Soil Potassium Availability and Role of Microorganisms in Influencing Potassium Availability to Plants

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Abstract

The availability of potassium in soils is of prime importance in maintaining the balance between nutrient use efficiency and sustainable agriculture. The potassium-solubilizing microorganisms (KSMs) play a significant role in the solubilization of fixed K. The site for solubilization and mineralization is the rhizospheric region and is referred to as biological hotspot. A range of bacterial and fungal strains are efficient K solubilizers regulating the nutrient flow by converting the insoluble K into its soluble forms and as a result show effective interaction between soil and plant system. Hence KSMs promote plant growth and yield, lessen the use of agrochemicals and reduce environmental pollution caused by leaching and over-fertilization. According to recent research on nutrient use efficiency, there will always be an incessant growing gap between the use and supply of nutrient, and so efforts are needed to ensure the nutrient requirement of plants and enhance the nutrient use efficiency. Hence the application of microbial inoculants is of great significance in promoting the agriculture productivity. More studies are needed for the identification of such new microbial strains and also understanding their mechanism of application to the agricultural lands.

Keywords

Potassium-solubilizing microorganisms (KSMs) · Microbial inoculants · K solubilization · Nutrient use efficiency · Rhizospheric zone

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4.1 Introduction

Potassium is one of the most dynamic plant nutrients responsible for various vital activities of plants. It enhances the antioxidant and phenolic composition (Khayyat et al. 2007) and triggers the regulation of several metabolic processes such as photosynthesis, protein synthesis, enzyme activation (Schwarz et al. 2018), osmo-regulation, cation-anion balance, energy transfer and many other vital activities (Hasanuzzaman et al. 2018) such as providing resistance against plant diseases, pests and stresses (Gurav et al. 2018). The utilization of K and its uptake are known to interact with the availability and uptake of various other nutrients. It is present abundantly in the agricultural fields and also applied as synthetic and natural fertilizers; however only 1–2% of it is available to the plants, and the rest is in bound forms with other minerals and therefore unavailable to plants (Meena et al. 2016). The unavailability of nutrient K is due to the strong affinity with exchange sites of clays. However the plant K demand varies with plant species, cultivars, yield and also the plant growth stage. During the vegetative stage, plant K demand is high, and hence the uptake can reach up to 10 kg/ha/day and above (Ramamurthy et al. 2017).

The interaction between the plant-soil and microorganism has gained significant importance in the recent years. According to Zhao et al. (2016), microorganisms can make nutrients available to plant by different mechanisms. The microbes are abundantly present in the soil and are in an association with the plants. They function as efficient biofertilizer agents for improving the agricultural productivity, protecting the environment and improving the soil fertility (Meena et al. 2016). Microorganism plays a central role in ion cycling and enhancing the availability of insoluble potassium by solubilization and mineralization. Hence the rhizospheric zone has become a biological hotspot in the soil (Singh et al. 2017).

The microorganism solubilizes the insoluble potassium to soluble forms and promotes plant growth and yield (Meena et al. 2014b). The K solubilization is carried out by a large number of saprophytic bacterial and fungal strains. The rhizospheric microorganisms are contributing to the biological and physiochemical parameters of soil through their useful activities and also suppress the activities of various pathogens and improve the soil nutrient and structure (Meena et al., 2014b). There are various functions of rhizospheric bacteria such as storage and release of nutrients, its mobilization and mineralization, decomposition of soil organic matter, exudation of various soluble compounds and K solubilization (Abhilash et al. 2013). Hence they are the crucial component of sustainable agricultural ecosystem (Meena et al. 2016).

4.2 Potassium Level in Soil

Soil is the source of nutrient and energy for all the living beings, and so maintaining a balance between the uptake and assimilation of nutrients is an important criterion in maintaining the soil health and also reducing environmental pollution. Among the major nutrients, potassium is the third important macronutrient required by plants and serves as one of the main pillars of balanced fertilization. It is absorbed by roots and translocated in the plant as positive cation (K^+) (Meena et al. 2016). Recent study suggests the net negative NPK balance as 19% N, 12% P and 69% K; this negative balance is due to the reason that plants lose an average of 1.5 times more K than N. Further the K applied as fertilizers are comparatively lower than that of N or P (Gurav et al. 2018), and the K status of the Indian soil is rated as medium to high. However the available K levels in the Indian soil range less than 0.5–3.00%, and hence poor correlation exists between the total and available soil K, and so the K fertility status of the soil remains unspecified (Meena et al. 2014b).

For maintaining the optimum K level and enhancing the soil fertility, frequent application of K is required by the use of K-rich fertilizers (Patra et al. 2017). The K status of the soil also varies depending upon the soil type in different agro-ecological regions (such as laterite soil, alluvial soil, red soil, medium and deep black soil) and the management practices involved (Srinivasarao et al. 2011). Depending on the type of soil, nearly 98% of total soil K is found in unavailable forms (Meena et al. 2016).

Recent research by scientists from the Indian Institute of Soil Science, Bhopal, and Tamil Nadu Agricultural University suggests that most parts of the country are categorized under low and medium K fertility level than the high and very high K category (Dey et al. 2017). This is because the K present in the soil remains in its insoluble bound form and hence is unavailable to plants. The current scenario of nutrient balance suggests that there will always be a continuous growing gap between the nutrient use and supply and therefore efforts are needed to ensure the nutrient requirement of plants and enhance the nutrient use efficiency.

4.3 Potassium-Solubilizing Microorganisms (KSMs) in the Soil

The mobilization of K in soil is affected by many environmental factors including the soil parameters such as physiochemical properties, pH along with the occurrence of a diverse group of microorganisms such as rhizospheric bacteria and mycorrhizal fungi and the plant root exudate composition (Meena et al. 2016). These potassium-solubilizing bacteria are ubiquitous in its distribution, and hence they vary in number from diverse soil type. The insoluble and fixed forms of K become available in its soluble form by the process of mineralization carried out by the potassium-solubilizing microorganism (KSMs) and hence are easily absorbed by plants. The KSMs are an indigenous rhizospheric microorganism and show efficient interaction between soil and plant. The insoluble forms of K like feldspar, mice and various others are solubilized into organic acids, capsular polysaccharides and siderophores by these microorganisms (Singh et al. 2017).

There are numerous members of KSMs such as *Bacillus edaphicus*, *Bacillus mucilaginosus*, *Bacillus circulans*, *Paenibacillus* spp., *Pseudomonas*, *Acidithiobacillus ferrooxidans*, *Burkholderia* (Meena et al. 2014a, b; Kumar et al. 2015), *Arthrobacter* spp. (Zarjani et al. 2013), *Enterobacter hormaechei* (Prajapati et al. 2013), *P. frequentans*, *Cladosporium* (Argelis et al. 1993), *Aminobacter*, *Sphingomonas*, *Burkholderia* (Uroz et al. 2007), *Paenibacillus glucanolyticus* (Sangeeth et al. 2012). These microbial strains are known to be actively involved in the K-solubilization process and release potassium from potassium-bearing minerals in the soil which is easily available to plants. Arbuscular mycorrhizae improve the solubility of mineral form of potassium by releasing the protons, CO_2 and organic acid anions such as citrate, malate and oxalate (Meena et al. 2014b) and hence significantly enhance the potassium, nitrogen, calcium and iron content in plant leaves and fruits (Veresoglou et al. 2011; Yousefi et al. 2011).

Increase in the K uptake in the maize crop was observed when the inoculants of *G. intraradices* and *G. mosseae* (species of arbuscular mycorrhizal fungi) were applied in soil on the weight basis (Wu et al. 2005). Some strains of potassium-solubilizing fungi (KSF) such as *Aspergillus niger* and *Aspergillus terreus* were found in soil samples rich in K, and both the species also showed the highest available K level in liquid medium when two insoluble forms of K such as potassium aluminium silicate and feldspar were used, based on their morphological features and colonies (Prajapati et al. 2012). However solubilization and acid production on both insoluble potassium sources were highest in *A. terreus* (Meena et al. 2016). Therefore KSMs promote the availability of nutrients and enhance the plant growth under field conditions.

4.4 Potassium-Solubilizing Mechanism

Plants generally take up the nutrients in its soluble forms, and there are several mechanisms that contribute to the availability of K in the soil and to the plants. The K-solubilization mechanism involves the solubilization and mobilization of unavailable forms of potassium compounds due to the production of various types of organic acids. Various studies suggest that K solubilization and the release of organic acids by the K-solubilizing strains improved the growth of plants (Meena et al. 2014b). The solubilization of structural K compounds by abundantly naturally occurring KSMs is widespread under in vitro conditions (Zarjani et al. 2013) and also under field and greenhouse condition (Prajapati et al. 2013; Parmar and Sindhu 2013).

Weathering is involved to release the K from the minerals and rocks, and that takes a longer time; however calcinations of rocks can break the structure and release K, but this is more expensive than evaporite ores (Rawat et al. 2016). The K solubilization and uptake can be enhanced by the bioinoculants and rhizospheric microorganism which produce organic acids and provide potassium and other minerals and hence enhance the crop productivity. However the K-solubilization efficiency varies with the nature of the potassium-bearing minerals and aerobic conditions (Uroz et al. 2009). Significant levels of fixed K are present in the biomass of the rhizospheric microorganism present in the soil and are potentially available to plants (Girgis 2006). Also the K released from the minerals was affected by oxygen, pH and the bacterial strain used (Sheng and Huang. 2002).

Table 4.1 Potassium-solubilizing microorganisms (KSMs) involved in the production of various organic acids in different strains (adapted from Meena et al. 2014b)

K-solubilizing microorganism	Predominant organic acids
Penicillium frequentans, *Cladosporium*	Oxalic, citric, gluconic acids (Argelis et al. 1993)
Paenibacillus mucilaginosus	Tartaric, Citric, Oxalic (Liu et al. 2012; Hu et al. 2006)
Pseudomonas spp.	Tartaric, Citric (Krishnamurthy 1989)
Aspergillus fumigatus, *Aspergillus candidus*	Oxalic, tartaric, citric, oxalic (Banik and Dey 1982)
B. megaterium, *Pseudomonas* sp., *B. subtilis*	Lactic, malic, oxalic, lactic (Taha et al. 1969)
B. mucilaginosus	Oxalate, citrate Sheng and He (2006)
Arthrobacter sp., *Bacillus* sp., *B. firmus*	Lactic, citric (Bajpai and Sundara 1971)
B. megaterium, *E. freundii*	Citric, gluconic (Taha et al. 1969)
Aspergillus niger, *Penicillium* sp.	Citric, glycolic, succinic (Sperberg 1958)
Pseudomonas aeruginosa	Acetate, citrate, oxalate (Sheng et al. 2003; Badar et al. 2006)

Three major reaction pathways are employed in the K-solubilization mechanism by potassium-solubilizing fungi *Aspergillus fumigatus* such as acid hydrolysis, secretion of insoluble macromolecules and polymers bound in the cell membrane along with direct biophysical forces which may possibly split the mineral grains (Lian et al. 2008). The potassium-solubilizing bacteria (KSB) involve various mechanisms like capsular absorption, acidolysis, enzymolysis and complexation by extracellular polysaccharides and solubilize rock K mineral powder such as orthoclases, illite and micas (Welch et al. 1999).The mechanism involved by KSMs in K solubilization is achieved by enhancing chelation of the cations bound to K, lowering the pH and acidolysis of the surrounding area of microorganism (Meena et al., 2014b). The protons and organic acids are released by the KSMs by lowering the pH of the medium (Zarjani et al. 2013).

Table 4.1 shows the list of potassium-solubilizing microorganisms (KSMs) which produces different organic acids in different strains and helps in the solubilization of insoluble potassium into its soluble form. The techniques involved in the detection of the organic acids produced by KSMs are high-performance liquid chromatography (HPLC) and enzymatic methods (Zhang et al. 2013). According to Liu et al. (2006), the chelating ability of different organic acids is also important as it is observed that the addition of 0.05 M EDTA into the medium has the same solubilizing effect as compared to the inoculation with *Penicillium bilaii*.

Mechanisms involved in the solubilization of K-bearing minerals can be done by various ways and are grouped into direct (bacterial cell wall) and indirect process involving mineral weathering, microbial weathering, bioleaching and mechanical fragmentation (Rawat et al. 2016).

4.4.1 Direct Method

4.4.1.1 Bacterial Cell Wall

The cell wall of prokaryotes secretes various metabolic products that reacts with ions and compounds and results in mineral deposition (Rawat et al. 2016). The cell wall of bacteria includes slimes, biofilm or sheath and dormant spores which acts as main sites for mineral nucleation, ion adsorption and growth (Banfield and Zhang 2001; Bauerlein 2003). In Gram-negative bacteria, the mineral nucleation in the layer external to the bacterial cell wall includes capsules, S-layer, slimes and sheaths, where the S-layer is acidic and has a net negative charge possess affinity towards the metal cation (Southam 2000). Also direct absorption of some of the exchangeable K occurs in the soil colloids directly through the roots which are negatively charged and hence are attracted towards the positively charged potassium ions (K^+) present on the surface of the clay mineral and the edges (Rawat et al. 2016).

4.4.2 Indirect Method

4.4.2.1 Microbial Weathering

Microbial weathering includes redox reaction during the production of organic acids due to which the chemical bonds of minerals weaken promoting mineral dissolution (Harley and Gilkes 2000) and also chelates molecules for mineral degradation (Uroz et al. 2009). Although among all the KSMs only two of the microbial strains such as *B. edaphicus* and *B. mucilaginosus* are highly capable of mobilizing and solubilizing K (Meena et al. 2016). These KSMs solubilize the potassium, aluminium and silicon from their insoluble K-bearing forms such as micas, illite and orthoclases through excreting organic acids by either chelating the silicon ions or by directly dissolving the K present in the rocks (Zhang and Kong 2014).

Hence these microbes are of significant importance in the weathering of rocks and release of important nutrients needed by plants.

4.4.2.2 Mineral Weathering

In mineral weathering the inorganic minerals are translocated by microorganism through processes such as uptake, release, biomineralization, oxidation and reduction (Berner and Berner 1996), and all the physical, chemical and biological forces act on the parent material and break them in fine fractions such as sand, silt and clay (Rawat et al. 2016). The availability of nutrients in plants increases due to the conversion of the insoluble K like mica, feldspar, biotite and feldspar into the soil solution form by the organic and inorganic acids. However the different types of organic acids produced by KSMs differ with different organisms (Meena et al. 2016). The organic acids produced by the microorganism in the solubilization of feldspar and illite are oxalic acid, citric acid, malic acid, succinic acid, gluconic acid, 2-ketogluconic acid, oxalic acid and tartaric acids (Sheng and He 2006). The most frequent agent of mineral K solubilization seems to be tartaric acid (Zarjani et al. 2013). The other organic acids which are identified as K solubilizers are propionic, malonic, succinic, acetic, lactic, citric, glycolic, oxalic and fumaric acids (Wu et al. 2005).

Microorganisms contribute to the mineral weathering and soil formation by releasing organic acids and ligands such as siderophores (Liermann et al. 2000, 2005). Inorganic nutrients are released by the chemical weathering of bedrock such as Ca, Mg, K, Fe and P which are cycled through the soil, saprolite and vegetation. Plants absorb the mineral ions in the root zones which are recycled back into the soil with the death and decomposition of the plant. Also the ratio of silt, sand and clay depends on the nature of parent material such as shale, limestone or mica from which the soil is derived and hence significantly influences the potassium fixation and its release (Rawat et al. 2016).

4.4.2.3 Bioleaching

Leaching is the process of removal of soluble materials present in the rocks in solution by percolating water. *Leptospirillum ferrooxidans*, *Thiobacillus ferrooxidans* and *T. thiooxidans* are some of the important bioleaching microbes. Among the minerals the carbonates and sulphates are sparingly soluble, whereas halite (NaCl) and sylvite (KCl) are highly water soluble (Rawat et al. 2016).

4.4.2.4 Mechanical Fragmentation

Mechanical fragmentation caused by the activity of the root increases the reactive surface and hence has direct positive influence of the bacteria on mineral weathering (Rawat et al. 2016). The rocks also undergo mechanical fragmentation when the microorganism is a fungus, and the hypha penetrates the interior of the minerals to derive the nutrition.

4.4.2.5 Biofilm

Microbial biofilm accelerates the weathering process of minerals. According to Warscheid and Braams (2000), the biofilms and biocrusts cause higher weathering rates due to biodegradation. Biofilm has multiple functions as it regulates the denudation losses by acting as a protective layer covering the root hair interface or the mineral-water-hyphae in the mycorrhizosphere and rhizosphere of vascular plants (Rawat et al. 2016). Besides it causes the weathering of minerals like biotite and anorthite, and also the biofilm formation on mineral surface promotes the corrosion of K-rich shale and the release of K along with Si and Al in the bacterial-mineral contact model (Li-yang et al. 2014).

4.5 Potassium-Solubilizing Microorganism (KSMs) Affecting Growth and Yield of Plants

Various studies suggest that inoculation with KSM produced beneficial effect on growth and yields of different plants as shown in Fig. 4.1 (Meena et al. 2015; Ahmad et al. 2016; Anjanadevi et al. 2016; Bakhshandeh et al. 2017; Xiao et al. 2017). Application of KSM is an alternative approach for increasing the unavailable K in its available and soluble forms to the plants. Microorganism applied as biofertilizer can prevent nutrient leaching and also add to soil enrichment. These beneficial microbes translocate the available nutrients and hence help in creating a positive microflora increasing fertility and enhancing soil health. Hence by the application of bioinoculants, the soil physical properties and the water-holding capacity can be improved. Various researchers suggest that KSMs can improve the agricultural productivity, lessen the use of agrochemicals (Prajapati et al. 2013) and reduce over-fertilization and environmental pollution caused by leaching.

4.6 Future Perspective

The potassium-solubilizing microorganism is an important and beneficial component of soil microflora, playing a central role in K solubilization and availability of soluble K to plants. Hence KSMs promote soil fertility, enhance crop growth and

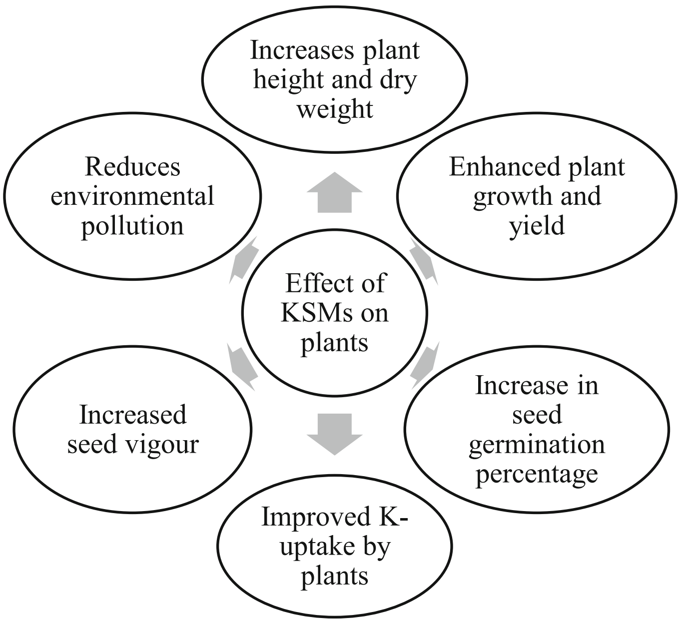

Fig. 4.1 Effect of KSM inoculation on seeds and seedlings of different plants

yield and prevent over-fertilization, nutrient leaching and environmental degradation. Hence more research should be conducted in relevance to the existence and role of KSMs in increasing the K-use efficiency and agricultural productivity and reducing the use of agrochemicals. Further the biochemical basis of such microbial interaction should also be studied, and various biotechnological applications should be employed to further improve the K-solubilizing efficiency of these microorganisms. Also more studies are needed for its application in agricultural fields besides in vitro and greenhouse condition so that application of KSMs can become a common practice along with the application of fertilizers and hence enhance the nutrient use efficiency and also the agricultural productivity.

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