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The use of soil microbial potassium solubilizers in potassium nutrient availability in soil and its dynamics

Faridat Temilomo Olaniyan[1,2,3], Elizabeth Temitope Alori[1,2,3*], Aruna Olasekan Adekiya[4], Bisola Bolajoko Ayorinde[1], Fisayo Yemisi Daramola[5], Osarenkhoe Omorefosa Osemwegie[1,2,6] and Olubukola Oluranti Babalola[7]

Abstract

Background: An increase in population has led to a higher demand for food. Meeting up this demand has necessitated the use of chemical fertilizers. However, utilization of these fertilizers has a considerable deleterious effect on the soil, plant, human, environmental sustainability, and only increase the cost and reduced profitability. With these identified problems, there is a need for efficient and sustainable methods regarding managing natural resources to enhance food production. Naturally, potassium (K) is an abundant element present in the soil but in an inaccessible form. There is therefore a need to seek an alternative method to improve the K availability to plants noting that K is an essential plant nutrient that plays a major role in plant physiological and metabolic processes. Subsequently, employing microbial potassium solubilizers is an efficient method to enhance the potassium availability in the soil, which in turn improves productivity. Therefore, this review discusses the various types of potassium solubilizing microorganisms in soil, their mechanism of action, and their importance in sustainable crop production.

Main body: Potassium solubilizing microorganisms (KSM) such as bacteria and fungi can solubilize K from an insoluble form to a soluble form to enhance uptake by plants. These microorganisms solubilize K through the production of organic acids such as tartaric acid, citric acid, and oxalic acid to release K from its minerals. Apart from making potassium available, these microbes can improve soil health and crop yield and act as bio-control agents by producing antibiotics. Potassium solubilizing microbes also produce hormones that help plants withstand both biotic and abiotic stresses. Hence, the application of KSM to agricultural soils will reduce the use of chemical fertilizers and enhance the sustainability of food production.

Conclusion: One of the most efficient ways of improving plant utilization of potassium in the soil is to use potassium solubilizing microbes, which can make potassium ions available from minerals of both igneous and sedimentary origins. The use of potassium solubilizing microbes as biofertilizers may be the awaited solution to increasing crop productivity, concerns linked to chemical fertilizer application, and earth resource diminution.

Keywords: Biofertilizers, Microbial inoculants, Potassium solubilizers, Agrosystem

Introduction

Potassium (K) plays a key role in plant growth, resilience to stress, metabolism, development, and reproduction. Ahmad et al. (2016) noted that potassium (K) is the third most important plant nutrient, the 7th most abundant

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*Correspondence: aloritope@yahoo.com

[3] Crop and Soil Science Department, Landmark University, Omuaran, Kwara State, Nigeria
Full list of author information is available at the end of the article

element in the earth crust (Etesami et al., 2017). It is considered by plant physiologists to be second to nitrogen in promoting plant growth (Meena et al., 2014). Soil potassium is also implicated in plant photosynthesis: adenosine triphosphate (ATP) production, translocation of sugars, water and nutrient transport, starch synthesis, legume-based nitrogen fixation, enzymes, and protein syntheses (Wolde, 2016). Despite its abundance, only less than 2 to 3% of soil K is available to plants in free soluble form because the rest remains bound to other soil minerals, constituting an estimated 95% of soil potassium (Etesami et al., 2017). 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). The fixed K is a reserve source of potassium, while the exchangeable K (ionic K) is readily taken up by the plant's root system and substitute for potassium on the exchange sites. Additionally, some are contained in organic matter within the soil microbial population (Kour et al., 2020). Potassium uptake by plants varies with different plants, and it is most needed at the early growth stage of the plant more than nitrogen and phosphorus (Sattar et al., 2019). Its uptake is mainly affected by soil moisture, soil temperature, and tillage system (Mouhamad et al., 2016).

Potassium deficiency is not readily manifested physically in plants unlike nitrogen and phosphorus (Wolde, 2016). This consequently attracted many farmers to the application of only nitrogen and phosphorus fertilizers over potassium (Hamid and Bashir, 2019). The unpopular use of inorganic K-fertilizers, particularly among the tropical farmers, with potassium-deficient soil alters plant physiology and reduced yields of crops as well as exacerbating crop sensitivity to pests and diseases (Hamid and Bashir, 2019). Potassium deficiency decreased the production in natural ecosystems (Chen et al., 2020). However, the application of K fertilization increased yields and improved N and P use efficiency (Niu et al., 2013).

Most soils around the globe are K-deficient (Dhillon et al., 2019). Römheld and Kirkby (2010) reported one fourth of arable soils and three fourths of paddy soils in China to be K-deficient. South Western Australia has also experienced increased K deficiencies in the production of wheat (Römheld and Kirkby, 2010). More also 72% of agricultural soils in India were reported to be K deficient (Yadav and Sidhu 2016). Norton (2022) reported K deficiency in soils of most Australia states. K had also been found to be the most limiting nutrient in 88% of soil from some sub-Saharan Africa countries such Kenya, Rwanda, Nigeria, and Sierra Leone (Baijukya et al., 2021). More also Kaiser and Rosen (2018) reported that even though some K are supplied by Minnesota soils, fertilizer program to supply K is employed when there is an inadequate supply from the soil. In Iowa, many corn and soybean fields are beginning to show K deficiency symptoms (Mallarino, 2022).

The use of K fertilizer has increased worldwide with a corresponding decrease in the fertilizer use efficiency (Dhillon et al., 2019; Alori et al., 2017). The demand for K fertilizer was projected to increase by 2.4 % between the years 2015 and 2020 (Food and Agricultural Organization-Rome, 2017). Schlesinger (2021) reported an increase in the demand for K fertilizer due to the need to increase agricultural production. An increase in the production of cereal by a factor of 3.2 was recorded as a result of 300% increase in consumption of K fertilizer between years 1961 and 2015 (Dhillon et al., 2019). However, potassium solubilizing organisms (KMS) have the capability to release soluble K from K bearing minerals (Das and Pradhan, 2016), therefore making the unavailable K available. KSMs like *Acidothiobacillus ferrooxidans*, *Aspergilus terreus*, *Bacillus circulans*, *B. edaphicus*, *B. mucilaginosus*, and *Paenibacillus* solubilize fixed form of K in soil making them available to plant via the processes such as organic acid production, acidolysis biofilm formation on mineral surfaces, and complex formation, hence improve growth and yield (Maurya et al. 2016).

In the developing world, addressing food security is a very important goal. This is due to the rapidly growing global population, which according to the United Nations projection may rise from 8.6 billion in 2030 to 9.8 billion by 2050, respectively (Tripathi et al., 2019).

Potassium solubilizing microorganisms solubilize mineral potassium that are unavailable to plant to become accessible and available to plant (Meena et al. 2016), PSM mobilizes K from soil mineral making such available to plants (Pandey et al. 2020). Jain et al. (2022) explains that potassium solubilizing microorganisms convert the unavailable form of mineral K to forms that are available to plant, indicating that KSMs possess a potential to improve the potassium availability in soils and hence can play an important role in the potassium nutrient management the condition of K-limited soils and can therefore reduce the use of potassium-based chemical fertilizers. This is because soil microorganisms such as KSMs play a significant role in natural K cycle (Hamid and Bashir, 2019).

Mineral K that is usually made available by KSM contributes immensely to K supply in many soils (Meena et al. 2016). This mineral K could make available the K required by plant and could also preserve ecosystem productivity in the long run by reducing K leaching (Pandey et al. 2020). This will hence reduce the quantity of chemical K fertilizer required to meet plant K requirement. This study therefore aims at reviewing the application of microbial potassium solubilizers in increasing crop production.

Harmful effects of chemical K fertilizer

Indiscriminate use of chemical K fertilizer to mitigate K deficiency in plant causes severe damage to soil microflora and hence spoilage of soil, human, and environmental health and in the long run reduction in crop yield (Hamid and bashir, 2019). Chemical K fertilizers cause displacement of microbial communities or the loss of some of their ecological functions (Vejan et al., 2016). Kour et al. (2020) reported that the deficiency of potassium is becoming a major limitation in the production of the crops due to the imbalanced application of K chemical fertilizers. Potassium chemical fertilizers constitutes the main cause of loss of soil fertility (Berger et al., 2018). John-Louis et al. 2017 explained further that the use of K chemical fertilizers results in a strong adsorption of K to the minerals K fixation and thereby making them inaccessible for the plants. According to Yadav (2022), the usage of potash fertilizers has resulted in soil precipitation. The continuing use of chemical K fertilizer generates groundwater contamination (Sun et al., 2020). There is therefore need to implicit eco-friendly and cost-effective agro-technologies to improve both the quality and quantity of crop production.

Sources of potassium in arable soil

Potassium is the third most essential nutrient required by plants (Dhillon et al., 2019), and it plays a role in governing the biochemical (metabolic), physiological, and photosynthetic processes of plant (Wang et al., 2015). It was noted by Mouhamad et al. (2016) that igneous rocks have higher contents of potassium than sedimentary rocks. The soil reservoir contains varying quantities of potassium-bearing minerals, among which the primary alumina silicates are the most abundant potassium-bearing minerals (Rawat et al., 2016). Primary alumina silicates comprise feldspar, mica, biotite, muscovite, and nepheline (Rawat et al., 2016). As described by various researchers such as Basak et al. (2017), Mancuso et al. (2014), and Mohammed et al. (2013), feldspar and mica are the largest and most common components of potassium in the soil. The non-exchangeable potassium is another form of soil potassium that acts as a reserve, and it is associated with 2: 1 clay minerals (Mouhamad et al., 2016). Clay minerals characterized by an octahedral sheet that is sandwiched between two tetrahedral sheets are called the 2:1 clay minerals (Ghadiri, 2015). The exchangeable ions found at the cation exchange sites are the third form of K while the fourth form of potassium in the soil is the readily available potassium found in the soil solution (Yadav and Sidhu, 2016). Only 0.1–0.2% of the K minerals is available for plant use (Rawat et al., 2016). The various forms of K in the soil and possible movement are illustrated in Fig. 1.

Microbial implications on the sources and dynamics of potassium in arable soil

Physical, chemical, mineralogical, and biological factors, particularly microbiotas govern the release of potassium from soil minerals through cation exchange reaction and dissolution processes (Ahmad et al. 2016; Yadav and Sidhu., 2016; Hamid and Bashir, 2019). Soil

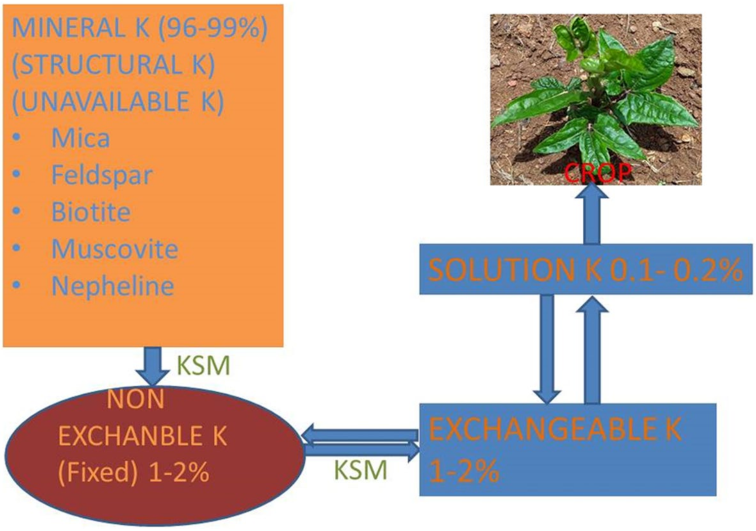

Fig. 1 The various forms of potassium (K) and circulation in the soil

microorganisms are differentially efficient organic matter decomposers, nutrients cyclers, soil fertility boosters, and liberators of essential nutrients, thereby increasing nutrients availability in the soil (Yadav and Sidhu., 2016). Soil microbes such as bacteria (*Bacillus mucilaginosus*, *Bacillus edaphicus*, *Bacillus circulans*), fungi (*Aspergillus niger*, *Aspergillus fumigatus*, and *Aspergillus terreus*), and actinomycetes have been identified as some of the important solubilizers of potassium from insoluble matrixes to accessible form for plant use (Yadav and Sidhu., 2016; Etesami et al., 2017; Hamid and Bashir, 2019).

Importance of potassium to crop production

Even though many interplaying factors are required for crop yield, adequate, and balanced use of mineral nutrients remains fundamental in achieving high crop production and quality in practical agriculture (Cakmak, 2010). Unbalanced state of potassium in the soil has become an important constraint to crop production in many developing countries (Cakmak, 2010). Potassium is an essential plant nutrient required for numerous plant growth processes (Cakmak, 2010). It enhances plant health, growth, and development; increases plant's resistance to diseases; improves crop quality and prolongs shelf life of crop produce; and increases the ability of plants to withstand stresses such as drought, frost, pest, disease, lodging, and poor drainage; potassium promotes photosynthesis, resulting in the formation of carbohydrates, oils, fats, and proteins and regulates the absorption of water by plant roots and helps in the development of healthy root system (Shirale et al., 2019).

According to studies, potassium is hardly a part of the chemical structure of plants compared to other essential nutrients (nitrogen and phosphorous) but involved in plant metabolism and water relations (Hamid and Bashir 2019). According to Shirale et al. (2019), potassium plays a key role as an enzyme activator or catalyst of chemical reactions. Furthermore, potassium-based enzyme activator is utilized in many other processes such as the neutralization of different organic anions and other compounds within the plants. This in turn regulates pH of enzyme reactions to optimal level, formation of organic substances, and respiration (exchange of CO_2), water vapor, and oxygen (O_2). Potassium also plays a major role in the regulation of leaf stomata opening and closing which in turn sustains turgor regulation, transpiration (cooling), osmotic adjustment, and nutrient cycling in the plants (Shirale et al., 2019). The activation of enzymes by potassium also aids the production of adenosine triphosphate (ATP) (Hasanuzzaman et al. 2018). ATP is more importantly used as the energy source for chemical reactions (Rawat et al., 2016) like transportation of sugars (Hasanuzzaman et al. 2018). Likewise, potassium is highly required for every process involved in protein and starch synthesis (Rawat et al., 2016; Shirale et al., 2019). This might suggest that potassium functions in photosynthesis influencing the increase leaf growth and leaf area index, and carbon dioxide assimilation. Potassium is therefore regarded as a quality nutrient which plays a significant role in improving crops' physical quality and health by contributing to plant resistance development as well as resilience to biotic and abiotic stresses like diseases, pests, drought, salinity, cold, frost, and waterlogging (Rawat et al., 2016).

The application of K showed significant results in increasing yield and yield attributing characteristics in several crops around the world. Bhosale et al. (2017) found that the application of K combined with N increased the fruit weight of watermelon and yield by 32.44% in lateritic soils of Konkan Region, India. Application of K increased the yield of tomato fruit by 50.49% and increased the number of tomato fruit per plant by 41.58% in a silty clay loam soil of Madhupur Tract Agro-Ecological Zone (AEZ-28), Sher-e- Bangla Nagar, Dhaka -1207 (Sultana et al., 2015). At the Coastal Region of Bangladesh, application of K increased plant height of White Jute by 26.30% and increased fiber yield by 35.10% (Piya et al., 2019). The yield of maize was increased by 32.1% by K fertilizer in Northeast China between 2005 and 2012 (Jiang et al., 2018). Ali et al. (2020) reported 18.33% increase in plant height, 33.91% in Cob length, and 17.88% in yield of maize by application of K fertilizer at College of Agriculture (COA), University of Sargodha (UOS), Pakistan. The application of K fertilizer increased aerial stems per plant of potato by 30.72% in a study conducted in the Research station of Hamelmalo Agricultural College, Hamelmalo, Eritrea, located in ZobaAnseba 12-km North of Keren (Zelelew et al., 2016). Hussain et al. (2021) recorded 22.5–24.19% increase in plant height and 3.3% increase in plant dry matter of cotton at the Research farm of Central Cotton Research Institute, Multan, Pakistan. These entire researchers confirmed that K fertilizer improves the growth and yield of various crops.

Role of microorganisms in potassium solubility and uptake

Microorganisms equally play a central natural role in potassium recycle (Prajapati et al., 2012). The natural presence of potassium solubilizing microorganisms in soil rhizospheric community and their effective interaction either with the plant root system or intra specifically validates this concept (Hamid and Bashir, 2019). However, bacteria are recognized by Ahmad et al. (2016) and Bashir et al. (2017) as the predominant microorganisms involved in the solubilization of potassium or its transformation from insoluble sources into accessible utilizable forms for plants compared to other soil inhabiting microbes (fungi, actinomycetes). Rhizospheric microorganisms, especially bacteria, have the potential to solubilize potassium from minerals for easy uptake by plant (Zeng et al. 2012; Ahmad et al., 2016; Hamid and Bashir, 2019; Sun et al., 2021). A wide range of microorganisms was reported to release potassium from minerals and supply in accessible form in soil to plants (Bashir et al., 2017; Hamid and Bashir, 2019). These include bacteria like *Acidothiobacillus ferrooxidans*, *Aminobacter* spp, *Arthrobacter* sp, *Bacillus amyloliquefaciens*, *Bacillus cereus*, *Bacillus circulans*, *Bacillus coagulans*, *Bacillus edaphicus*, *B. megaterium*, *Bacillus mucilaginosus*, *Bacillus subtilis*, *Burkholderia* spp. *Cladosporium*, *Enterobacter hormaechei*, *Flectobacillus* spp. *Paenibacillus* spp. and *Pseudomonas* spp. Also a few documented fungal strains like *Aspergillus niger*, *A. fumigatus*, and *A. terreus* and yeasts such as *Torulaspora globose* are implicated in potassium supply in soil for plant use (Bashir et al., 2017, Prajapati et al. 2013; Ahmad et al., 2016; Lodi et al., 2021).

Potassium solubilizing microorganisms (KSMs) as biofertilizer

Soil potassium replenishment, particularly in smallholder agriculture, remains a challenge as it is achieved mainly by fertilizer (Prajapati et al., 2012). However, one of the best methods applied by farmers to combat potassium deficiency in arable soil is the use of soluble mineral potassium fertilizers (Prajapati et al., 2012). These soluble fertilizers are commercially branded and limited in supply due to their high cost and dismal number of manufacturing outlets. Their indiscriminate but continuous use leads to soil degradation, deterioration of soil fertility, elimination of eco-beneficial microorganisms, contamination of water and environment with diverse pollutants making crop prone to disease, accumulation of pollutants, nutritional quality coupled with yield degeneration (Bashir et al., 2017; Mahmud et al., 2021). Due to these, collaborative efforts are escalating in the search for some functionally equivalent alternatives that could replenish soil potassium cost effectively, benignly, and benefit the agricultural ecosystem (Bashir et al., 2017; Etesami et al., 2017; Macik et al., 2020). The discovery and utilization of potassium solubilizing microorganisms like bacteria as bio-fertilizer will regress reliance on agrochemicals, particularly soluble potassium fertilizer (Hamid and Bashir, 2019).

Biofertilizers are substance that contains live microorganisms or their inocula and resting spores which possess plant beneficial properties (Macik et al., 2020), especially impacting the seed, root, or soil (Hamid and Bashir, 2019). Biofertilizers play a crucial role in maintaining soil fertility and have been used to improve soil health, plant nutrient status, and crop yield in sustainable agriculture. They positively affect soil structure, provide plant-protection against soil-borne disease, and pest and contribute to efficient plant-water relation (Hamid and Bashir, 2019; Macik et al., 2020). Biofertilizers are phyto-stimulants that enhance quality plant growth and development through the improvement of soil nutrient utilization. This may be due to increased soil nitrogen-fixation, phytohormones excretion, phytopathogenic suppressants, stress-tolerant activities, remediation pollutants, and potassium and phosphorus solubilization (Macik et al., 2020; Adetunji et al., 2022). The use of potassium solubilizing bacterial as biofertilizers is a promising in improving plant nutrient and production (Bashir et al., 2017; Hamid and Bashir, 2019). Also, employing them over chemical fertilizers for the improvement in soil fertility, production of high healthy crops, and their accessible to farmers may offer crucial promise in resolving global food crisis and the economic exports of many nations (Bashir et al., 2017; Mateusz et al., 2020).

Inoculation of potassium solubilizing bacteria alone or their co-inoculation with other plant growth-promoting microorganisms (PGPMs) like phosphorus solubilizers, nitrogen fixers, and mycorrhizae increases the availability and uptake of potassium in soil and promote plant growth (Ahmad et al., 2016; Meena et al. 2016; Hamid and Bashir, 2019; Kour et al., 2020). Soil inoculation with PGPMs or indirect application to soil in compost material also regulates plant nutrition. It enhances potassium ion (K+) uptake over sodium ion (Na+) in plants, even under salt stress conditions and adequately ensure the mobilization of nutrients for optimal use in different agro-climatic regions of the great northern Indian plains (Kumar et al., 2015; Meena et al., 2015). For instance, a study by Han et al. (2006) showed that in a greenhouse experiment using Aquepts Series, Typic Endoaquepts (USDA, Inceptisols) soil collected from Chinju, Kyungnam province, Korea, co-inoculation of *Bacillus Mucilaginosus* with *B. megateriuma* which is a phosphorus-solubilizing bacterium enhanced the supply of phosphorus and potassium for improved growth of cucumber and pepper. Similarly, the co-inoculation of *Bacillus mucilaginosus* and nitrogen (N) fixing *Azotobacter chroococcum* (A-41) along with waste mica resulted in higher accumulation of biomass and nutrient acquisition in an Alfisol family of Typic Haplustalf, Hazar-ibagh, Jharkhand, India (Basak and Biswas, 2010). Therefore, the application of K-solubilizing microbes is rapidly attracting attention as biofertilizers critical to driving solution to global food insecurity and integrated nutrient management (INM) (Shrivastava et al., 2016).

Potassium solubilizing microorganism (KSM) as bio-control agents

Biological control premised on the diverse degree of antagonisms among biological agents, particularly microorganisms such as phytopathogens. Even though potassium solubilizing microbes are more popular for their services in improving plant nutrient utility, some also exhibit bio-control characteristics (Kour et al., 2020). Plant disease and pest agents are chief factors limiting agricultural development in most nations of the world (Kour et al., 2020). Many strains of bacteria have been observed to exhibit antagonistic behavior due their innate ability to produce hydrogen cyanide (HCN), lytic enzymes, antibiotics, phenazines, pyoluteorin, and pyrrolnitrin. According to El-Hadad et al. (2011), four strains of N-fixing bacteria (*Paenibacillus polymaxa*), three strains of *B. megaterium*, and 3 strains of *B. circulans* significantly suppressed the root-knot nematode pest of tomatoes. Seven different isolates of bacteria SRI-156 (*Pseudomonas plecoglossicida*; NCBIAccession Number: JQ247008), SRI-158 (*Brevibacterium antiquum*; NCBI Accession Number: JQ247009), SRI-178 (*Bacillus altitudinis*; NCBI Accession Number: JQ247010), SRI-211 (*Enterobacter ludwigii*; NCBI Accession Number: JQ247011), SRI-229 (*E. ludwigii*; NCBI Accession Number: JQ247012), SRI-305 (*Acinetobacter tandoii*; NCBI Accession Number: JQ247013), and SRI-360 (*P. monteilii*; NCBI Accession number: JQ247014) showed biocontrol potential against charcoal rot of sorghum and enhanced its total dry matter, tillers number, root length, volume, and dry weight (Gopalakrishnan et al., 2012).

Low crop yield and productivity can occur when plants with natural immunity or tolerance are exposed to many biotic stresses such as phytopathogens, pests, fungal, and bacterial diseases and abiotic stresses such as drought, salinity, high or low temperature, high light intensity, and nutrient deficiency (Zahedi, 2016; Sattar et al., 2019; Kour et al., 2020). The availability of potassium nutrient in the soil was found to greatly enhance plant resistance to different forms of stress as confirmed by Zahedi (2016) and Sattar et al. (2019). Therefore, potassium solubilizing microbes may be beneficial to plants by improving growth, rhizospheric services, resistance to disease and pest attacks, and nutrient uptake. In addition, the inoculation of crop plants with potassium solubilizing bacteria was also found to significantly enhance plant germination, growth, and yield.

Mechanisms of actions

As reported by various researchers, KSM adopt different mechanisms which may include the production of different organic acids for solubilization (Prajapati et al., 2012; Ahmad et al., 2016; Sattar et al., 2019), complex formation methods (Ahmad et al., 2016; Sattar et al., 2019; Hamid and Bashir, 2019), polysaccharides secretion (Sattar et al., 2019; Kour et al., 2020), and biofilm formation on mineral surfaces (Etesami et al., 2017; Sattar et al., 2019).

Potassium solubilisation by KSM involves mobilizing and solubilizing insoluble potassium bearing minerals such as micas, muscovite, feldspar, biotite, illite, and orthoclase. One of the mechanisms is to release potassium nutrients by the production of different organic acids (Kumar et al., 2016; Meena et al., 2016). These secreted acids (Table 1) results in the acidification of the rhizosphere and enhance the solubilization of potassium from minerals (Ahmad et al., 2016). It was reported that low pH facilitates the production of various organic acids and protons by these microorganisms (Meena et al., 2016). These organic acids directly dissolve potassium minerals due to slow releases of exchangeable and readily available

Table 1 Some potassium solubilizing microorganisms and their excreted organic acids

Microorganism	Organic acid produced	References
Aspergillus terreus and *Aspergillus niger*	Citric, oxalic acids	Prajapati et al. (2012)
B. edaphicus	Citric, oxalic, tartaric, succinic, α-ketogluconic acids	Shin (2017)
B. megaterium, Pseudomonas sp.	Lactic, malic, oxalic acids	Meena et al. (2016)
B. megaterium	Citric acid	Meena et al. (2014)
B. mucilaginosus	Carboxylic acid	Lin et al. (2002)
B. mucilaginosus	Citric, oxalic acids,	Sheng and He (2006)
B. mucilaginosus	Citric, oxalic, tartaric acids	Basak and Biswas (2010)
B. mucilaginosus	Citric, oxalic, tartaric acids	Bhattacharjya et al. (2021)
Enterobacter hormaechei	Oxalic, citric acids	Prajapati and Modi (2012)
E. hormaechei	Oxalic, citric acids	Prajapati et al. (2013)
Paenibacillus mucilaginosus	Citric, oxalic, tartaric acids	Liu et al. (2012)
Pseudomonas aeruginosa	Acetic, citric, oxalic acids	Badr et al. (2006)
Rhizobium tropici strain Q34	Tartaric, succinic, citric acids	Wang et al. (2015)

exchangeable potassium (Ahmad et al., 2016). Thus, the synthesis and discharge of organic acids by potassium solubilizers into the surrounding environment lowers pH and ultimately result in the release of potassium ions from the minerals via protonation (Kour et al., 2020).

The organic acids produced by potassium solubilizers can release potassium ion from potassium bearing minerals (phlogopite) by chelating (metal-organic complexes) Al^{3+}, Si^{4+}, Ca^{2+}, and Fe^{2+} ions which may dissociate the lattice structure and release potassium into soil solution (Ahmad et al., 2016; Shrivastava et al., 2016; Estesami 2017; Sattar et al., 2019). For example, Ahmad et al., (2016) noted that potassium-solubilizing rhizobacteria released potassium ions from phlogopite through aluminium chelation and acidic solubilization of crystal network. It was also noted by Etesami et al. (2017) that *B. altitudinis* strain produced organic acids which dissolves potash feldspar and in turns released Al, Si, and Fe elements. The various organic acids involved in releasing potassium from potassium bearing minerals are illustrated in Fig. 2

Microorganisms also produce exopolymers to form thick gel layers or biofilms (Shrivastava et al., 2016). Biofilms comprise of syntrophic consortium of microorganisms in which cells stick to each other and a surface. The cells within the biofilm produce extracellular polysaccharides (EPS); a typically conglomeration of proteins, lipids, and DNA (Aggarwal et al., 2016). Some microorganisms form biofilms on mineral or rock surfaces to promote controllable optimal microenvironments around its cells for effective solubilization using organic acids and secondary metabolites. The mechanism may also include the reduction of rhizospheric pH to accelerate solubilization potassium bearing mineral and availability for uptake by plants (Sattar et al., 2019).

Effect of potassium solubilizing microbial inoculants on plant growth and yield

Beneficial soil microorganisms reduce the amount of mineral fertilizer inputs by increasing the efficiency of nutrient availability and other plant growth-promoting activities (Emmanuel et al., 2021). According to Etesami et al. (2017) beneficial bacteria improve plant growth and following this, potassium solubilizing bacteria could also be regarded as plant growth promoting bacteria/rhizobacteria (PGPR).

Inoculation of potassium solubilizing bacterial in seeds and seedlings of different plants has generally increased seedling vigor, overall plant growth, and development due to potassium uptake by plants under both controlled and field conditions (Meena et al., 2014). Emmanuel et al. (2021) reported that application of microbial inoculant enhances plant growth and yield of cowpea. Parmar (2010) observed that inoculating K-solubilizing isolate HWP47 in wheat increased root dry weight by 51.46%. Similarly, the inoculation of tobacco seedlings with four potassium solubilizing bacterial strains significantly increased dry weight of tobacco seedlings and nutrient uptake (Zhang and Kong 2014). Maize and wheat co-inoculated with *Bacillus mucilaginosus*, *Azotobacter chroococcum*, and *Rhizobium* spp. showed an increase in biomass, potassium content, and uptake.

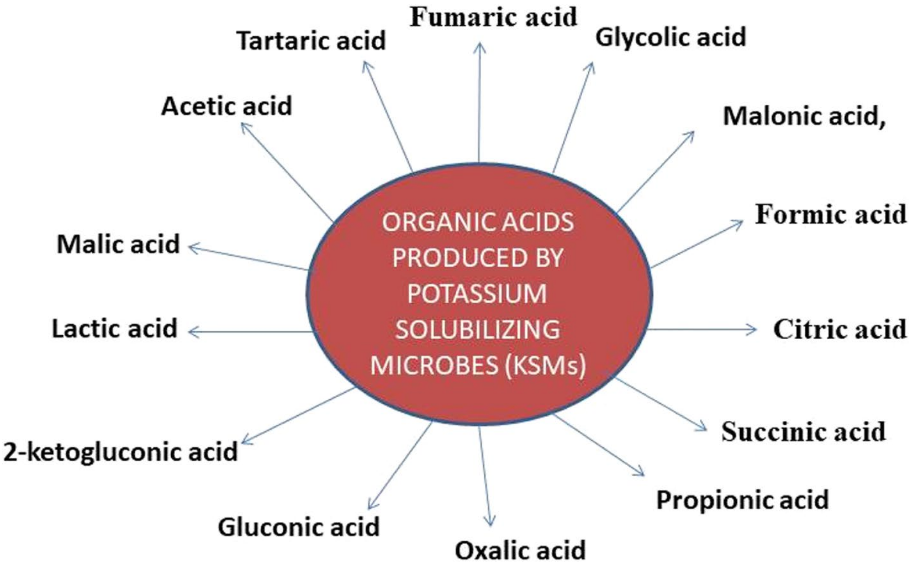

Fig. 2 Diversity of organic acids produced by potassium solubilizing microorganisms

Potassium solubilizing microorganisms improved; the potassium status and uptake in the soil, the growth of Sudan grass, and physicochemical cues in soil (Basak and Biswas 2010). Similar outcomes were observed by Chen et al. (2020) after treating poplar with *Bacillus aryabhattai* (SK1-7) for effective potassium solubilization. Therefore, the co-inoculation of potassium solubilizing bacteria with other beneficial soil microorganisms could be a sustainable means of nutrient management in crop production (Meena et al. 2014). *Bacillus mucilaginosus* and nitrogen (N) fixing (*Azotobacter chroococcum* A-41) bacteria co-inoculated with mica improved biomass accumulation and nutrient uptake by Sudan grass in a Typic Haplustalf soil (Basak and Biswas, 2010). A phosphorus solubilizing bacterium (*Bacillus megaterium* var. phosphaticum) co-inoculated with potassium dissolving bacteria (*Bacillus mucilaginous* and *B. subtilis*) together with phosphorus and potassium mineral materials (rock) boosted phosphorus and potassium availability as well as their uptake in the limited calcareous soils by enhancing the shoot and root growth (Abou-el-Seoud and Abdel-Megeed, 2012). The combine application of potassium solubilizing microorganisms with other organic materials has proved useful in crop production. For instance, the combination of potassium solubilizing strain *Frateuria aurantia* and enriched phospho-compost was reported to enhance the production of *Capsicum* sp (Pindi and Satyanarayana, 2012). Table 2 reveals the effects of potassium solubilizing microorganisms on crop growth and yield. Figure 3 shows the benefits and mechanisms of action of potassium solubilizing microorganism

Factors that affect the solubilization of potassium by potassium solubilizing bacteria

There are different factors that affect the release of potassium from insoluble sources that may be physical, chemical, or even anthropogenic. The nature of potassium bearing minerals (amount and type of clay minerals present in the parent material) impacts the effectiveness of bacterial strains to solubilize potassium from insoluble form (Uroz et al. 2009). In a study by Sheng and He, (2006) *Bacillus edaphicus* solubilized illite more effectively than feldspar when grown on liquid media. It was observed by Basak and Biswas (2009) that mineralogical variations in Alfisols due to clay, sand, and silt contents affect potassium release. Also fluctuation in soil pH is critical to soil potassium kinetics and release from their respective sources by microbes including bacteria (Ahmad et al., 2016; Shrivastava et al., 2016; Estesami 2017; Masood and Bano, 2017; Sattar et al., 2019; Kour et al., 2020). According to Chen et al. (2020), pH decline to 3.3 resulted in approximately 32.6% increase in the concentration of soil potassium and this is affirmed by the study of Buragohain et al. (2018).

Potassium solubilizing bacteria involving the processes of organic acid production, complex formation, polysaccharide secretion, and bio-film formation are subject to climate changes (Sattar et al., 2019; Kour et al., 2020). For

Table 2 Effect of potassium solubilizing microorganisms on crop growth and yield

Test crop	Potassium solubilizing microorganism (ksm)	Effect compared to control	Reference
Tomato	*Pseudomonas* sp.	The yield of tomatoes was significantly increased by 1.6–33.7%	Lynn et al. (2013)
Maize	*Bacillus mucilaginosus*, *Azotobacter chroococcum*, and *Rhizobium* spp.	Increased fresh weight by 28.9–86.2% and dry weight by 21.6–75%	Singh et al. (2010)
Wheat	*Bacillus mucilaginosus*, *Azotobacter chroococcum*, and *Rhizobium* spp.	Increased fresh weight by 12.5–24.3% and dry weight by 21.3–37%	Singh et al. (2010)
Peanut	*Bacillus pasteurii*	Increased straw weight by 117% and grains by 46.2%	Youssef et al. (2010)
Sesame	*Bacillus pasteurii*	Increased straw weight by 118% and grains by 39.4%	Youssef et al. (2010)
Black pepper	*Paenibacillus glucanolyticus*	Increased tissue dry mass by 37–68.3%	Sangeeth et al. (2012)
Sudan grass	*Bacillus mucilaginosus*	Higher biomass accumulation 48.2% and 70%	Basak and Biswas (2010)
G. nut	MCRCPL bacterium	Increased dry matter by 125% and oil by 35.41%	Sugumaran and Jonarthanam, 2007
Okra	*Enterobacter hormaechei* and *Aspergillus terreus*	Increased root weight 84–125%, and shoot weight 7.6–33%	Prajapati et al. (2013)
Tobacco	*Frateuria aurantia*	Increased K content of leaf by 39%	Subhashini (2015)
Corn and Chinese Kale	KJB30, KJB30, KJB9/2, KJB7/2	Enhanced growth 2 times as compared to control experiment	Leaungvutiviroj et al. (2010)

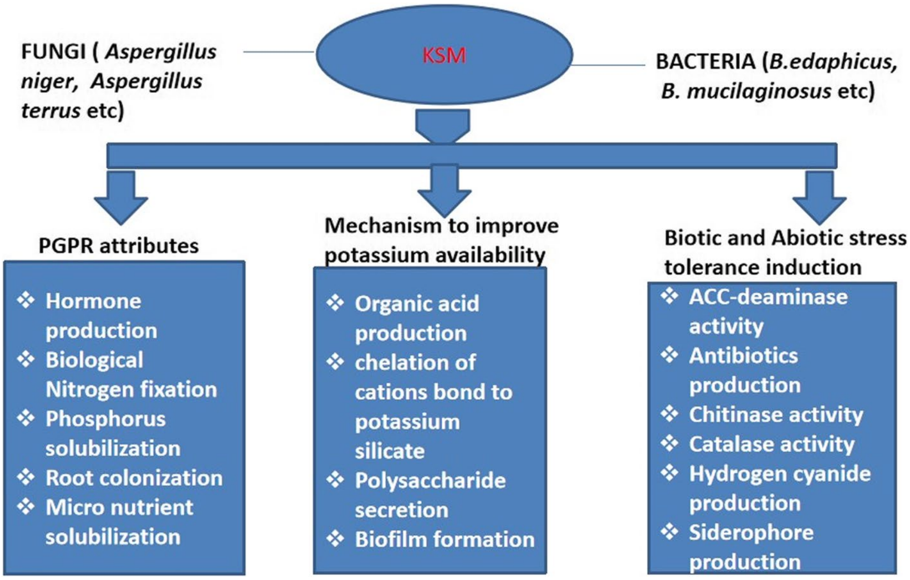

Fig. 3 Benefits and mechanisms of action of potassium solubilizing microorganisms

example, biofilm formation on mineral surface promotes the corrosion of potassium-rich shale from Chaoyang of Liaoning, China, and facilitates the release of K, Si, and Al at the bacteria-mineral interface (Man et al., 2014). The variety of organic acids produced by potassium solubilizing bacterial strains was another factor reported by Maurya et al. (2014) to cause differences in solubilization of minerals or mineral reactivity (Lodi et al., 2021). Other factors that affect the solubilization of soil potassium include rapidly changing habitat climate such as temperature, moisture, and salinity (Masood and Bano, 2017).

Conclusion

Potassium is one of the important nutrients required for healthy plant growth and yield. It is a common practice in most parts of the world to replenish K-deficient arable soils with supply of soluble potassium fertilizer to meet the crop requirement. However, the repercussion from the chronic application of this kind of fertilizer has given impetus to consider the use of KSMs for improved crop production and soil nutrient management. Consequences of concern linked to the misguided use of water-soluble chemical K fertilizers like potassium chloride, potassium nitrate, monopotassium phosphate, and sulphate potash have been found to facilitate a paradigm shift. Most of these concerns are related to agricultural soil fertility deterioration due to water molecule disruption, inhibition of biochemical energy flow, chelation, salination, and acidification. From an economic and environmental perspective, the water-soluble fertilizers are expensive, sources of public health and environmental risks, and undermine food quality. It is these premises that have escalated the exploitation of potassium-solubilizing microorganisms. One of the most efficient ways of improving plant utilization of potassium in the soil is to use potassium solubilizing microbes, which can make potassium ions available from minerals of both igneous and sedimentary origins. The application of this group of microorganisms enhances plant nutrition and nutrient management without any known consequence of under or over application on the plant as is the case with most chemical fertilizers. It may also have the advantage of service assistance from other microbial members of the rhizospheric community in achieving potassium release and bio-mobilization for plant growth. Hence, the use of potassium solubilizing microbes as biofertilizers may be the awaited solution to increasing crop productivity concerns linked to chemical fertilizers application and earth resource diminution. The understanding of factors that optimize the activities of these potassium solubilizing microorganisms and the role of non-potassium solubilizing micrrobes on the mineralization of potassium are critical for their widespread application.

Abbreviations

K: Potassium; KSM: Potassium solubilizing microorganisms; N: Nitrogen; P: Phosphorus; ATP: Adenosine triphosphate; PGPMs: Plant growth-promoting microorganisms; PGPR: Plant growth-promoting rhizobacteria.

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ETA conceptualise the research. FTO, ETA, AOA, BBA, FYD, and OOO wrote the article, ETO, OOO, and OOB revised the article. The authors read and approved the final manuscript.

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Declarations

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Competing interests

The authors declare that they have no competing interests.

Author details

[1]Landmark University SDG 2 (Zero Hunger), Omuaran, Kwara State, Nigeria. [2]Landmark University SDG 15 (Life on Land), Omuaran, Kwara State, Nigeria. [3]Crop and Soil Science Department, Landmark University, Omuaran, Kwara State, Nigeria. [4]Agricultural Programme, College of Agriculture, Engineering and Science, Bowen University, Iwo, Osun State, Nigeria. [5]Department of Agriculture, Cape Peninsula University of Technology Wellington Campus, Wellington 7654, South Africa. [6]Department of Food Science and Microbiology, College of Pure and Applied Sciences, Landmark University, Omu Aran, Kwara, Nigeria. [7]Food Security and Safety Focus Area, Faculty of Natural and Agricultural Sciences, North-West University, Mmabatho 2735, South Africa.

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