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EFFECT OF POTASSIUM SOLUBILIZING BACTERIA ON PLANT GROWTH

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ABSTRACT

For plant growth and development, potassium (K) is important. It is involved in plant cellular osmotic pressure change and compound transport in plants. It promotes enzyme activation, nitrogen utilization, and sugar and protein synthesis.It also improves photosynthesis in plants. K deficiency causes yellowing of the leaf edges in plants, giving them a burnt look. Slow growth and incomplete root development may also be caused by it. Supplementation of soil potassium depends heavily on the use of chemical fertilizer, which has a major negative effect on the environment. Plants are only able to get k through the soil. In India, the detrimental use of chemical fertilizers has a significant adverse effect on the economy and environmental sustainability.The need to return to nature or sustainable agents that encourage evergreen agriculture is growing. Among these natural bio-agents, one such alternative is considered to be potassium solubilizing micro-organisms which solubilize fixed forms of potassium in soil via different mechanisms, including acidolysis, chelation, exchange reactions, complexity and organic acid productionKSM represents an immense opportunity for changing the challenges of the agricultural sector. In making potassium available to plants, potassium solubilizing microorganisms play a vital role in that solubilize potassium from insoluble forms such as feldspar, mica through the processing of organic acids and various enzymes. This review workcovers the work done on various potassium solubilizing microorganisms and their effects on plant's growth.

Keywords: Bio-fertilizer, potassium solubilization, plant and bacteria interaction, PGPRs, potassium bearing minerals

INTRODUCTION

Feeding an increasing world population that is expected to reach 9 billion by 2050, embracing more effective and sustainable methods of production, responding to growing concerns about natural resource management. Some of the major challenges that agriculture will face in the 21st century are adjusting to climate change and drought conditions in many developing regions **[24, 31]**.

Agriculture must be intensive and sustainable in the future to feed the growing world population. It is however, well established that food production by agriculture can generally not be maintained unless the nutrients extracted from the soil are replaced as a result of increased crop production. An adequate quantity of one or more important plant nutrients is missing in many agricultural soils, such that plant growth is suboptimal. Farmers have become increasingly dependent on chemical fertilizer sources to avoid this issue and achieve higher plant yields **[25]**. While chemical fertilizers have helped grow plants, the properties of the soil have not changed. Constant use of chemical fertilizers, primarily phosphorous, nitrogenous, and potassium fertilizers, is well known to have adverse environmental effects **[2, 24]**.

Constant use of chemical fertilizers, primarily phosphorous, nitrogenous, and potassium fertilizers, is well known to have adverse environmental effects **[2, 24]**. The populations of most developing countries in the world continue to grow at controlled rate; one of the biggest challenges facing the human population would be the demands put on agriculture to provide future food **[49]**. A great deal of effort is required to overcome this problem by focusing on the soil biological system and the agro-ecosystem as a whole, allowing for a deeper understanding of the dynamic processes and interactions between soil and plant micro-organisms regulating agricultural land stability.Soil is a lively natural body on the surface of the earth. There are many minerals in the soil that contain essential elements, but nitrogen (N), phosphorus (P), and potassium (K) are the most common minerals **[49]**. The third significant plant nutrient is K.It plays a key role in the development, metabolism, and growth of plants. The plants would have poorly formed roots, grow slowly, produce small seeds and have lower yields without sufficient potassium supply **[45, 95]** and increased vulnerability to diseases and pests **[6, 10, 5, 91]**. In plants where agricultural soils lack adequate phyto-available K for crop production, the requirement for K increases sometimes **[67]**. In both intensive and comprehensive agricultural systems, it is typically delivered as K-fertilizers **[61, 22, 62, 99, 105]**. Significant areas of the world's agricultural land are deficient in potassium, including three-fourths of China's paddy soil and two-thirds of Southern Australia's wheat bel **[49]**.

Globally, high inputs of chemical fertilizers such as nitrogen (N), phosphorus (P) and potassium (K) have been used to improve crop growth and productivity **[73]**. In the meantime, the intensive use of N, P and K chemicals has resulted in a dramatically destructive improvement in soil properties and environmental quality. However, research on the relationship between the use of fertilizers and their negative environmental effects are minimal **[73]**. It is therefore appropriate to explore and recognize alternative methods that can guarantee competitive crop yields and environmental health while ensuring the sustainability of the agro-ecosystem **[106, 34]**. The use of microbial inoculants or plant growth-promoting (PGP) bacteria in soils has recently been shown to be a promising method in intensive agricultural production systems around the world for sustainable production **[19, 21, 42, 73]**.

Potassium in soils:

The third most important common nutrient in the soil is potassium, the most abundant cation in plant cells and the most abundant nutrient in the leaves after N **[51, 96].** It is less abundant than P **[70]** than N and accounts for 2.6% of earth crusts by weigh **[68]**. In the soil, the rich sources of K are igneous and sedimentary rocks. Igneous rocks such as syenites (approximately 54 g K kg^{-1}), granites (approximately 46 g K kg^{-1}), basalts (approximately 7 g K kg^{-1}) and peridotites (approximately 2 g K kg^{-1}) have a higher K content than sedimentary rocks such as clay shales and lime stones containing approximately 30 g kg^{-1} and 6 g kg^{-1} **[43]**. Mineral soil K concentration varies between 0.04 and 3% in the lithosphere **[89]** and 3000 and 100,000 kg K ha-1 are present in surface soils **[71]**. Out of these total K contents, 98% K is present in non-exchangeable form (silicate minerals such as mica and feldspar **[78, 54]** and the remaining 2% is available in a plant uptake solution **[18, 50]**. Non-exchangeable K, which differs from mineral K, is another type of K in soil. The non-exchangeable K is retained between the trioctahedral and dioctahedral micas, vermiculites, and intergrade clay minerals of neighbouring tetrahedrallayers **[86]**. In these interlayers, non-exchangeable K^+ ions are retained and coulombically bound to the negatively charged interlayer surface sites **[35]**. These binding forces surpass the hydration forces between individual K^+; the crystal structure then partially collapses, and K^+ is physically trapped within structures **[44]**. Depending on the different soil parameters, these non-exchangeable K-pools are moderately to sparsely accessible to plants **[28, 86]**. K^+ can be released from this complex structure when levels of solution K are reduced **[23]** by plant removal or leaching **[84]** and perhaps the equilibrium K from the non-exchangeable pool is released by significant increases in microbial activity **[71]**.

Potassium availability to plants is highly dependent upon type of minerals with respect to bio-availability, and the most important K minerals are muscovite (white mica) KAl_2 $(AlSi_3O_{10})$ $(F,OH)_2$, or $(KF)_2(Al_2O_3)_3(SiO_2)_6(H_2O)$, which is a phyllosilicate mineral of aluminium and potassium; biotite (black mica) $K(Mg,Fe)_3Al_2Si_3O_{10}(OH,F)_2$ and orthoclase $(KAlSi_3O_8)$, potassium-taranakite, zeolite, vermiculite, chlorite, glauconite, illite **[59]**. Among these, biotite and muscovite mica groups are of particular interest since they are a major source of many essential nutrients such as Mg, K, Mn and Zn and are more readily soluble than other minerals **[87]**. Thus, in soils with mixed minerals, such as in Pakistan, where approximately 57% of the K applied is fixed, K transformations are very complex **[57]** because of high pH, the presence of non-expanded clay minerals such as vermiculite $(Mg, Fe^{++}, Al)_3$ $(Al, Si)_4$ O_{10} $(OH)_2$ $(4H_2O)$ and illite $(K, H_3O)_2$ $(Si, Al)_4$ O_{10} $[(OH)_2, (H_2O)]_2$ $(Al, Mg, Fe)_2$ (Si, Al) [27]. The bio-availability of K in various pools, however, follows the order solution > replaceable > fixed >mineral **[85, 71]**.

Only K can be absorbed from the solution by plants and microbes **[56]**, which is typically very low in concentration (1-2%), and readily subject to leaching/fixation. After plant and microbe removal of K, K is released from mineral and non-exchangeable pools to maintain a balance between strength and quantity phases **[86, 26]**. Solution K is depleted with time due to intensive agriculture-driven continuous plant uptake, and its low concentration (0.1–0.2 percent) is not adequate to meet plant growth(showing ∼5% of total crop demand) [80, 49]. This condition is worse in Southeast Asian, African and Oceanian countries because of a small reserve of minerals containing natural K. K-released from two other K reservoirs electrostatically bonded to humic substances and clay minerals, namely exchangeable K (EK) and slowly exchangeable K (SEK), to preserve equilibrium, make up 1-2% and 1-10% of total soil K, respectively **[46]**. This EK is retained in the soil by negatively charged clay minerals and organic matter, which is slowly released by mineral weathering and easily exchanged to become bio-available by other cations from both sites (EK and SEK) in the form of K^+ ions **[51, 71]**.

K-solubilizing microorganism (KSMs):

In the solubilization of insoluble and glued kind of K into usable forms of K readily absorbed by plants, a various community of soil micro-flora has been reported to be involved **[38, 103, 30]**. Microbial inoculants that are capable of dissolving K from minerals and rocks, increasing the expansion and yield of plants, additionally being economically viable and environmentally sustainable. The first proof of microbial involvement in rock potassium solubilization was shown by Muentzz (1890). A broad kind of KSMs are reported to release potassium in accessible form from K-bearing minerals in soils, namely *Bacillus mucilaginosus*, *Bacillus edaphicus*, *Bacillus circulans*, *Paenibacillusspp*., *Acidothiobacillus ferrooxidans*, *Pseudomonas*, *Burkholderia* **[75, 32, 65, 41, 15, 82]**. Several fungal and bacterial species, commonly referred to as KSMs, aid the growth of plants by mobilizing insoluble forms of K. KSMs, whose numbers vary from soil to soil, are ubiquitous. Rhizospheric microorganisms make an important contribution to the solubilization of bound mineral types in the soil **[88, 39, 81]**. Solubilizers of silicate minerals have been shown to have a number of soil microorganisms **[78]**. Even on the surface of mountain rocks, many microorganisms such as bacteria, fungi and actinomycetes have been colonized **[29, 30]** stated that the silicate solubilizing bacteria B. Sub spp. of mucilaginosus. Siliceus frees K from aluminosilicates and feldspar.According to Aleksandrov **[3]**, which were isolated at different locations from agricultural land and found that various bacterial species such as silicate bacteria were found to dissolve K, silicates and aluminium from insoluble minerals, it also assisted in organic matter decomposition, crop residues, etc., and indicated that they play a major role in the cycling of nutrients in the soil-plant system.*B. Mucilaginosus* stain CS1 is a silicate bacterium that has shown inhibitory activity on gram-negative bacteria growth **[49]**. Silicate solubilizing bacteria present in the rhizosphere and non-rhizosphere soil have also been recorded as **[39, 40]**. K-solubilizing rhizobacteria were isolated from the roots of cereal crops grown in soil modified by potassium and silicate **[52]**. Hutchens **[33]** reported that 27 heterotrophic bacteria strains were isolated and grown in liquid and solid minimum media as well as mica containing media under aerobic condition **[49]**.

In the solubilization of insoluble and fixed forms of K to available forms of K taken up by plants, a diverse community of soil microorganisms has been reported to be involved **[17]**. The first proof of microbial involvement in rock potassium solubilization was shown by Muentzz **[17]**. A number of microorganisms have been reported to release potassium in accessible form from k minerals in soil, namely *Bacillus mucilaginosus*, *Bacillus circulans*, *Bacillus edaphicus*, *Acidothiobacillus ferrooxidans*, *pseudomonas*, *Burkholderia* **[17]**. In order to solubilize silicate minerals, a number of soil microorganisms have been found. *Arthrobacter sp*., *Paenibacillus mucilaginosus*, *P. frequentans, Enterobacter hormaechei* (KSB-8), *Cladosporium*, *Aminobacter*, *Sphingomonas*, *Burkholderia*, *Paenibacillus glucanolyticus* **[17]**. Potassium solubilizing fungi (KSF) strains such as *Aspergillus terreus* and *Aspergillus niger* were isolated from different soil samples rich in K and increased soil fertility was observed **[17]**.

Many microbes, such as fungi, bacteria and actinomycetes, are capable of colonizing rock surfaces **[30]**. Silicate solubilizing bacteria (*B. mucilaginosus* sub sp. *siliceus*) can release K from feldspar and aluminosilicate minerals among these microbes, as well as from organic matter decomposition and crop residues **[3]**. K solubilizing rhizobacteria (KSR) such as *B. mucilaginosus* stain CS1 have been isolated from the roots of a variety of crops grown in K and silicate modified soil **[52]**. These microbes are present in both the rhizosphere and non-rhizosphere soil silicate solubilizing **[39, 48, 47, 101]**. From the last decade, a big number of bacterial species were found which involved with K solubilization including *B. mucilaginosus* **[14, 103]**, *B. edaphicus* **[76]**, *Burkholderia* sp., *B. circulanscan* **[39]**, *A. ferrooxidans* **[32]** Arthrobacter sp. **[103]**, *Paenibacillus glucanolyticus* **[69]**, *Paenibacillus mucilaginosus* **[32, 41]**. These bacteria can do some degree solubilize K into the plant form available, but only a few bacterial strains, such as *B. mucilaginosus*. In solubilizing K minerals, Edaphicus is highly effective **[76, 41]**. A few strains of fungi, such as *A. Niger*.and*A.Terreus*, which has been isolated from soil samples rich in K, can also solubilize insoluble K **[53]**. In addition to above mentioned microbes, some others including *Paenibacillus mucilaginosus* **[41]**, *Arthrobacter sp*. **[103]**, *Cladosporium* **[9]**, *Paenibacillus glucanolyticus* **[69]**, *Aminobacter*, *Penicillium* frequentans, *Burkholderia*, *Sphingomonas* **[92]**, *Pseudomonas* have the ability to solubilize both K and P **[71]**.

Plant growth promotion (PGP) activities: Through various direct and indirect growth promotion mechanisms, the KSMs support plant growth. KSM inoculation in the soil improves nutrient uptake, promotes K solubilization, decomposition of organic matter and many other functions **[36]**. Microbes play a vital role through direct mechanisms in N_2-fixation, P-solubilization, development of plant growth hormones like auxin, cytokinins, ethylene, IAA and GA3 **[77]**, production of organic acid and solubilization of K Alexander 1977 **[77, 58]**. Microbes improve plant growth through the development of siderophores, antibiotics, H_2S, antifungal compounds, starch hydrolysis and cellulose degradation in indirect mechanisms **[48]**. In most cases, KSMs also encourage plant growth through these beneficial mechanisms **[39]**. Increased nutrient uptake and promotion of plant growth are usually attributed to plant growth hormones released in the soil and plant rhizosphere and useful for root growth **[36]**. The key characteristics of KSMs willsolubilization from K mineral, which significantly enhances soil fertility status and eventually promotes plant growth **[65]**. The use of Potassium solubilizing microorganisms for growth promotion is a sound approach that can restore unproductive soils **[15, 65]**. Several studies have examined the effect of KSMs on plant growth and the solubilization of K minerals*Bacillus mucilaginosus* inoculation in nutrient-limited soil showed a positive response to growth and eggplant yield. In addition, in soil modified with K minerals and *B Mucilaginosus*, maximum K release and uptake were observed byHan and Lee, 2005.*Frateuria aurantia* belonging to the family *Pseudomonaceae* substantially improved K solubilization and plant growth upon inoculation, according to the findings of Ramarethinam and Chandra **[66]**. In this analysis, K solubilization and PGP activities were indicated to be due to the secretion of organic acids and enzymes formed by KSMs **[71]**. Such microbes can release organic acids that affect the release of K from structural compounds.In addition, various types of substances that promote amino acids, vitamins and plant growth promoters are released, such as gibberellic acid (GA3) and indole-3-acetic acid (IAA), which help to plants achieve maximum growth **[63, 83]**. In the presence of B, high production of auxin was observed. NBT strain of edaphicus, which ultimately enhances plant growth. The NBT strain has a high solubilization capacity for K and was found to optimize cotton and rape growth **[77, 71]**.

Effect of KSMs on plant growth and yield

Seed inoculation and seedling treatment of plants with KSMs generally showed a substantial increase in the percentage of germination, seedling vigor, plant growth, yield and K uptake by plants in field and greenhouse **[13, 15, 14, 100, 82, 11, 105]**.

Aleksandrov **[4]** first reported the use of organic minerals with a combination of silicate bacteria to increase plant growth and maize and wheat yields. More specifically, research conducted on field-level test crops such as wheat, forage crops, maize, and sudan grass crops showed that KSMs could significantly reduce the use of chemical or organic fertilizers **[98]**. As previous researchers have stated **[82, 79, 104]** the improvement of plant K nutrition may be due to the stimulation by unique microorganisms of ramroot growth or the elongation of root hairs. Therefore, no direct increase in soil solution K's availability is anticipated. The KSMs were isolated from different plants' rhizospheric soil and from potassium bearing minerals such as wheat feldspar **[75]**, Ceramic industry soil **[64]**, potato–soybean cropping sequence **[20]**, Iranian soils **[103]**, mica core of Andhra Pradesh **[30]**, biofertilizers [**102]**, common bean **[37]**, sorghum, maize, bajra, chilli **[7]**, cotton, tomato, soybean, groundnut and banana **[8]**, soil of Tianmu Mountain, Zhejiang Province China **[32]**, rice **[55]**, tea **[12]**, valencia orange **[72]**, black pepper **[69]**, potato **[1]**, another beneficial effect of microorganisms with K-solubilizing ability is growth through improvement by N-fixer, P, and K-solubilizers **[94, 93, 15]**. **[82]** Singhcarried out a hydroponics analysis to determine the impact of *B. Azotobacter chroococcum, mucilaginosus,* and *Rhizobium spp*. On their ability to mobilize K from waste mica under a phytotron growth chamber using maize and wheat as the test crops **[49]**. Substantial K assimilation was recorded for maize and wheat, where waste mica was the sole source of K, which was transformed into higher biomass accumulation, K content and plant uptake, as well as chlorophyll and crude protein content in plant tissue **[49]**. Within the rhizobacteria, *B. Mucilaginosus* has resulted in substantially greater potassium mobilization than *A. Chroococcum* and inoculation with *Rhizobium*. Research into K mobilization by the wild-type strain NBT of B, according to **[74]**. In a pot experiment, Edaphicus, wheat was grown on yellow-brown soil with a limited amount of K available. The root growth and shoot growth of wheat were significantly increased after inoculation with bacterial strains and they had higher NPK content of plant components compared to those un-inoculated **[49]**.

CONCLUSION

Microorganisms of the rhizosphere contribute substantially to the solubilization of fixed types of soil minerals K in soil solution K. It has been shown that soil inoculation of KSMs improves the solubilization of insoluble mineral K, resulting in higher crop efficiency. In addition to the K-solubilizing capacities, the KSMs have the capacity to generate plant growth hormones, ammonia, siderophore and phosphorus solubilization, etc. Although KSMs are abundant in many soils, they have not been successfully commercialized at present and are therefore still found to be limited in their application.This communication highlighted the contribution of rhizospheric soil K-solubilizing microorganisms to the production of efficient indigenous microbial consortia needed to boost plant growth and yield of different crops as well as to improve soil fertility.In order to improve sustainable agriculture, this sort of microbial consortium is cost-effective and environmentally friendly.

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REFERENCES

[1] Abdel-Salam MA, Shams AS. Feldspar-K fertilization of potato (*Solanum tuberosum* L.) augmented by biofertilizer. J Agric Environ Sci 2012; 12(6): 694–9.

[2] Adesemoye, A.O., Kloepper, J.W. 2009. Plant–microbes interactions in enhanced fertilizer-use efficiency. Appl. Microbial. Biotechnol. 85, 1-12.

[3] Aleksandrov VG, Blagodyr RN, Ilev IP. Liberation of phosphoric acid from apatite by silicate bacteria. Microchem J 1967; 29: 111–4.

[4] Aleksandrov VG. Organo-mineral fertilizers and silicate bacteria. Dokl Akad Nauk 1985; 7: 43–8.

[5] Amtmann A, Hammond JP, Armengaud P, White PJ. Nutrient sensing and signaling in plants: potassium and phosphorus. Adv Bot Res 2006; 43: 209–57.

[6] Amtmann A, Troufflard S, Armengaud P. The effect of potassium nutrition on pest and disease resistance in plants. Physiol Plant 2008; 133: 682–91.

[7] Archana DS, Nandish MS, Savalagi VP, Alagawadi AR. Characterization of potassium solubilizing bacteria (KSB) from rhizosphere soil. Bioinfolet 2013; 10: 248–57.

[8] Archana DS, Nandish MS, Savalagi VP, Alagawadi AR. Screening of potassium solubilizing bacteria (KSB) for plant growth promotional activity. Bioinfolet 2012; 9(4): 627–30.

[9] Argelis, D.T., Gonzala, D.A., Vizcaino, C., Gartia, M.T., 1993. Biochemical mechanism of stone alteration carried out by filamentous fungi living in monuments. Biogeo. Chem. 19, 129–147.

[10] Armengaud, Breitling R, Amtmann A. Coronatine-intensive 1 (COII) mediates transcriptional responses of *Arabidopsis thaliana* to external potassium supply. Mol Plant 2010; 3(2): 390–405.

[11] Awasthi R, Tewari R, Nayyar H. Synergy between plants and P-solubilizing microbes in soils: effects on growth and physiology of crops. Int Res J Microbiol 2011; 2: 484–503.

[12] Bagyalakshmi B, Ponmurugan P, Balamurugan A. Impact of different temperature, carbon and nitrogen sources on solubilization efficiency of native potassium solubilizing bacteria from tea (*Camellia sinensis*). J Biol Res 2012; 3(2): 36–42.

[13] Basak BB, Biswas DR. Co-inoculation of potassium solubilizing and nitrogen fixing bacteria on solubilization of waste mica and their effect on growth promotion and nutrient acquisition by a forage crop. Biol Fertile Soils 2010; 46: 641–8.

[14] Basak BB, Biswas DR. Influence of potassium solubilizing microorganism (Bacillus mucilaginosus) and waste mica on potassium uptake dynamics by sudan grass (*Sorghum vulgare* Pers.) grown under two Alfisols. Plant Soil 2009; 317: 235–55.

[15] Basak BB, Biswas DR. Modification of waste mica for alternative source of potassium: evaluation of potassium release in soil from waste mica treated with potassium solubilizing bacteria (KSB). Germany: Lambert Academic Publishing; 2012, ISBN 978-3-659-29842-4.

[16] Basak, B.B., Biswas, D.R., 2009. Influence of potassium solubilizing microorganism (*Bacillus mucilaginosus*) and waste mica on potassium uptake dynamics by sudan grass(*Sorghum vulgare* Pers.) grown under two Alfisols. Plant Soil 317, 235–255.

[17] Bashir, Z., Zargar, M.Y., Husain, M., Mohiddin, F.A., Kousar, S., Zahra, S.B., Ahmad, A. and Rathore, J.P., Potassium Solubilizing Microorganisms: Mechanism and Diversity, Int. J. Pure App. Biosci. 5(5): 653-660 (2017).

[18] Bertsch, P.M., Thomas, G.W., 1985. Potassium status of temperate region soils. In: Potassium in Agriculture. pp. 131–162.

[19] Bhattacharyya, P. N., and Jha, D. K. (2012). Plant growth-promoting rhizobacteria (PGPR): emergence in agriculture. World J. Microbiol. Biotechnol. 28, 1327– 1350. doi: 10.1007/s11274-011-0979-9

[20] Biswas DR. Nutrient recycling potential of rock phosphate and waste mica enriched compost on crop productivity and changes in soil fertility under potato–soybean cropping sequence in an Inceptisol of Indo-Gangetic Plains of India. NutrCyclAgroecosyst 2011;89:15–30

[21] Chauhan, H., Bagyaraj, D. J., Selvakumar, G., and Sundaram, S. P. (2015). Novel plant growth promoting rhizobacteria-prospects and potential. Appl. Soil Ecol. 95, 38–53. doi: 10.1016/j.apsoil.2015.05.011Commun. Soil Sci. Plant Anal. II, 435–449.

[22] Dasan AS. Compatibility of agrochemicals on the growth of phosphorous mobilizing bacteria Bacillus megaterium var. phosphaticum potassium mobilizing bacteria Frateuria aurantia. Appl Res DevInst J 2012;6(13):118–34

[23] Doll, A.C., Lucas, R.E., 1973. Testing soils for potassium, calcium, and magnesium. In: Walsh, L.M., Beaton, J.D. (Eds.), Soil Testing and Plant Analysis. Soil Science Society of America, Madison, WI, pp. 133–151.

[24] Etesami, H., Emami, S., & Alikhani, H. A. (2017). Potassium solubilizing bacteria (KSB): Mechanisms, promotion of plant growth, and future prospects - a review. *Journal of Soil Science and Plant Nutrition, 17*(4), 897-911.

[25] Glick, B.R. 2012. Plant Growth-Promoting Bacteria: Mechanisms and Applications. Scientifica. 2012, 963401.

[26] Goldstein, A.H., 1994. Involvement of the quinoprotein glucose dehydrogenase in the solubilization of exogenous mineral phosphates by gram-negative bacteria. ISBN 1555810802 In:

[27] Goulding, K.W.T., 1987. Potassium fixation and release. Proceedings of the colloquium of the international Potash Institute. 10, 131–136.

[28] Goulding, K.W.T., Talibudeen, O., 1979. Potassium reserves in a sandy clay soil from the Saxmundhum experiment: kinetics and equilibrium thermodynamics. J. Soil Sci. 30, 291–302.

[29] Groudev SN. Use of heterotrophic microorganisms in mineral biotechnology. Acta Biotechnol 1987;7:299–306

[30] Gundala PB, Chinthala P, Sreenivasulu B. A new facultative alkaliphilic, potassium solubilizing, Bacillus Sp. SVUNM9 isolated from mica cores of Nellore District, Andhra Pradesh, India. Research and Reviews. J Microbiol Biotechnol 2013;2(1):1–7.

[31] Haub, C., Gribble, J., Jacobsen, L. 2012. World Population Data Sheet 2012. Population Reference Bureau, Washington.

[32] Hu, X., Chen, J., Guo, J., 2006. Two phosphate and potassium-solubilizing bacteria isolated from Tianmu Mountain, Zhejiang, China. World J. Microbiol. Biotechnol. 22, 983–990.

[33] Hutchens E, Valsami-Jones E, McEldowney S, Gaze W, McLean J. The role of heterotrophic bacteria in feldspar dissolution – an experimental approach. Mineral Mag 2003; 67(6): 1157–70.

[34] Jiao, W. T., Chen, W. P., Chang, A. C., and Page, A. L. (2012). Environmental risks of trace elements associated with long-term phosphate fertilizers applications: a review. Environ. Pollut. 168, 44–53. doi: 10.1016/j.envpol.2012.03.052

[35] Kittrick, J.A., 1966. Forces involved in ion fixation by vermiculite. Soil Sci. Soc. Am. Proc. 30, 801–803.

[36] Kloepper, J.W., Zablotowicz, R.M., Tipping, E.M., Lifshitz, R., 1991. Plant growth promotion mediated by bacteria rhizosphere colonizers. In: Keister, D.L., Cregan, P.B. (Eds.), The rhizosphere and Plant Growth. Kluwer Academic Publishing, Dordrecht, pp. 315–326

[37] Kumar P, Dubey RC, Maheshwari DK. Bacillus strains isolated from rhizosphere showed plant growth promoting and antagonistic activity against phytopathogens. Microbiol Res 2012; 67: 493–9.

[38] Li FC, Li S, Yang YZ, Cheng LJ. Advances in the study of weathering products of primary silicate minerals, exemplified by mica and feldspar. Acta Petrol Mineral 2006; 25: 440–8.

[39] Lian, B., Fu, P.Q., Mo, D.M., Liu, C.Q., 2002. A comprehensive review of the mechanism of potassium release by silicate bacteria. Acta Mineral. Sin. 22, 179–182.

[40] Liu GY. Screening of silicate bacteria with potassium releasing and antagonistic activity. Chin J Appl Environ Biol 2001; 7: 66–8.

[41] Liu, D., Lian, B., Dong, H., 2012. Isolation of *Paenibacillus* sp. and assessment of its potential for enhancing mineral weathering. Geomicrobiol. J. 29, 413–421.

[42] Majeed, A., Abbasi, M. K., Hameed, S., Imran, S., and Rahim, N. (2015). Isolation and characterization of plant growth-promoting rhizobacteria from wheat rhizosphere and their effect on plant growth promotion. Front. Microbiol. 6:198. doi: 10.3389/fmicb.2015.00198

[43] Malavolta, E. (1985). Potassium status of tropical and subtropical region soils. *Potassium in agriculture*, 163-200.

[44] Martin, H.W., Sparks, D.L., 1983. Kinetics of nonexchangeable potassium release from two Coastal Plain soils. Soil Sci. Soc. Am. J. 47, 883–887.

[45] McAfee J. Potassium, a key nutrient for plant growth. Department of Soil and Crop Sciences; 2008, http://jimmcafee.tamu.edu/files/potassium

[46] Mclean, E.O., Watson, M.E., 1985. Soil measurement of plant-available potassium. In: Mund-son, R.D.E. (Ed.), Potassium in Agriculture. Madison, WI, ASA CSSA and SSSA, pp. 277–278.

[47] Meena, R.S., Meena, V.S., Meena, S.K., Verma, J.P., 2015b. Towards the plant stress mitigate the agricultural productivity: a book review. J. Cleaner Prod. 102, 552–553.

[48] Meena, V.S., Maurya, B.R., Bahadur, I., 2014b. Potassium solubilization by bacterial strain in waste mica. Bangladesh J. Bot. 43 (2), 235–237.

[49] Meena, V.S., Maurya, B.R., Verma, J.P., 2014a. Does a rhizospheric microorganism enhance K+ availability in agricultural soils? Microbiol. Res. 169, 337–347.

[50] Meena, V.S., Maurya, B.R., Verma, J.P., Meena, R.S., 2016a. Potassium Solubilizing Microorganisms for Sustainable Agriculture. Springer India.00

[51] Mengel, K., Kirkby, E.A., Kosegarten, H., Appel, T., 2001. Principles of Plant Nutrition, fifth ed. Kluwer Academic Publishers, Dordrecht, Netherlands.

[52] Mikhailouskaya, N., Tcherhysh, A., 2005. K-mobilizing bacteria and their effect on wheat yield. Latvian J. Agron. 8, 154–557.

[53] Mirminachi, F., Zhang, A., Roehr, M., 2002. Citric acid fermentation and heavy metal ions. Acta Biotechnol. 22, 363–373

[54] Mohamed, H.M., El-Homosy, R.F., Abd-Ellatef, A.H., Salh, F.M., Hussein, M.Y., 2017. Identification of yeast strains isolated from agricultural soils for releasing potassiumbearing minerals. Geomicrobiol. J. 34 (3), 261–266.

[55] Muralikannan N, Anthomiraj S. Occurrence of silicate solubilizing bacteria in rice ecosystem. Madras Agric J 1998; 85: 47–50.

[56] Oborn, I., Andrist-Rangel, Y., Askeaard, M., Grant, C.A., Watson, C.A., Edwards, A.C., 2005. Critical aspects of potassium management in agricultural systems. Soil Use Manage. 21, 102–112.

[57] Pal, Y., Wong, M.T.F., Gilkes, R.I., 1999. The forms of potassium and potassium adsorption in some virgin soils from South-Western Australia. Aust. J. Soil Res. 37, 695–709.

[58] Park, M., Singvilay, O., Seok, Y., Chung, J., Ahn, K., Sa, T., 2003. Effect of phosphate solubilizing fungi on P uptake and growth to tobacco in rock phosphate applied soil. Korean J. Soil Sci. Fertil. 36, 233–238.

[59] Parker, D.R., Hendricks, G.J., Sparks, D.L., 1989. Potassium in Atlantic Coastal Plain soils: II. Crop responses and changes in soil potassium under intensive management. Soil Sci. Soc. Am. J. 53, 397–401.

[60] Parmar P, Sindhu SS. Potassium solubilization by rhizosphere bacteria: influence of nutritional and environmental conditions. J Microbiol Res 2013;3(1): 25–31.

[61] Pettigrew WT. Potassium influences on yield and quality production for maize, wheat, soybean and cotton. Physiol Plant 2008; 133:670–81.

[62] Phua CKH, Abdul Wahid AN, Abdul Rahim K. Development of multifunctional biofertilizer formulation from indigenous microorganisms and evaluation of their N2-fixing capabilities on Chinese cabbage using 15 N tracer technique. Pak J Trop AgricSci 2012;35(3):673–9

[63] Ponmurugan, P., Gopi, C., 2006. Distribution pattern and screening of phosphate solubilizing bacteria isolated from different food and forage crops. J. Agron. 5, 600–604.

[64] Prajapati KB, Modi HA. Isolation and characterization of potassium solubilizing bacteria from ceramic industry soil. CIBTech J Microbiol 2012; 1:8–14.

[65] Rajawat, M.V.S., Singh, S., Singh, G., Saxena, A.K., 2012. Isolation and characterization of K-solubilizing bacteria isolated from different rhizospheric soil. In: Proceeding of 53rd Annual Conference of Association of Microbiologists of India. p. 124.

[66] Ramarethinam, S., Chandra, K., 2006. Studies on the effect of potash solubilizing bacteria *Frateuria aurantia* (Symbion-K-Liquid Formulation) on brinjal (Solanummelongena L) growth and yield. Pestology 11, 35–39.

[67] Rengel Z, Damon PM. Crops and genotypes differ in efficiency of potassium uptake and use. Physiol Plant 2008; 133:624–36.

[68] Rittenhouse, P. A., 1979. Potash and Politics. Econ. Geol. 74, 353-357.

[69] Sangeeth, K.P., Bhai, R.S., Srinivasan, V., 2012. *Paenibacillus glucanolyticus*, a promising potassium solubilizing bacterium isolated from black pepper (*Piper nigrum* L.) rhizosphere. J. Spic. Aromat. Crops 21 (2), 118–124.

[70] Sardans, J., Penuelas, J., Coll, M., Vayreda, J., Rivas-Ubach, A., 2012. Stoichiometry of potassium is largely determined by water availability and growth in Catalonian forests. Funct. Ecol. 26, 1077–1089

[71] Sattar, A., Naveed, M., Ali, M., Zahir, Z. A., Nadeem, S. M., Yaseen, M., *et al*. (2019). Perspectives of potassium solubilizing microbes in sustainable food production system: A review. *Applied soil ecology, 133*(12), 146-159.

[72] Shaaban EA, El-Shamma IMS, El Shazly S, El-Gazzar A, Abdel-Hak RE. Efficiency of rock-feldspar combined with silicate dissolving bacteria on yield and fruit quality of valencia orange fruits in reclaimed soils. J Appl Sci Res 2012; 8:4504–10.

[73] Shen H, H. X. (2016). A Complex Inoculant of N2-Fixing, P- and K-Solubilizing Bacteria from a Purple Soil Improves the Growth of Kiwifruit (*Actinidia chinensis*) Plantlets. *Front. Microbiol, 7*(841), 1-12.

[74] Sheng XF, He LY. Solubilization of potassium-bearing minerals by a wild type strain of *Bacillus edaphicus* and its mutants and increased potassium uptake by wheat. Can J Microbiol 2006; 52: 66–72.

[75] Sheng XF, Zhao F, He H, Qiu G, Chen L. Isolation, characterization of silicate mineral solubilizing *Bacillus globisporus* Q12 from the surface of weathered feldspar. Can J Microbiol 2008; 54: 1064–8.

[76] Sheng, X.F., 2005. Growth promotion and increased potassium uptake of cotton and rape by a potassium releasing strain of Bacillus edaphicus. Soil Biol. Biochem. 37, 1918–1922.

[77] Sheng, X.F., Huang, W.Y., 2001. Physiological characteristics of strain NBT of *silicate bacterium*. Acta Pedol. Sin. 38, 569–574.

[78] Sheng, X.F., Huang, W.Y., 2002. Study on the conditions of potassium release by strain NBT of silicate bacteria. Sci. Agric. Sin. 35, 673–677.

[79] Sindhu SS, Parmar P, Phour M. Nutrient cycling: potassium solubilization by microorganisms and improvement of crop growth. In: Parmar N, Singh A, editors. Geomicrobiology and biogeochemistry: soil biology. New York, Germany: Springer-Wien; 2012.

[80] Sindhu, S.S., Parmar, P., Phour, M., 2014. Nutrient cycling: potassium solubilization by microorganisms and improvement of crop growth. In: Parmar, N., Singh, A. (Eds.), Geomicrobiology and Biogeochemistry. Springer, Berlin, pp. 175–198.

[81] Sindhu, S.S., Verma, M.K., Suman, M., 2009. Molecular genetics of phosphate solubilization in rhizosphere bacteria and its role in plant growth promotion. In: Khan, M.S., Zaidi, A. (Eds.), Phosphate Solubilizing Microbes and Crop

Productivity. Nova Science Publishers, USA, pp. 199–228.

[82] Singh G, Biswas DR, Marwah TS. Mobilization of potassium from waste mica by plant growth promoting rhizobacteria and its assimilation by maize (*Zea mays*) and wheat (*Triticum aestivum* L.). J Plant Nutr 2010; 33: 1236–51.

[83] Singh, N.P., Singh, R.K., Meena, V.S., Meena, R.K., 2015. Can we use maize (Zea mays) Rhizobacteria as plant growth promoter? Vegetos 28 (1), 86–99.

[84] Sparks, D.L., 1980. Chemistry of soil potassium in Atlantic Coastal Plain soils: a review.

[85] Sparks, D.L., 2000. Bioavailability of soil potassium, D-38-D-52. In: Sumner, M.E. (Ed.), Handbook of Soil Science. CRC Press, Boca Raton, FL.

[86] Sparks, D.L., Huang, P.M., 1985. Physical chemistry of soil potassium. In: Munson, R.D. (Ed.), Potassium in Agriculture. Am. Soc. Agron. J., USA, pp. 201–276.

[87] Sugumaran, P., Janarthanam, B., 2007. Solubilization of potassium containing minerals by bacteria and their effect on plant growth. World J. Agric. Sci. 3 (3), 350–355.

[88] Supanjani, Han, H.S., Jung, S.J., Lee, K.D., 2006. Rock phosphate potassium and rock solubilizing bacteria as alternative sustainable fertilizers. Agro. Sust. Dev. 26, 233–240.

[89] Syers, J. K. (2002). Potassium in soils: current concepts. *Feed the soil to feed the people The role of potash in susta-inable agriculture*, 301.

[90] Torriani-Gorni, A., Yagil, E., Silver, S. (Eds.), Phosphate in Microorganisms: Cellular and Molecular Biology. ASM Press, Washington, pp. 197–203.

[91] Troufflard S, Mullen W, Larson TR, Graham IA, Crozier A, Amtmann A, Armengaud P. Potassium deficiency induced the biosynthesis of oxylipins and glucosinolates in *Arabiodopsis thaliana*. Plant Biol 2010; 10(1): 172.

[92] Uroz, S., Calvaruso, C., Turpault, M.P., Frey-Klett, P. 2009. Mineral weathering by bacteria: ecology, actors and mechanisms. Trends Microbiol. 17, 378–387.

[93] Verma JP, Yadav J, Tiwari KN, Lavakush, Singh V. Impact of plant growth promoting rhizobacteria on crop production. Int J Agric Res 2010; 5: 954–83.

[94] Verma JP, Yadav J, Tiwari KN. Effect of Mesorhizobium and plant growth promoting rhizobacteria on nodulation and yields of chickpea. Biol Forum – An Int J 2009; 1(2): 11–4.

[95] White PJ, Karley AJ. Potassium In: Hell R, Mendel RR, editors. Cell biology of metals and nutrients, plant cell monographs, vol. 17. Berlin: Springer; 2010. p. 199–224.

[96] White, A.F., 2003. Natural weathering rates of silicate minerals. Treatise Geochem. 5,133–168

[97] Wood N. Nodulation by numbers:the role of ethylene in symbiotic nitrogen fixation. Trends Plant Sci 2001; 6: 501–2.

[98] Xie JC. Present situation and prospects for the world's fertilizer use. Plant NutriFertilSci 1998; 4: 321–30

[99] Yadegari M, Farahani GHN, Mosadeghzad Z. Biofertilizers effects on quantitative and qualitative yieldof Thyme (Thymus vulgaris). AfrJAgricRes 2012;7(34):4716–23.

[100] Youssef GH, Seddik WMA, Osman MA. Efficiency of natural minerals in presence of different nitrogen forms and potassium dissolving bacteria on peanut and sesame yields. J Am Sci 2010; 6(11): 647–60.

[101] Zahedi, H., 2016. Growth-promoting effect of potassium-solubilizing microorganisms on some crop species. In: Meena, V.S., Maurya, B.R., Verma, J.P., Meena, R.S. (Eds.), Potassium Solubilizing Microorganisms for Sustainable Agriculture. Springer, India, pp. 31–42.

[102] Zakaria AAB. Growth optimization of potassium solubilizing bacteria isolated from biofertilizer. Malaysia Pahang: Bachelor of Chem. Eng. (Biotech.), Fac. of Chem., Natural Resources Eng. Univ; 2009. p. 40.

[103] Zarjani JK, Aliasgharzad N, Oustan S, Emadi M, Ahmadi A. Isolation and characterization of potassium solubilizing bacteria in some Iranian soils. Arch Agro Soil Sci 2013; 77: 7569, http://dx.doi.org/10.1080/03650340.2012.

[104] Zeng X, Liu X, Tang J, Hu S, Jiang P, Li W, *et al*. Characterization and potassium solubilizing ability of *Bacillus circulans* Z1-3. AdvSciLett 2012; 10: 173–6.

[105] Zhang A, Zhao G, Gao T, Wang W, Li J, Zhang S, *et al*. Solubilization of insoluble potassium and phosphate by *Paenibacillus kribensis* CX-7: a soil microorganism with biological control potential. Afr J Microbiol Res 2013; 7(1): 41–7.

[106] Zhang, F. S., and Ju, X. T. (2002). Disscusion on nitrogen management and environment in agro-ecosystems of sustained development of agriculture. AtcaPedol. Sin. 39(Suppl.), 41–55.