Probiotic Microbiome: Potassium Solubilization and Plant Productivity

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Abstract

The rhizosphere of plant roots supports a range of potassium-solubilizing microbes (KSMs). These KSMs solubilize the insoluble and unavailable potassium (K) to forms of K available for uptake and transport by the plant. Potassium is one of the unavoidable elements required for growth and yield. The specific rhizospheric microbes that perform the process of K solubilization include both bacteria and fungi, the foremost of which are: *Bacillus* sp. (*B. Mucilaginosus*, *B. megaterium*, *B. globisporus*, *B. edaphicus) Pseudomonas putida*, *Enterobacter hormaechei*, *Acidothiobacillus ferrooxidans*, *Paenibacillus* sp., and *Arthrobacter* sp.) *Aspergillus terresus*, *Fusarium oxysporum*, *Aspergillus fumigatus*, and *Aspergillus niger*. Agricultural soil particulates hold minerals such as illite, biotite, orthoclase, mica, and feldspar that contain potassium; however, this is not accessible to plants due to its immobilized form. In soil chemistry, after N and P, K is an important element; a major role is played by the rhizosphric microbes in mobilizing the inaccessible form of K to the roots of the plant. The rhizospheric K-solubilizing microbes such as *Bacillus*, *Pseudomonas*, and *Aspergillus* expel organic acids, which solubilize the insoluble K and make it available to plant roots. Most of the research work in this area has been conducted on nitrogen fixing and phosphate-solubilizing microbes. Solubilized K (quickly available) in

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addition to the existing biofertilizers needs additional consideration at a profitable scale. The current chapter presents information to fill the knowledge gaps about K-solubilizing/mobilizing microorganisms in soil, and looks at the current and future facets of K-solubilizing microbes for enhanced crop production.

24.1 Introduction

The letter K is used to symbolize potassium; it is taken from the German word "Kalium." For a long time, locals used to prepare soap by burning organic matters and wood in vessels. The ashes left after burning wood and other materials were rinsed and the residue left behind after the evaporation of the rinse water consisted of potassium salts. The remainder was popularly acknowledged as potash or "pot ashes." The left-over salts were mixed with animal fat and boiled to manufacture soap. Samuel William Jackson, a botanist from Connecticut, examined the ash of burned organic matters and wood. It was observed that there was a great amount of potassium in various parts of plants, besides other minor and macro minerals.

Potassium (K) is an important and indispensable nutrient for the growth of plants. A vast amount of K is absorbed by the roots of the plant for growth and development and it is therefore classified as a macronutrient. K plays a key role in activation of enzymes, synthesis of protein, photosynthesis, and production. With the ever-increasing extent of rigorous and extensive agriculture, the K levels of soil have been depleted due to leaching, plant uptake, soil erosion, and water runoff (Li et al. 2006). Therefore, it is necessary to build up various alternative sustainable biological methods that can efficiently diminish the loss. K is a fundamental element that is allied with transportation of water, nutrients, and carbohydrates in plant tissues. If K is lacking or insufficient in the soil, the growth of plants is stunted and yield is reduced. Approximately 95% of K fertilizers are available in the form of muriate of potash, which is also known as potassium chloride. For crops that are unable to withstand it, chloride-free salts are used, such as potassium sulfate and potassium nitrate.

Diverse research shows that K encourages early growth, rise in protein production along with improved efficiency of water use, is essential for prolonged existence, affords winter hardiness, and increases resistance to diseases and insects. It is also essential for plant cells in high measure and possesses vital biochemical and physiological functions relating to cell osmotic regulation and activation of enzymes (Hasanuzzaman et al. 2013). The use of microbes as an option for biological processes to influence the release of K from rocks and minerals in the soil is an unconventional view (Rogers et al. 1998). There are a number of sets of microbes, for instance bacteria, fungi and yeast, which are capable in solubilizing unavailable K restricted in rock and soil minerals through mineralization (Sugumaran and Janarthanam 2007; Magri et al. 2012; Meena et al., 2014). The discharge of K from the soil and rock minerals is largely commenced by the release of organic acids which are produced by the microbes as they survive and proliferate in the rhizosphere. The organic acids produced by rhizospheric microbes include oxalic acid, malic acid, formic acid, and citric acid. The organic acids provide protons and form complexes with Ca^{2+} ions in soil, and thus enhance solubilization of the K ions in the soil system.

Sheng and He (2006) have revealed that organic compounds excreted by microbes, for example citrate, acetate, and oxalate, can enhance mineral solubilization in the soil. The complex formation between various metal ions like calcium, aluminum, and iron and organic acids also enhances K solubilization (Uroz et al. 2009).

Over the last few decades the knowledge of rhizosphere biology has increased greatly with the discovery of a significant and specific collection of microbes, acknowledged as plant growth–promoting microbes (PGPMs). The plant root system inhabits the PGPM, which implement valuable and affirmative effects on plant growth using various means (Ahemad and Kibret 2014). In addition, the use of K-mobilizing microbes (KMMs) as bioinoculants unaccompanied or accompanied by other microbes, has been shown to improve plant growth (Wu et al. 2005). In a phytotron growth chamber wheat and maize yields increased with the use of KMMs such as *Bacillus mucilaginosus*, *Azotobacter chroococcum*, and *Rhizobium* spp., as shown by Gupta et al. (2015). The outcome revealed that the assimilation of K was considerably enhanced by both maize and wheat by the application of KMMs, wherever waste mica was the only resource of K. Under abiotic or biotic stress and nutrient-imbalance conditions, KMMs have been found to be significant organisms for plant nourishment, root establishment, root escalation archetype, and competitiveness (Zhanga and Konga 2014). The use of KMMs in agriculture can significantly reduce the use of agrochemicals and maintain eco-friendly production of crops (Sheng et al. 2002; Pettigrew 2008). Diverse KMMs together with associative bacteria and fungi, for example *Paenibacillus*, *Azospirillum*, *Bacillus*, *Pseudomonas*, *Azotobacter*, *Enterobacter*, and *Aspergillus*, have been used for their favorable results on plant growth (Archana et al. 2013; Diep and Hieu 2013; Zhang et al. 2013). KMMs improve plant growth and development through a variety of means, but the exact and precise mechanisms involved are still not properly described (Shanware et al. 2014). The KMMs have been shown to candidly boost plant augmentation by diverse techniques like solubilization of minerals (Argelis et al. 1993; Valmorbida and Boaro 2007) and synthesis of phytohormones (Kumar and Narula 1999; Kumar et al. 2012). Direct enhancement of plant growth by solubilization and the mobilization of minerals due to amplification of the precise ion fluxes by KMMs present on the surface of roots has also been reported (Sheng et al. 2008; Meena et al. 2014). Microbes in soil and in plant rhizospheres play a key role in the natural K cycle and solubilizing of K (Zörb et al. 2014).

24.2 Soil and Potassium

Potassium is an essential, fundamental, and indispensable macronutrient found in soil. It has an important function in growth, metabolism, and the development of the plant. Plants with insufficient K will have poorly developed root systems, retarded growth, produce diminutive seeds, and have smaller yields. Although K comprises of about 2.52% of the top layer of the earth's crust, the tangible sum of this nutrient fluctuates from 0.04% to 3.0% in the soil (Blake et al. 1999; Lopo de SáI et al. 2014). The plants gain K from the soil of the rhizosphere and the accessibility of K depends upon the quantity present in the soil and its dynamics. There are usually three types of K in soil that are available to plants. Foremost is the readily unavailable form, minerals such as mica and feldspar contain most of the K, depending on soil type. These minerals are the basis of about 90–98% of K that exists in the soil (Memon et al. 1988; Zörb et al. 2014). The K is liberated at a slow rate to the more available forms as these break down. The second type is the slowly available K form, which make up 1–10% of K in soil and forms the colloidal portion of the interlayer of K in non-expanded clay minerals such as illite and lattice K. Potassium-feldspars in the soil contribute significantly to plant uptake (Sheng et al. 2008; Zörb et al. 2014). The slowly available K form is also recognized as “non-exchangeable” potassium; it cannot be reinstated by customary cation exchange processes. The third form is readily available K, which includes water-soluble K and transferable K in the soil. It is absorbed on the soil colloid surfaces and is freely available to plants (Maathuis and Sanders 1997; Blake et al. 1999). Despite this, higher plants obtain the majority of their K from the soil solution fraction. The liberation of unavailable K to the less available and easily available water-soluble form takes place when levels of exchangeable/available K or solution K are reduced via crop runoff, erosion, exclusion, or leaching, as shown in Fig. 24.1.

The quantity of accessible and inaccessible K differs from soil to soil and the active balance interaction between the different pools of K in soil. Thus, the fixation and discharge of K from mineral soils are influenced by numerous physical and chemical characteristics of the soil in addition to the plant interactions and soil microbial community. Potassium is taken up in greater measure by the plant than

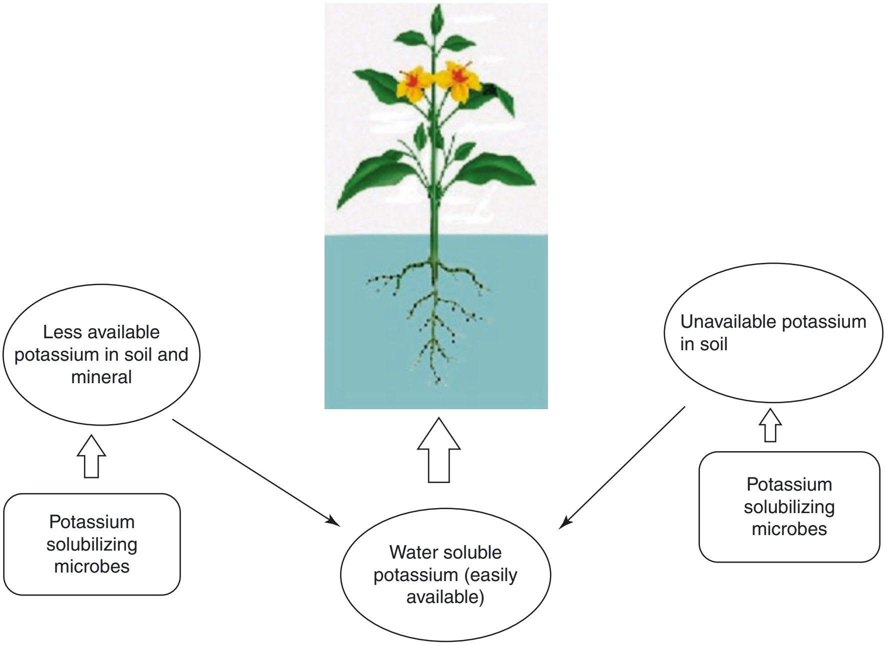

Fig. 24.1 The less available, water-soluble, and unavailable K in soil. Microbes play an important role in K mobilization

other vital elements except for N. The plant roots absorb the mineral nutrients that are dissolved in the water in soil. Nevertheless, the sum of nutrients in soil is always random and is not adequate for the growth of plants. Potassium comprises about 2.1% of the earth's crust and is therefore the seventh most plentiful element. Although the soil K treasury in the structural form is large in the soil (Sardans and Peñuelas 2015), vast areas of agricultural land in the world are still found to have poor availability of K, including 75% of the paddy soils in China and 66% of the wheat belt in southern Australia. This scarcity is due to the sluggish release compared to the requirement of K by the crop. Biofertilizer is a superior means of conveying this prime macronutrient to plants with the aid of K-solubilizing microorganisms (KSMs), which switches the inaccessible K to available K. With the employment of high-yielding varieties of crops, hybrids, and other progressive amplifications in agriculture, the K reserves of the soil are becoming exhausted at a quicker pace. Furthermore, K deficiency is also becoming one of the chief restraints in crop production due to excessive fertilizer application. This has placed emphasis on the search to unearth a remarkable indigenous supply of K for plant uptake and to maintain the K level in the soil for sustainable agriculture (Supanjani et al. 2006; Sardans and Peñuelas 2015). Soil microbes have been found to play a major role in natural K cycles and, thus, K-solubilizing microbes present in soil could provide a substitute system for formulating K available for plant uptake (Mikhailouskaya and Tcherhysh 2005). Therefore, detection of microorganisms that are able to solubilize K minerals quickly can safeguard the existing resources and shun environmental pollution perils caused by harmful application of chemical fertilizers.

Many soil bacteria such as *Acidothiobacillus ferrooxidans*, *Burkholderia*, *Pseudomonas*, *Bacillus mucilaginosus*, *Bacillus edaphicus*, *B. circulans*, and *Paenibacillus* sp. can liberate K from minerals and provide it to plants (Han et al. 2006; Andrist-Rangel et al. 2007). It is reported that the K-solubilizing bacteria leach out organic acids, siderophores, and hydrogen ions found in mobilizing K from minerals like illite, feldspar, and micas (Li 1994; Liu 2001; Lian et al. 2002; Liu et al. 2012). Some crops, for instance wheat (Mikhailouskaya and Tcherhysh 2005, Pettigrew 2008; Singh et al. 2010), sorghum (Basak and Biswas 2010; Gopalakrishnan et al. 2013) cucumber and pepper (Han et al. 2006), eggplant (Han and Lee 2005), soybean and cotton (Pettigrew 2008), rape and cotton (Xeng 2005), rice (Gopalakrishnan et al. 2013), and maize (Singh et al. 2010; Abou-el-Seoud and Abdel-Megeed 2012) have been boosted with K-solubilizing microbial isolates, and have generated motivating and convincing results. Likewise, a bacterium recognized as *Paenibacillus glucanolyticus* strain IISRBK2 that has huge potential to solubilize potash was isolated from the rhizosphere of the black pepper plant. This bacterial strain was also reviewed for growth and K uptake by black pepper in the soil. It was administered with 0.5, 1, and 1.5 g K kg^{-1} soil in pot, where the source of K was wood ash, which contained 53.1 g kg^{-1} K. In view of this, K-mobilizing microbes are being extensively engaged as bioinoculants in a number of countries where K is undersupplied or less accessible to plants in the agricultural soils (Gundala et al. 2013; Zarjani et al. 2013; Diep and Hieu 2013). Hence, application of K-mobilizing microbiomes as bioinoculants for superior crop production possibly will lessen the use of chemical fertilizers to uphold and prolong crop production (Sheng et al. 2002; Singh et al. 2010).

Presently, very little is known regarding KSMs and their effectiveness, mechanism of solubilizing K, making it accessible to plant roots, and lastly affecting plant growth structure in a range of agro-climatic conditions (Shanware et al. 2014). Sheng and Huang (2002) showed that pH, oxygen concentration, and the types of bacterial strains engaged influenced K expulsion from soil minerals. The efficacy of K solubilization by various microbes was observed to alter according to different environmental conditions and types of minerals. There is information regarding K solubilization by a *Bacillus* sp. in the liquid medium that showed that K mineral illite exhibited added growth as compared to feldspar (Sheng and He 2006). Therefore, there could be enormous potential for added and augmented crop production via application of K-bearing rock materials with K-solubilizing microbes as probiotic agents.

24.3 Potassium and Plant Productivity

Potassium is crucial for many plant processes. Its function encompasses the fundamental physiological and biochemical activities of plants. K is taken up by plants in larger amounts as compared to several other mineral elements apart from nitrogen and, in a number of cases, calcium (Bahadur et al. 2014). K is required in large quantities for a crop to attain its utmost yield. K assists in the building up of proteins and sugar, boosts photosynthesis, improves fruit quality, and reduces the incidence of diseases (Wang et al. 2013). It also encourages activation of the enzyme and nitrogen (N) utilization. K is supplied to plants with soil minerals, organic resources, and fertilizer. Plants are able to absorb K only through the soil or as water-soluble K. K deficiency in plants causes yellowing of leaf edges, giving the plant a burned facade. It could also be a reason for slow growth and for imperfect root growth of the plant. A plant growing in soil devoid of ample K produces small seeds and has smaller yields (Sparks and Huang 1987). Despite the fact that K is not a fundamental part of the chemical structure of plants, it plays many vital authoritarian roles in the natural growth and development of plants. To bring about every chemical reaction, enzymes act as the catalysts without being exploited and consumed in the reaction process. The element K "triggers" a minimum of 60 different enzymes that are involved in the overall plant growth, development, and yield. K modifies the physical characters of the enzyme molecule and exposes the chemically suitable efficient sites for the reaction. Diverse organic anions in addition to organic as well as inorganic compounds are too neutralized by K, inside the cells of a plant, resulting in stabilization of the pH of the plant cell between 7 and 8, which is most favorable for the majority of enzymatic reactions (Zörb et al. 2014). The amount of K present within the cell determines the number of enzymes that can be activated and the pace at which a chemical reaction can advance. Thus, the rate of a specific chemical reaction is administered by the swiftness at which the K ions enter or leave the cell cytoplasm. K plays a significant role opening and closing of the leaf stomata in plants (Armengaud et al. 2009). Appropriate functioning of stomatal opening and closing is obligatory for a lot of plant processes like photosynthesis, water transport, nutrient uptake, and also plant cooling. Upsurge of the K ions in the roots of a plant creates a gradient of the osmotic pressure so as to absorb water molecules into the roots. The insufficiency of K ions in plants leads to stress conditions and less water absorption (Sparks and Huang 1987; Wang et al. 2013).

During K deficiency in plants, the rate of generation of ATP molecules and photosynthesis is turned down, and the majority of the processes within the cell are ATP dependent. Consequently, the cellular activities are also slowed down. ATP is also required for the transportation of carbohydrates that are produced during the process of photosynthesis to different parts of the plant via phloem for usual growth, consumption, and storage (Bahadur et al. 2014). This transport system of plants utilizes energy in the shape of the ATP. If K is insufficient, not as much ATP is available, and the plant's transport system breaks down (Arquero et al. 2006). This leads the photosynthates to assemble in leaves, which reduces the pace of photosynthesis. Since K is a requisite for almost all key steps of protein synthesis like the "reading" of the genetic code in plant cells, which leads to the manufacturing of proteinaceous enzymes that control all growth and developmental processes, these processes would be unfeasible if the cells are deficient in K (Wang et al. 2013). Plants that are deficient in K are unable to synthesize proteins regardless of the presence of N in large amounts. Instead, amino acids, amides, and nitrates that are the "resources" or precursors of protein accumulate in the cells (Britzke et al. 2012).

In plants, K is a fairly mobile element and is transported from older to younger leaves. Consequently, K deficiency indications characteristically occur initially on the lower older leaves of the plant, and advance to the upper younger leaves, in accordance with the increasing severity of the K deficiency. The commonly prevalent and worldwide signs and indicators of K deficiency is yellow chlorosis or yellow scorching along the length of the leaf margin (Sparks and Huang 1987). In heightened and severe cases, the yellow and dried margins of the leaf may fold over. Conversely in crops with wide leaves such as cotton, soybeans, and banana, the entire leaf can be cast off, which results in untimely defoliation of the plant. Severe K deficiency in wheat and other cereal crops may cause a slowed growth rate, poorly developed roots, weak stalks, and undersized grain of poor quality. Death of frequent winter crops such as alfalfa and grasses may also occur in conditions of insufficient K (Dordas 2008) (Table 24.1).

K deficiency and K fertilizer deficiency in soil has become a vital limiting reason for the growth and sustainability of the agriculture system (Sheng et al. 2002). Escalating employment of chemical fertilizers in cultivation makes countries self reliant in food production but it depreciates the environment and ecosystem due to the harmful impacts on living organisms. Inadequate uptake of these chemical fertilizers by plants results in their leaching or discharge into water bodies through rain or irrigation water, which causes eutrophication in the water bodies and has a significant effect on living organisms together with plant growth–inhibiting microbes (Uroz et al. 2009). The excess use of chemical fertilizers in farming is expensive and also has a range of unfavorable effects on soils such as depleting water-holding capacity, poor soil fertility, and inconsistency in soil nutrients. For some time now, efforts have been made to build up various economical, effectual, and eco-friendly fertilizers which work without distressing effects on the ecosystem. Currently, various species of microbes are extensively employed that have exceptional assets in

Table 24.1 Percent nutrient content in potassium (K) fertilizers

Chemical formula	K_2O	Element	N	S
$K_2CO_3KHCO_3$	<68	Potassium carbonate		
$K_2SO_42MgSO_4$	22	Potassium magnesium sulfate		22
K_2SO_4	50–52	Potassium sulfate		18
$KNa(NO_3)_2$	14	Potassium sodium nitrate	15	
KPO_3	38	Potassium metaphosphate		
KCl	60–62	Potassium chloride		
KOH	83	Potassium hydroxide		
$K_4P_2O_7$	22–48	Potassium polyphosphate		
$KH_2PO_4K_2HPO_4$	30–50	Potassium orthophosphate		
KNO_3	44	Potassium nitrate	13	

terms of natural products, and provide the same results as a good chemical fertilizer. The surplus application of chemical fertilizer can increase expenses, reduce the effectiveness of K fertilizer, and eventually harm the environment (Zhang et al. 2013). A substitute for the synthetic K fertilizer is essential for the sustainable improvement of agriculture. It is anticipated that by the year 2020, to realize the target production of nearly 321 million tons of food grain, the nutrient requirement will be 28.8 million tons, whereas the accessibility will be just 21.6 million tons, i.e. a deficit of about 7.2 million tons (Swaminathan and Bhavani 2013). There is a growing concern about environmental hazards and increasing threat to sustainable agriculture because of diminishing soil fertility resulting in an amplifying gap between nutrient elimination and supplies. Above and beyond these issues, the extensive use of biofertilizers is not hazardous to the environment, is inexpensive and more efficient and productive, and is within reach for small-time farmers compared to chemical fertilizers (Subba Rao 2001).

24.4 Microbial Mechanism for Potassium Solubilization

The mechanism of K solubilization signifies the means through which the insoluble K and structural inaccessible forms of K complexes are mobilized and solubilized due to the excretion of a wide range of organic acids by microbes. These acids undergo a sequence of exchange reactions like acid lysis and complex lysis. In addition, these reactions are input processes which cause the alteration of insoluble forms of K into soluble forms. The KSMs produce organic acids, which enables them to dissolve K from insoluble minerals like micas, orthoclases, and illite (Shanware et al. 2014). These organic acids may either directly solubilize rock K or excrete the chelated silicon ions to turn K into a solution form that is available to plants. Microbial organic acids enhance the mobilization of K compounds by offering protons and also by chelating with Ca^{2+} ions present in the soil (Singh et al. 2010). Organic compounds produced by microorganisms such as oxalate, citrate, and acetate can improve mineral dissolution in soil (Sheng et al. 2003). In another study by Styriakova et al. (2003) it was reported that K solubilization ensues through the configuration of complexes among organic acids and metal ions such as iron, calcium, and aluminum**.** Microbial arbitrated organic chelates, ligands, and other metabolic derivatives like excreted enzymes and simple or complex molecules of organic acids enhance the solubilization of the aluminosilicate (usually quartz) minerals in *in vitro* and *in situ* environments (Zeng et al. 2012). The solubilization of K within feldspar and illite is enhanced by production of microbial organic acids like oxalic and tartaric acid (Sheng and He 2006). A study by Groudev (1987) revealed that solubilization of K by inorganic and organic acid production is also supported by the production of mucilaginous casing made up of exopolysaccharides formed by bacteria like *Bacillus* sp., *Clostridium* sp., and *Thiobacillus* sp. Sugumaran and Janarthanam (2007) have reported an analogous feasible method of K solubilization wherein *Bacillus mucilaginosus* was examined for K solubilization. During the period of bacterium inoculation, there was no decrease in pH of the medium, implying that *Bacillus* sp. did not excrete organic or inorganic acids and slime formation by bacterium could possibly be responsible for K solubilization. The soil microbiome involved in mineral weathering produces organic and inorganic acids, protons, chelates, siderophores, and ligands. Similar potential has been reported in fungal species like *Cladosporium*, *Aspergillus*, and *Pencillium*. These have been found to excrete enormous amounts of citric acid, gluconic acid, and oxalic acids in *in vitro* conditions, causing the mobilization of silicates, mica, and feldspar in soil (Lian et al. 2008). Similarly, Yang et al. (2014) reported the leaching of K from minerals containing K-rich shale was caused by the formation of biofilm by bacteria growing on it. These biofilms were made up of acids, protein, and polysaccharides produced by bacteria.

The ability of K-solubilizing microbes to solubilize insoluble K has been quantitatively examined by various researchers. The media generally used for quantitative assessment of solubilization of K by KSM is Aleksandrov medium. It contains 0.5% mica as a source of an insoluble form of K, besides 1% glucose, 0.05% $MgSO_4.7H_2O$, 0.0005% $FeCl_3$, 0.01% $CaCO_3$, 0.2% $CaPO_4$ and agar 3%, with pH adjusted to 6.5. The dishware are incubated at 28 ± 2 °C for 2–3 days and bacterial colonies displaying clear zones are selected and the diameter of the solubilization zone can then be measured (Kumar and Narula 1999; Prajapati et al. 2013).

$$\text{Ratio} = \text{Diameter of zone of clearance} / \text{Diameter of growth}$$

The quantitative evaluation of K solublization is done using flame photometry or atomic absorption spectrophotometry, in which the supernatant obtained after centrifugation of culture broth is used for precipitation of cobalt nitrite. Potassium chloride is employed as the standard for the quantification of K (Hu et al. 2006).

24.5 Contemporary State of K Solubilization and Crop Production

Potassium replenishment in soil depends heavily on the application of synthetic fertilizer; however, these products have a noteworthy negative effect on the environment. The use of K-solubilizing microbes (KSMs) as inoculants has potential, as these KSMs transform insoluble forms of K in the soil into a soluble form which is accessible to plants. This embodies a competent strategy for enhancement of K absorption by the plant, in addition to reducing the use of chemical fertilizer (Zhanga and Konga 2014). Many workers have reported the significant role played by potassic biofertilizers in agriculture, especially for enhancing soil fertility, yield-attributing characters, and thereby final yield (Basak and Biswas 2010; Archana et al. 2013; Mikhailouskaya and Tcherhysh 2005). Additionally, the application of potassic biofertilizers to soil improves the soil microbiota and reduces the soil compactness and application of chemical fertilizers. It is well recognized that, although the Indian soil is a rich source of K within secondary minerals, it is not easily accessible to the plant. This could be made possible by application of K-solubilizing microbes that could make K available to plants. Consequently, inoculatng soil with K-solubilizing bacteria and application of additional beneficial microbial inoculants become obligatory to reinstate and uphold soil fertility.

The use of an efficient microbiome for fixed K solubilization, mobilization, and accessibility of other micro- and macronutrients to obtain superior and sustainable yield. The growth-enhancing microbiome found in the rhizosphere of the plant implements beneficial effects on the uptake of nutrients and their mobilization together with various other means such as nitrogen fixation, siderophores, HCN and phytohormone production, and mobilization of micro- and macronutrients minerals like K, iron, phosphorous, copper, and zinc. The total K amount in Indian soil is by and large adequate to sustain the crop production and growth. The reachable amount and allocation pattern of this mineral element varies in different types of soil in various regions, which results in K unavailability for plant uptake (Zörb et al. 2014). The microbes replenish the root zone environment by liberating accessible and transferable forms of K, which accomplish the basic requirements of a plant. The restoration of mineral nutrients in the rhizospheric zone is vital and a necessity for higher crop yields, and the deliberate inoculation of microbes or those naturally present play a very important part (Sheng et al. 2002). Researchers have established that KSMs performed nicely with several crops under a diverse agro-climatic environment. Supanjani et al. (2006) illustrated that K-solublizing bacteria amplified photosynthesis by 16% in hot pepper *Capsicum annuum* L. along with increasing leaf area by 35%, in contrast to the control plants. Moreover, biomass and fruit production of the treated plants were also enhanced by 23% and 30%, respectively, compared to control plants. Researchers also established that there is a similar effect on plants when treated with either phosphorus or K rocks along with phosphorus/potassium-solubilizing bacterial strains or with a usual, soluble fertilizer. Sheng (2005) studied the effect of *Bacillus edaphicus* NBT (K-releasing bacterial strain) on cotton and rape for plant growth–promoting effects and nutrient uptake by plants in K-deficient pot soil. The experiment showed that inoculation with the bacterial strain *B. edaphicus* NBT increased the root and shoot growth of cotton and rape plants. Strain NBT was also capable of mobilizing K competently in both crop plants after the addition of illite to the soil. There was also an increase in the K content by 30% and 26% in cotton and rape, respectively, when grown in soil treated with insoluble K and inoculated with the bacterial strain NBT. The inoculation also resulted in elevated N and P contents of above-ground parts of the plant. Furthermore, the bacterial strain was also able to inhabit and proliferate in the rhizosphric soil of cotton and rape after root inoculation.

Basak and Biswas (Basak and Biswas 2008) investigated the effectiveness of K-solubilizing bacteria (*Bacillus mucilaginosus*) on Sudan grass (*Sorghum vulgare* Pers.) var. Sudanensis as a test crop grown in two Alfisols. Results demonstrated that the use of mica appreciably improved biomass yield, mineral uptake, and percent K recoveries by Sudan grass as compared to control plants (without KSM). Furthermore, when the mica was inoculated with the bacterial strain in both the soils, there was an additional boost in biomass yield, K uptake, and percent K recoveries in contrast to those soils without the application of KSM-inoculated mica. Another study conducted by Zhanga and Konga (Zhanga and Konga 2014) on 27 K-solubilizing strains revealed that among them, 17 strains were from *Klebsiella variicola*, two strains each from *Enterobacter cloacae* and *Enterobacter asburiae*, and the other six strains belonged to *Agrobacterium tumefaciens*, *Enterobacter aerogenes*, *Microbacterium foliorum*, *Pantoea agglomerans*, *Burkholderia cepacia*, and *Myroides odoratimimus*, respectively. *Klebsiella variicola* showed the highest frequency of occurrence with 17 strains. A greenhouse pot experiment was conducted using four K-solubilizing bacterial isolates, GL7, JM3, XF4, and XF11, for determination of the K-solubilizing capabilities. The tobacco seedlings were treated with the four KSM strains to observe the effectiveness of K-solubilizing isolates; it was found that the treatment significantly enhanced K and N uptake and plant dry weight. This increase was further elevated with the application of a combination of K-solubilizing bacterial inoculation along with feldspar powder. Isolate XF 11 exhibited the most prominent and advantageous effect on tobacco seedling plant growth and nutrient (K and N) uptake. Therefore, a potential substitute to commercial chemical K fertilizer that will possibly help to maintain the viability of soil nutrients could be a combination of KSM with the addition of K feldspar powder.

Recently, Prajapati et al. (2013) studied the effects of KSMs *Enterobacter hormaechei* and *Aspergillus terreus* (a fungal strain) on Okra (*Abelmoscus esculantus*) grown in pot soil deficient in K. Results showed that the *Enterobacter hormaechei* enhanced shoot and root growth of the plant. Furthermore, with the application of feldspar into the pot soil, both the microbes were able to mobilize K in the Okra plant. The K content was increased in Okra plants when the pot soils were modified with insoluble K and inoculated with *Enterobacter hormaechei* and *Aspergillus terreus*. Likewise, Han et al. (2006) considered the outcome of bacterial KSM *Bacillus mucilaginosus* on pepper and cucumber plants. The experiment confirmed that coinoculation of phosphate-solubilizing bacteria (PSB) and the KSM resulted in elevated P and K availability in contrast to the control which did not have bacterial inoculum and rock fertilizer. The inoculation of PSB with phosphorus incorporated-rock enhanced the accessibility of P and K in the soil, boosted N, P, and K uptake by shoots and root, and increased the biomass of pepper and cucumber plants**.** Comparable but less prominent results were attained when rock K and KSM were applied concurrently. Hassan et al. (2010) measured the efficacy of *Bacillus circulans*, a KSM, on *Ammi visnaga* (Khella) augmentation. The plant growth parameters were enhanced by the inoculation of KSMs in conjunction with feldspar. Sugumaran and Janarthanam (2007) measured the K solubilization efficiency of isolated K-solubilizing bacteria (*Bacillus mucilagenosus*). The maximum K solubilization was found to be 4.29 mg l^{-1}. Another striking research effort by Bagyalakshmi et al. (2012) exhibited an improvement in productivity and nutrient uptake in tea plants inoculated with K-mobilizing bacteria (*Pseudomonas putida*). Tea excellence factors like aflavin, arubigin, highly polymerized substances, sum liquor color, caffeine, vigor, color of leaf, and flavor indexes were enhanced to a great extent in plants treated with K-solubilizing bacteria.

24.6 Future Aspects of K Mobilizing Microbes

The prime nutrients for the development and growth of crop plants include minerals like N, P, and K. Haphazard employment of chemical fertilizers for the sustenance of crop plants is a major cause of contamination and infertile soil, in addition to causing pollution of water basins and destruction of microbes, which results in poor soil health. On the other hand, application of biofertilizers is an eco-friendly approach for the replenishment of nutrients to the soil for the sustainable growth of plants. Complex and elaborate transactions between the KSM, potential rhizospheric microorganisms, the roots of a plant, and the surrounding ecosystem are responsible for the mobilization of rock K and its inconsistency in uptake have a large effect on plant growth and development. Potential and probable approaches include cloning of genes liable for K solubilization in the genome of those microbes that have additional advantageous functions, for instance, exceptional proliferation and endurance in the rhizosphere, nitrogen-fixing ability, phosphate-solubilizing capacity, and production of biocontrol metabolites and phytohormones. Furthermore, the effectiveness of the KSMs can be amplified by development of superior culture techniques and deliverance protocols that sustain their existence in the rhizospheric zone. The amalgamation and utilization of plant growth endorsing microbes with varied beneficial functions embracing the ability for K and P solubilization is an ecologically favorable and enhanced approach as it may result in improved endurance, propagation, and superior adaptation to varied agroclimatic fluctuations that occur throughout the plantation period. An additional beneficial prospect could be the recent approaches incorporating application of molecular biology along with techniques for exploitation of useful microbial functions that would enhance K-solubilization capability. Moreover, the commercial utilization of these superior microbes as K bioinoculants will further increase crop productivity and growth for feasible, sustainable, and enduring agriculture. Further and extended studies that focus on such comparable issues related to other existing micro- and macronutrient elements in soil, particularly in rhizospheric soil, and an account of the microbial molecular means of plant nutrition uptake will definitely assist in increasing our knowledge about the development of improved microbial inoculants to augment the K requirement of the plant.

Conclusions

Evidently, the application of synthetic fertilizers and organic manures cannot be diminished radically or eradicated at this stage without a considerable decrease in food production. Concurrently, there are toxic after-effects on the environment from the use of chemical fertilizers like the increasing dead zones in marine ecosystems throughout the world. These cannot be ignored in the long term, as this will result in devastating effects on the ecological balance. Therefore, there is an urgent need for an integrated approach of nutrient management that would endeavor to reduce agricultural inputs along with decreasing the adverse and objectionable environmental side effects of synthetic or organic agricultural fertilizer use and production. It is very important to have an advanced understanding about the intricate relationships between microbes, fertilizers, and plants. There is a call for additional information, besides the techniques mentioned earlier, the application of which is also bi-pronged. First, there is a need for the introduction of added applied K nutrients into the plant through microbial inoculants, since not as much K nutrient is lost to the environment for the period during and after crop production. Secondly, loss of fertilizer could be curtailed by escalating the efficiency of the plant's nutrient uptake. This may possibly be accomplished by application of K solubilizers. In either case, there would be a huge drop in agricultural environmental pollution caused by the unsystematic use of synthetic fertilizers. The results show that inoculating the rhizosphere with PGPMs along with microbial strains of KSMs have greatly enhanced crop production. Consequently, the utilization of this arrangement will be a healthier approach, utilizing a mapping system that puts together the consortium of microbial strains. In the meantime, several related areas need to be better understood, such as where K solubilization under *in vitro* and in field conditions is required. However, there are no apparent information/data available about the amount of K solubilization and absorbtion by plants, either *in vitro* or under field conditions, besides the consumption of K by the microbes for their individual growth and metabolic activities. The present study along with other related information will undoubtedly assist in understanding as well as determining the status of insoluble K, and the use of bioinoculants may possibly be required for a realistic approach in an actual field situation. In the meantime, it is essential to measure the solubilized K as there are many apparent factors that may possibly influence K solubilization and uptake by the plant, among them predominantly the K needs of microbes, root exudation by each plant, and the soil environment, such as levels of pH, total dissolved solids, and total and available K.

These outcomes show that plant type influences the root colonization of inoculated strains. Research has illustrated that effectual plant-growth-endorsing bacterium-plant synchronization ought to be tested and recognized in controlled floral experimental designs with defined ecological site conditions and practical applications, such as the soil and plant type. Alternatively, besides the plant growth-enhancing capability of commercially used microbes, the amount of stimulus of crop plants in addition to their perseverance in the rhizosphere remains uncertain and indistinct under real field conditions. As a result, experiments pertaining to the stimulation of cotton and rape should be pursued by examination under authentic field conditions. Currently the application of K-solubilizing microbes in our agricultural system in soils that are K deficient where K is lacking or undersupplied will definitely help to resolve the K element quandary and advance research in this field. Aiming towards development of potential K solubilizers may perhaps help lead Indian agriculture to an unconventional means of K nutrition enrichment for use in our cropping system.

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