{3+}, Ca^{2+}), thereby releasing potassium ions into the soil solution (Sheng and He, 2006). For example, *Bacillus mucilaginosus* was reported to solubilize up to 32% of the total potassium content from feldspar by secreting oxalic and citric acids (Zhang and Kong, 2014).

A comparative study by Parmar and Sindhu (2013) demonstrated that inoculation with potassium-solubilizing strains of *Bacillus* and *Pseudomonas* significantly increased the available potassium content in both clay and loamy soils, outperforming untreated controls by 20–40%. In a pot experiment with tomato (*Solanum lycopersicum*), these strains increased soil available K from 58.2 mg kg^{-1} to 93.6 mg kg^{-1} and improved the K uptake by 42%.

Moreover, Pramanik *et al*. (2019) isolated a novel strain of *Bacillus pseudomycoides* from the rhizosphere of tea plants that enhanced potassium release from mica waste, leading to a 1.5-fold increase in tea biomass in greenhouse trials. Similarly, Meena *et al.* (2016) found that co-application of *Frateuria aurantia* (a known KSB) with vermicompost improved available potassium in the root zone by 27% in wheat and maize under field conditions.

The mode of action of these microbes is not restricted to acid production alone. They also release extracellular enzymes and polysaccharides that modify the micro-environment of the rhizosphere, promoting mineral dissolution. An investigation by Ahmad *et al*. (2021) found that KSB could bio-weather silicate minerals like biotite and muscovite, enhancing potassium mobilization up to 35% in 60 days.

Further, KSB activity also improves soil structure and microbial diversity. Ramesh *et al*. (2022) observed that repeated KSB inoculation led to higher microbial biomass carbon and dehydrogenase activity, contributing to improved potassium cycling in the rhizosphere.

In summary, the capacity of KSB to transform non-exchangeable and mineral-bound potassium into plant-available forms is well-supported by various studies. Their application as biofertilizers not only improves K nutrition but also reduces dependency on chemical potassium fertilizers, thus offering a sustainable approach to nutrient management.

4.2 Promotion of Plant Growth Parameters

The influence of potassium solubilizing bacteria (KSB) on plant growth extends beyond mere enhancement of potassium availability. These microbes also exert significant effects on a wide range of plant growth parameters including germination rate, root and shoot elongation, biomass accumulation, chlorophyll content, and overall vigor. This multifaceted plant growth promotion is the result of a combination of mechanisms including nutrient solubilization, phytohormone production, siderophore release, and stress mitigation.

Several studies have reported that KSB strains, particularly from genera like *Bacillus*, *Frateuria*, and *Pseudomonas*, stimulate seed germination and seedling vigor. For instance, Basak and Biswas (2010) demonstrated that inoculation of rice seeds with *Bacillus mucilaginosus* significantly improved seedling length (by 28%) and dry weight (by 34%) over uninoculated controls, attributed to increased K availability and enhanced production of indole-3-acetic acid (IAA), a plant growth-promoting hormone.

Similarly, *Frateuria aurantia*, a known KSB species, was tested on tomato plants by Meena *et al*. (2016). The results indicated not only a 20–25% increase in shoot length and leaf number but also a substantial increase in chlorophyll content and flowering rate. These improvements were linked to the bacterium's dual ability to mobilize potassium and produce cytokinins, which modulate cell division and shoot development.

Potassium plays a pivotal role in osmoregulation, enzyme activation, and photosynthesis. Therefore, its enhanced availability via KSB activity can significantly improve physiological parameters. In a greenhouse study, Sheng and He (2006) reported that wheat plants inoculated with *Bacillus edaphicus* exhibited higher stomatal conductance, photosynthetic rate, and relative water content. These physiological enhancements translated into a 35% increase in dry matter accumulation compared to uninoculated controls.

Moreover, KSB have shown synergistic effects when applied with other plant growth-promoting rhizobacteria (PGPR). For instance, Parmar and Sindhu (2013) observed that co-inoculation of KSB with phosphorus-solubilizing bacteria (PSB) in maize resulted in a 45% increase in plant height and a 30% increase in leaf area index compared to either inoculant alone. This suggests that nutrient solubilization by KSB creates a conducive environment for overall microbial synergism, boosting plant growth.

In a field experiment, Ahmad *et al*. (2021) applied a KSB-based biofertilizer to potato crops. The treated plots not only yielded 18% more tubers but also showed significant increases in root volume and shoot-to-root ratio. Furthermore, these plants had higher potassium content in leaf tissues, which correlated positively with photosynthetic efficiency and biomass productivity.

Some strains of KSB also contribute to abiotic stress alleviation. Under saline or drought conditions, potassium acts as an essential osmoprotectant. Khan *et al.* (2015) reported that plants treated with *Enterobacter* sp. KSB isolates under salt stress maintained higher relative water content and exhibited less electrolyte leakage. This was partly due to improved K^+/Na^+ balance facilitated by microbial solubilization and uptake regulation.

Beyond growth metrics, KSB influence reproductive development. Experiments on sunflower by Prasad *et al.* (2020) revealed that application of *Frateuria aurantia* increased flower diameter, seed set percentage, and 1000-seed weight, leading to an overall 22% yield increase. Such findings emphasize the potential of KSB not only as growth enhancers but also as yield boosters.

4.3 Impact of KSB on nutrient uptake efficiency

Potassium solubilizing bacteria (KSB) have been increasingly recognized not only for their capacity to mobilize potassium but also for their broader impact on improving the overall nutrient uptake efficiency in plants. This includes enhanced absorption of macronutrients such as nitrogen (N), phosphorus (P), and potassium (K), as well as several important micronutrients like magnesium (Mg), zinc (Zn), and iron (Fe). By improving root growth, increasing root surface area, and altering the rhizosphere chemistry, KSB help plants acquire more nutrients efficiently, even in nutrient-poor soils.

A landmark study by Meena *et al.* (2016) demonstrated that inoculation of maize with *Frateuria aurantia* significantly increased uptake of N (by 23%), P (by 31%), and K (by 45%) compared to uninoculated controls. This improvement in nutrient uptake was attributed to the enhanced root length and surface area induced by microbial activity as well as better mobilization of nutrients in the soil matrix. The researchers observed a corresponding increase in biomass accumulation and yield parameters.

Similarly, Parmar and Sindhu (2013) reported that co-inoculation of KSB with nitrogen-fixing and phosphate-solubilizing bacteria in wheat led to improved uptake of all three major nutrients (NPK), with potassium uptake showing the highest improvement of 50%. The synergistic microbial interactions appeared to trigger a cascade of beneficial changes in soil enzymatic activity and rhizosphere bioavailability of essential ions.

KSB also impact micronutrient uptake through indirect mechanisms such as siderophore production, pH modification, and chelation of soil minerals. For example, Basak and Biswas (2010) observed a marked increase in Fe and Zn uptake in rice following treatment with *Bacillus mucilaginosus*. The bacteria secreted siderophores and organic acids that helped in chelating Fe^{3+} and releasing Zn^{2+} from insoluble complexes in soil, thus improving micronutrient availability.

The influence of KSB on nutrient uptake is not restricted to controlled conditions. In a field experiment conducted by Ramesh *et al*. (2022) on chickpea, KSB inoculation led to a 38% increase in phosphorus uptake and a 47% increase in potassium uptake compared to standard fertilizer application alone. Soil analysis showed a significant rise in available P and exchangeable K, likely due to organic acid secretion and root-induced changes in rhizosphere pH.

Another study by Adhikari *et al*. (2018) investigated the combined impact of KSB and compost on nutrient uptake in mustard plants. Results showed that microbial inoculation significantly enhanced the availability and plant uptake of nitrogen (by 19%), phosphorus (by 24%), and potassium (by 36%), suggesting that organic matter and microbial synergy can further improve the nutrient acquisition process. Interestingly, this study also noted enhanced sulfur and magnesium concentrations in treated plants, further illustrating the broad-spectrum benefit of KSB.

Moreover, some strains of KSB can modulate nutrient transporters in plants. Ahmad *et al*. (2021) demonstrated that inoculation with a strain of *Enterobacter cloacae* upregulated the expression of K^+ and NO_3^- transporter genes in maize roots, resulting in improved nutrient translocation to aerial parts. This kind of plant–microbe signaling indicates that the benefits of KSB go beyond solubilization and extend to influencing plant metabolic and transport processes.

In legumes, potassium is especially important for nodule function and biological nitrogen fixation. A recent study by Narayanasamy *et al*. (2023) on soybean demonstrated that KSB inoculation increased both nodule number and nitrogenase activity, thereby boosting nitrogen uptake efficiency. This illustrates the indirect but critical role of K in facilitating N_2 fixation and overall plant nutrition.

4.4 KSB mediated stress tolerance and yield enhancement

In addition to improving nutrient availability, potassium solubilizing bacteria (KSB) play a crucial role in enhancing plant resilience to abiotic stresses such as drought, salinity, and nutrient deficiency, ultimately contributing to improved crop yields. This multifaceted benefit arises from the combined action of enhanced potassium uptake, modulation of stress-responsive genes, production of plant growth-promoting compounds, and improvement in soil health parameters. Potassium is a key osmolyte and plays a significant role in regulating plant water balance, enzyme activation, and stomatal functioning. Thus, any increase in its bioavailability through microbial action can greatly influence plant adaptation to stress conditions.

Several studies have highlighted the influence of KSB on drought tolerance. For instance, Verma *et al*. (2017) demonstrated that *Bacillus mucilaginosus* inoculation in wheat under limited irrigation led to increased root biomass, relative water content, and improved chlorophyll stability index. This was attributed to the enhanced K uptake facilitated by microbial activity, which allowed better osmotic regulation and stomatal conductance. The study also observed a 25% increase in grain yield under stress conditions, underlining the practical significance of KSB in real-world agriculture. Similarly, Singh and Reddy (2020) observed that maize plants inoculated with a consortium of KSB and arbuscular mycorrhizal fungi showed improved drought resistance through enhanced antioxidant enzyme activity and reduced membrane damage, leading to yield stability under water-limited regimes.

Salinity stress, another major yield-limiting factor, can also be mitigated by the action of KSB. Potassium plays a pivotal role in maintaining ionic balance by reducing sodium uptake and maintaining high K^+/Na^+ ratios within cells. In a controlled pot experiment, Rahi *et al.* (2019) reported that tomato plants inoculated with *Frateuria aurantia* exhibited significantly higher potassium content and reduced Na^+ accumulation in leaves under salinity stress, leading to enhanced biomass production and fruit quality. The bacterial strain produced high levels of gluconic and citric acid, facilitating K solubilization from feldspar and mica in saline soils. Furthermore, Sharma *et al*. (2021) reported that the application of KSB in rice improved electrolyte balance and osmotic potential, ultimately mitigating the adverse effects of salt stress.

Beyond abiotic stress, the role of KSB in boosting crop yield in normal agronomic conditions has also been substantiated through multiple field trials. Ahmad *et al*. (2018) conducted multi-season trials in chickpea and observed that the use of KSB inoculants increased grain yield by 20–30% compared to uninoculated controls. This increase was directly linked to enhanced nutrient uptake, increased photosynthetic efficiency, and better reproductive development. The biofertilizer treatment also improved root-to-shoot ratio, which is often associated with efficient nutrient translocation. In another study, Ghosh and Banerjee (2022) found that sugarcane plots treated with a mixture of KSB and vermicompost showed 18% higher cane yield and improved sugar recovery, highlighting the commercial relevance of microbial potassium mobilization.

The ability of KSB to produce secondary metabolites such as indole-3-acetic acid (IAA), gibberellins, and ACC deaminase also contributes to stress tolerance and yield improvement. These phytohormones stimulate cell elongation, lateral root proliferation, and delay senescence during stress episodes. For example, an isolate of *Paenibacillus* sp. reported by Thakur *et al*. (2020) exhibited dual functionality of K solubilization and IAA production, which significantly enhanced the root architecture and nutrient acquisition potential in soybean. This resulted in a 22% increase in pod yield under suboptimal potassium availability.

Interestingly, KSB-mediated improvements in soil health parameters such as soil structure, microbial biomass carbon, and cation exchange capacity also indirectly contribute to plant growth and yield. Long-term experiments in wheat by Dwivedi *et al*. (2019) demonstrated that repeated use of KSB inoculants enhanced the soil aggregate stability and maintained higher levels of exchangeable K, even after successive cropping seasons. The authors suggested that the build-up of beneficial microbial populations and enhanced nutrient cycling played a vital role in sustaining crop productivity.

4.5 Synergistic interactions of Potassium-Solubilizing Bacteria (KSB) with other soil microorganisms

Potassium-solubilizing bacteria (KSB) play a pivotal role in enhancing plant nutrient uptake by converting insoluble potassium forms into bioavailable forms. Their interactions with other soil microbes, such as nitrogen-fixing bacteria, phosphate-solubilizing bacteria (PSB), and mycorrhizal fungi, can lead to synergistic effects that further promote plant growth and soil health. This section delves into these interactions, highlighting their mechanisms and implications for sustainable agriculture.

Interaction with Nitrogen-Fixing bacteria

Nitrogen-fixing bacteria, such as *Rhizobium*, *Azotobacter*, and *Acinetobacter* species, convert atmospheric nitrogen into ammonia, a form usable by plants. When co-inoculated with KSB, these bacteria can synergistically enhance plant growth by simultaneously improving nitrogen and potassium availability. For instance, a study demonstrated that the combined application of *Acinetobacter guillouiae* (a nitrogen fixer) and *Acinetobacter calcoaceticus* (a potassium solubilizer) significantly improved shoot and root length, biomass, and chlorophyll content in onion plants compared to individual inoculations or control treatments .

Similarly, Basak and Biswas (2010) investigated the co-inoculation of *Bacillus mucilaginosus* (KSB) and *Azotobacter chroococcum* (nitrogen-fixing bacteria) on sudan grass grown in Typic Haplustalf soil. The study revealed that this microbial consortium, in the presence of waste mica as a potassium source, led to significantly higher biomass accumulation and nutrient acquisition compared to single inoculations or control treatments. These findings underscore the potential of integrating KSB with nitrogen-fixing bacteria to enhance plant growth and nutrient uptake.

Interaction with Phosphate-Solubilizing Bacteria

Phosphorus is another essential macronutrient often limited in soils. PSB, such as *Bacillus megaterium*, solubilize inorganic phosphate compounds, making phosphorus available to plants. The co-inoculation of KSB and PSB has been shown to enhance the availability of both potassium and phosphorus. In maize, dual inoculation with KSB and PSB led to increased microbial populations and enzyme activities in the rhizosphere, resulting in enhanced nutrient availability and plant growth. Similarly, in chamomile, the combined application of *Bacillus megaterium* (PSB) and *Frateuria aurantia* (KSB) with reduced fertilizer doses improved plant height, flower number, and dry weight, indicating the potential of such combinations in sustainable agriculture.

Han *et al*. (2006) evaluated the effect of co-inoculation with PSB (*Bacillus megaterium* var. phosphaticum) and KSB (*Bacillus mucilaginosus*) on pepper and cucumber. The study demonstrated that this microbial combination significantly increased the availability of phosphorus and potassium in the soil, leading to enhanced nutrient uptake and plant growth. These results highlight the synergistic potential of PSB and KSB in improving nutrient dynamics and crop performance.

Interaction with mycorrhizal fungi

Mycorrhizal fungi form symbiotic associations with plant roots, extending the root system and enhancing nutrient uptake, particularly phosphorus. While specific studies on the direct interaction between KSB and mycorrhizal fungi are limited, it's well-established that mycorrhizal associations enhance nutrient uptake, including potassium. The presence of KSB in the rhizosphere can complement mycorrhizal functions by increasing the availability of potassium, which mycorrhizal fungi can then transport to the plant, suggesting a potential synergistic relationship that warrants further research.

Combined effects on plant growth and soil health

The integration of KSB with other beneficial microbes not only improves nutrient solubilization but also enhances overall soil health. For example, the co-inoculation of KSB and PSB in maize resulted in increased enzyme activities like dehydrogenase, urease, and phosphatase in the rhizosphere, indicating a more active and healthy soil microbial community. Such microbial consortia can reduce the reliance on chemical fertilizers, promoting sustainable agricultural practices.

4.6 Formulation, commercialization, and application of KSB biofertilizers

The effectiveness of potassium-solubilizing bacteria (KSB) in sustainable agriculture depends not only on their isolation and mechanistic potential but also significantly on their formulation, commercialization, and application methods. Formulating KSB as stable, viable, and scalable products is essential for their successful integration into agricultural practices.

Formulation involves incorporating live microbial cells into carriers that ensure their survival during storage and field application. Several studies have demonstrated the importance of carrier materials in maintaining microbial viability. For example, Basak and Biswas (2010) found that peat-based formulations preserved *Bacillus mucilaginosus* viability for over 180 days at ambient temperatures, whereas charcoal and vermiculite showed lower efficacy. In another study, Gopalakrishnan *et al*. (2015) used talc as a carrier and noted improved shelf life and colonization efficiency of KSB strains when used in chickpea rhizospheres, promoting growth and potassium uptake. Such results underscore the importance of optimizing carrier type and moisture content to enhance microbial fitness and functional performance.

Encapsulation technology has emerged as a superior approach to bioformulation. Pandey and Maheshwari (2013) developed sodium alginate-based beads to encapsulate *Frateuria aurantia*, a known KSB, and observed a higher survival rate and controlled release of viable cells in rhizosphere soil. This technique improved both microbial stability and colonization efficiency under field conditions. Similarly, Adesemoye *et al*. (2015) reported that encapsulated formulations of *Bacillus aryabhattai* not only extended shelf-life but also improved nutrient acquisition in tomato plants, suggesting that encapsulation can be a game-changer for biofertilizer commercialization in regions with erratic climate and storage challenges.

The commercialization of KSB-based products has gained momentum in recent years, especially in India and China, where the demand for low-cost, environmentally safe fertilizers is growing. Companies like IFFCO and Krishak Bharati Cooperative (KRIBHCO) have launched KSB-based formulations such as *Frateuria aurantia* biofertilizer and potassium mobilizing consortia targeting rice and wheat systems. According to Sharma *et al*. (2021), these products have shown promising results in multi-location field trials, increasing K uptake by 25–30% and yield by 12–

20% compared to control plots. Nevertheless, the success of these products hinges not only on microbial efficacy but also on awareness, farmer training, and policy support to encourage adoption.

In terms of application, KSB biofertilizers can be delivered through multiple methods, including seed coating, seedling root dipping, soil broadcasting, and fertigation. Each technique has specific advantages depending on crop type, soil texture, and agroecological conditions. For instance, Pindi and Satyanarayana (2012) reported that seed coating of chili (*Capsicum annuum*) with a talc-based *Bacillus mucilaginosus* formulation enhanced early root colonization and significantly increased fruit yield. In contrast, soil drenching methods were more effective for perennial crops like banana and citrus, where root surface exposure is limited.

Field experiments conducted by Verma *et al*. (2013) demonstrated that a dual inoculation approach - combining KSB with phosphate-solubilizing bacteria - resulted in synergistic effects, improving nutrient uptake, soil fertility, and plant biomass in maize. This highlights the potential of integrating KSB within consortia-based biofertilizer products. However, large-scale application also requires compatibility with existing farming practices and agricultural inputs, including irrigation methods, chemical fertilizers, and organic amendments. Compatibility studies, such as those by Ahmad *et al*. (2016), showed that KSB strains could withstand co-application with low doses of muriate of potash, indicating flexibility in use.

Despite these advancements, there remain challenges in maintaining microbial viability during transport, achieving consistent field performance, and registering microbial strains for legal commercialization. Regulatory frameworks in many countries, especially in Africa and Latin America, lack standardization, which hampers the global scale-up of KSB-based biofertilizers. Therefore, further research into strain stability, formulation science, and product validation under diverse climatic zones is essential for widespread adoption.

5. Challenges and Future Directions

The implementation of potassium-solubilizing bacteria (KSB) in sustainable agriculture presents considerable promise, yet several persistent challenges restrict their widespread use, efficacy, and market penetration. A primary issue lies in the variability of KSB performance under field conditions. Numerous studies have demonstrated that the efficiency of KSB observed in vitro or under greenhouse conditions does not always translate reliably to open-field scenarios. For instance, Basak and Biswas (2010) reported significant potassium solubilization and plant growth enhancement by *Bacillus mucilaginosus* under controlled conditions, but noted only marginal improvements under natural field settings, attributing the discrepancy to factors such as competition with indigenous microbial populations, climatic variations, and soil heterogeneity. Such findings highlight the pressing need for context-specific selection and testing of microbial strains.

Another major obstacle is the formulation and shelf-life stability of KSB-based products. The efficacy of biofertilizers is highly dependent on their ability to maintain viable cell counts over time without loss of functional properties.

Conventional formulations using talc or peat often suffer from rapid viability loss during storage and transportation, particularly in tropical climates. Gopalakrishnan *et al*. (2015) explored talc-based formulations and found a significant decline in viable cell counts beyond 90 days under ambient storage, limiting the utility for large-scale commercial distribution. While encapsulation techniques using alginate or starch matrices have shown potential in prolonging shelf-life and ensuring controlled release (Pandey and Maheshwari, 2013), such technologies remain cost-intensive and are yet to be widely adopted by small-scale biofertilizer producers.

Moreover, the absence of well-defined regulatory frameworks for microbial biofertilizers, especially in developing countries, has emerged as a substantial barrier to commercialization. In many regions, KSB products are marketed without mandatory validation of microbial content, efficacy, or strain identity, leading to inconsistent quality and skepticism among end-users. Sharma *et al*. (2021) emphasized that several commercially available KSB products in India contained lower-than-claimed viable cell counts or included unverified strains, pointing to the urgent need for stringent quality control mechanisms, certification processes, and legislative oversight.

From a scientific standpoint, incomplete understanding of the molecular mechanisms underlying potassium solubilization also hampers the development of more efficient KSB strains. While it is well-established that organic acid production plays a key role in mobilizing potassium from insoluble minerals, the genetic regulation of this process remains inadequately explored. Recent genome analyses of *Bacillus aryabhattai* and *Frateuria aurantia* have revealed potential gene clusters associated with acidogenesis and mineral dissolution, yet their functional characterization remains incomplete (Ahmad *et al*., 2016). Targeted research utilizing transcriptomics and proteomics could elucidate stress-responsive pathways and identify markers for strain selection under specific agroecological conditions.

Another concern is the compatibility of KSB with prevailing agricultural practices. KSB strains often exhibit reduced survival when applied in fields treated with chemical pesticides or excessive mineral fertilizers. Verma *et al*. (2013) demonstrated that the combined application of KSB and potassium chloride (KCl) at moderate doses improved plant growth and nutrient uptake in maize. However, higher doses of KCl suppressed microbial activity and neutralized the solubilizing effects, underscoring the need for precise integration within existing nutrient management systems.

Looking forward, research must focus on developing genetically robust and ecologically adaptable KSB strains through advanced biotechnological interventions such as CRISPR-based genome editing and adaptive evolution techniques. Additionally, low-cost, locally available carrier materials - such as sugarcane bagasse, fly ash, or rice husk ash - should be explored to design stable and farmer-friendly bioformulations. Furthermore, widespread farmer awareness campaigns and extension services must be deployed to bridge the knowledge gap between scientific research and practical application. Lastly, region-specific consortium-based formulations that combine KSB with other beneficial microbes, such as nitrogen fixers and phosphate solubilizers, could offer synergistic effects that enhance overall soil fertility and crop productivity.

Addressing these multifaceted challenges through coordinated scientific, technological, and policy efforts will be pivotal for translating the laboratory success of KSB into field-level agricultural benefits, thereby contributing to long-term soil health and global food security.

6. Conclusion

Potassium solubilizing bacteria (KSB) represent a promising solution for enhancing potassium availability in soils, which is crucial for sustainable agricultural practices. The review presented above has discussed various facets of KSB, starting with the underlying biogeochemical processes that govern their function in soil. KSB play a key role in mobilizing potassium from insoluble mineral sources, thereby making this essential nutrient more accessible to plants. The diversity and taxonomy of these microorganisms reveal a vast array of bacterial species with different mechanisms for potassium solubilization, which are yet to be fully understood at the molecular level.

In terms of their application, KSB have demonstrated substantial benefits in greenhouse and controlled-environment studies, improving plant growth and yield in a variety of crops. However, translating these findings to the field remains a challenge due to environmental factors such as soil type, microbial community interactions, and climate variability. The performance of KSB biofertilizers often varies under different field conditions, highlighting the need for careful selection and optimization of microbial strains based on local agricultural practices.

Formulation, commercialization, and application of KSB biofertilizers have faced hurdles such as formulation stability, shelf-life, and regulatory issues. Several studies have indicated that current formulations, such as talc-based carriers, are not always effective in maintaining the viability of KSB during storage and application. Advances in formulation technologies, such as encapsulation and the use of organic materials, show promise in enhancing product stability, but these solutions still require cost-effective scaling for mass production. Furthermore, the regulatory landscape for KSB-based products remains underdeveloped, which may restrict the widespread use of these biofertilizers in global markets.

The integration of KSB into integrated nutrient management systems is a promising direction for future research. Studies suggest that combining KSB with other beneficial microbes, such as nitrogen-fixing bacteria and phosphate-solubilizing microorganisms, can lead to synergistic effects that further enhance soil fertility and crop productivity. Nevertheless, challenges related to microbial competition, environmental stress, and the lack of detailed molecular understanding of KSB mechanisms need to be addressed for more effective applications.

Future research should prioritize advancing the molecular understanding of KSB through genomics and proteomics, which will allow for the development of more efficient and resilient strains. Additionally, strategies aimed at improving the compatibility of KSB with conventional farming practices, such as chemical fertilizers and pesticides, must be explored. Strain improvement and formulation innovation will be critical in overcoming the current limitations of KSB biofertilizers and enabling their widespread adoption by farmers.

In conclusion, while significant progress has been made in understanding and utilizing KSB for sustainable agriculture, challenges remain that must be overcome to realize their full potential. A concerted effort involving scientific research, technological innovation, regulatory development, and farmer education is essential to ensure the successful application of KSB in modern agriculture, ultimately contributing to more sustainable and resilient farming systems worldwide.

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