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Basak, B.B., Sarkar, B., Biswas, D.R. et al. (2017) Bio-Intervention of Naturally Occurring Silicate Minerals for Alternative Source of Potassium: Challenges and Opportunities. *Advances in Agronomy*, 141. pp. 115-145. ISSN: 0065-2113

<https://doi.org/10.1016/bs.agron.2016.10.016>

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1 **Bio-intervention of naturally occurring silicate minerals for alternative source of**
2 **potassium: Challenges and opportunities**

3

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20

21 **Abstract**

22 Soil needs simultaneous replenishment of various nutrients to maintain its inherent fertility status
23 under extensive cropping systems. Replenishing soil nutrients with commercial fertilizer is
24 costly. Among various fertilizers, deposits of potassium (K) ore suitable for the production of
25 commercial K fertilizer (KCl) are distributed in few northern hemisphere countries (Canada,
26 Russia, Belarus and Germany) which control more than 70% of the world's potash market.
27 Naturally occurring minerals, particularly silicate minerals, could be used as a source of K, but
28 not as satisfactorily as commercial K fertilizers. In this context, bio-intervention (in combination
29 with microorganisms and/or composting) of silicate minerals has been found quite promising to
30 improve plant K availability and assimilation. This is an energy efficient and environmentally
31 friendly approach. Here we present a critical review of existing literature on direct application of
32 silicate minerals as a source of K for plant nutrition as well as soil fertility enhancement by
33 underpinning the bio-intervention strategies and related K solubilization mechanisms. An
34 advancement of knowledge in this field will not only contribute to a better understanding of the
35 complex natural processes of soil K fertility, but also help to develop a new approach to utilize
36 natural mineral resources for sustainable and environmental friendly agricultural practices.

37

38 **Key words:** Alternative K fertilizer, Silicate minerals, Bio-intervention, Plant nutrition,
39 Sustainable agriculture

40

41 **1. Introduction**

42 Potassium (K) ranks third among the essential plant nutrients after nitrogen and phosphorus and
43 seventh among all the elements in the earth's crust. Modern intensive agriculture leads to a
44 decline in soil nutrient levels due to mining through crop uptake and other losses. The issue of K
45 is more pronounced in the developing countries as most of the farmers have mainly focused on
46 the application of nitrogen and phosphorus for crop production neglecting K and micronutrients.
47 Such an imbalanced nutrient management practice has badly impaired the productivity of soil.
48 According to an estimate by the Food and Agriculture Organization of the United Nations
49 (FAO), the global demand of potash fertilizer was likely to increase annually by 2.6% over 2014
50 and the supply would balance the demand. Of the overall increase in demand for 3400,000
51 tonnes of potash between 2014 and 2018, 56% would be in Asia, 27% in the America, 11% in
52 Europe, 6% in Africa and 0.4% in Oceania (FAO, 2015). Most of these have to be imported to
53 respective continents (FAO, 2015). Most importantly, K fertilizers make up only 10% or less of
54 the total fertilizer inputs despite the fact that K undergoes the highest nutrient depletion rates in
55 developing countries, especially in African countries. These countries do not have any suitable K
56 bearing mineral ores from which commercial K fertilizers can be produced. Potash ores have a
57 rather limited distribution globally (Rittenhouse, 1979; Moores, 2009), with the bulk of the
58 world's K mined in Canada, Europe and the Middle East (Figure 1). Most of the Kores suitable
59 for commercial K fertilizer production are distributed in few countries in northern hemisphere
60 (Canada, Russia, Belarus and Germany) and control more than 70% of the existing potash
61 market. In terms of the consumption patterns, it is in the order of East Asia> Latin America>
62 South Asia> Africa (Figure 1) where no significant K ore deposit is available for commercial K
63 fertilizer production. Thus, there is a very little scope for many developing countries to be self-

64 sufficient in K nutrition by using conventional fertilizers. On global basis the supply of K
65 experiences an annual deficit of 20 kg K ha⁻¹ (Sheldrick et al. 2002). In African countries and
66 China, the total annual K deficits reach up to 4.1 and 8.3 million tonnes respectively, which
67 correspond to a respective estimate of (20 and 60 kg K ha⁻¹ year⁻¹) in these regions (FAO, 2015).
68 The K deficit in East Asia is in excess of 9 million tonnes per year, mostly dominated by China
69 (FAO, 2015). India and other developing countries are having almost a similar situation. The
70 extent of K fertilizer deficit in these areas is increasing over the years. On the other hand,
71 removal of K from soil in comparison to N and P is remarkably high in different cropping
72 systems particularly in those involving cereal and fodder crops. A huge gap between K removal
73 and replenishment has been found in various cropping systems (Yadav et al.1998). For example,
74 the gap between soil K removal and replenishment in India was estimated as high as 196, 170
75 and 255 kg ha⁻¹ in the rice-wheat, soybean-wheat and rice-wheat-green gram cropping systems,
76 respectively (Yadav et al.1998).

77 Potassium bearing minerals are limited and finite resource in selected few countries. Therefore, to
78 satisfy the K demand for world crop production, the amount of additional potash required is
79 more than the current global production. The requirements of potash fertilizers in developing
80 countries are so substantial that production must be more than double to sustain the soil K stocks
81 (Manning, 2010). The cost of K-fertilizers increased tremendously throughout the world. The
82 situation in Southeast Asia, Africa and Oceania are alarming because there is no reserve of K-
83 bearing minerals. The whole consumption of K-fertilizers is imported in these regions. Thus,
84 there is an urgent need to find alternative K sources to mitigate plant needs and thereby to reduce
85 the dependency on costly K fertilizers. To address the problem it is necessary to consider the

86 unconventional sources of K like naturally occurring rocks and minerals, particularly the silicate
87 minerals.

88 Despite silicate minerals are not as effective as commercial K fertilizers, novel approaches may
89 speed up K release from the mineral structures, which is appropriate in circumstances where
90 farmers are presently deprived of the global K fertilizer market. This review aims to demonstrate
91 the importance of alternative K sources for plant nutrition since commercial K fertilizers are
92 under shortage, particularly in developing countries. Critically, the review focuses on the K
93 dynamics in soil, K bearing minerals, approaches of K mobilization from different K bearing
94 minerals, evidence of use of K bearing minerals as K fertilizers, and the effect of modification,
95 especially microbial inoculation and composting, on K mobilization in soils. By critically
96 analyzing the K nutrition results from existing published trials, this review also discusses
97 whether K bearing minerals with suitable modification can be considered as an alternative to
98 conventional K fertilizers for sustainable crop production.

99

100 **2. Potassium dynamics in soil**

101 Potassium exists in soil in different forms, which are in quasi-equilibrium with each other. Based
102 on the availability to plants and microbes, forms of soil K are categorized into four groups,
103 namely water-soluble (solution-K), exchangeable, non-exchangeable and structural or mineral-K.
104 Exchangeable K or available K is held by negatively charged clay minerals and organic matter in
105 soils, while non-exchangeable K is consisted predominantly of interlayer K of non-expandable
106 clay minerals such as illite and lattice K in K-minerals such as K-feldspars (Sparks 1987). The
107 major portion of the total soil K exists in the mineral fraction. Total soil K reserves are large in
108 most of the soils, but the distribution of different K forms differs from soil to soil as a function of

109 the dominant soil minerals present (Jiyun1993;Steingrobe and Claassen 2000; Shanwal and
110 Dahiya, 2006). It is reported that about 92 to 98% of the total soil K exists as part of mineral or
111 structural-K in a fixed or non-exchangeable form. The sum of solution and exchangeable forms
112 of K is considered as the ‘readily available form’ which constitutes about 1 to 2% of the total K
113 in soil. Further, the share of the readily available forms is 98% in exchangeable and 2% in
114 solution. However, all these forms exist in dynamic equilibrium with each other (Subba Rao and
115 Brar, 2002; Tripler et al. 2006). It is evident that non-exchangeable K (also called as ‘slowly
116 available K’) is released and become available to plant uptake when solution and exchangeable
117 K are depleted (Sharpley 1989).The various K forms in soils and their transformation into soil
118 solution through various pools and pathways are represented schematically in Figure 2. The
119 exchangeable K tends to attain equilibrium with solution K rapidly but only slowly with non-
120 exchangeable K. Because of the crop removal, soil solution K gets depleted. The replacement of
121 the K-depleted soil solution is then affected primarily by the release of exchangeable K from
122 mineral K (clay minerals). As and when the exchangeable K-fraction is depleted substantially or
123 exhausted by crop uptake, the non-exchangeable K replenishes the exchangeable form, thus the
124 K supply is maintained.

125

126 **3. Potassium bearing minerals in soil environment**

127 Potassium in soil is mainly present as K-bearing minerals. The K-supplying power of a soil
128 depends on the content and the nature of K-bearing minerals as well as on the rate at which
129 structural and fixed-K become available to plants. More than 90% of the total K in soils is found
130 in mineral form or as structural K. Mineral K is generally assumed to be only slowly available to
131 plants; however, the availability is dependent on the level of K in other forms, and the degree of

132 weathering of the mineral K fractions (Sparks and Huang 1985; Sparks 1987; Jiyun1993; Tripler
133 et al. 2006). The major rock-forming minerals of almost all igneous and metamorphic rocks are
134 silicates. Similarly, the dominant rock-forming minerals in sediments are also usually silicates.
135 The mineralogy of sedimentary rocks is very important as many nutrients are associated with the
136 layer silicate clay minerals. However, both igneous and metamorphic rocks consist of mixtures
137 of the four major rock-forming mineral groups: quartz, feldspar, mica and ferromagnesian
138 minerals (Steingrobe and Claassen 2000; Harley and Gilkes 2000; Manning 2010). The primary
139 sources of K-bearing minerals in soils are feldspars, micas (e.g., muscovite - white micabiotite -
140 black mica and phlogopite), zeolite, glauconite, potassium-taranakite, illite, vermiculite and
141 chlorite. Mica-group minerals are of special interest for plant nutrition as they may be a major
142 source of K, Mg, Zn and Mn. It may be either muscovite (white mica), biotite (black mica) or
143 phlogopite. Muscovite is dioctahedral mica, while biotite and phlogopite are trioctahedral micas
144 which exhibit greater repulsion, and thus weather more easily and release K. Another important
145 mineral is glauconite which is essentially a hydrated-iron-magnesium-potassium-aluminium-
146 silicate (hydrated-Fe-Mg-K-Al-silicate). It contains about 5-6% K₂O and can be used as a source
147 of K. Potassium is also present in the form of secondary or clay minerals like illite or hydrous
148 mica, vermiculite, chlorite and interstratified minerals (Jiyun 1993; Mengel and Rahmatullah
149 1994). Due to advanced weathering process, the K in these secondary or clay minerals are
150 relatively easily available to plants than primary minerals. The principle K fertilizer ore minerals
151 together with the dominant rock-forming K silicate minerals are listed in Table 1.

152

153 **3.1. Silicate minerals as a source of potassium**

154 A number of studies have presented the ability of different K bearing silicate minerals to yield
155 nutrients under laboratory, pot and field trial conditions (Table 2). These trials include pot
156 (greenhouse) and field experiments using a range of crops, different time scales and under
157 different climates. The most commonly trialed minerals include granite, glauconite, phlogopite,
158 biotite, gneiss, feldspar, etc.

159 The agronomic effectiveness of K bearing minerals is largely determined by their mineralogy
160 and chemical composition. A consistent set of trials were carried out in Western Australia, in
161 which granite was used in pot trials on wheat, clover and ryegrass (Coroneos et al. 1996;
162 Hinsinger et al. 1996; Bolland and Baker 2000).The application of granite (2.29% K₂O)
163 significantly increased biomass yield (10%–20%) in wheat, whereas ground diorite (0.3% K₂O)
164 did not show any significant response. Pot trials conducted with clover and ryegrass (Coroneos et
165 al.1996; Wang et al.2000; Silva et al.2013) also showed that application of granite powder
166 enhanced both yield and shoot K content significantly compared to the control.

167 Agronomic effectiveness is also greatly influenced by the plant species and soil types. Among
168 several plant species investigated, the utilization of K from gneiss followed the order: maize >
169 ryegrass > alfalfa and a greater uptake was possible from finer sized particles (Wang et al. 2000).
170 So, type of plants and their root architecture played a vital role in releasing K from minerals. In
171 another study, phlogopite mica and K-feldspars significantly improved the yield and K uptake by
172 rice grown in a sandy soil having very low exchangeable K (Weerasuriya et al. 1993). These
173 minerals might be effective K suppliers in highly weathered soils where use efficiency of
174 chemical fertilizer is very low. For example, application of K-feldspar served as an alternative to
175 KCl in Colombia, where economic and agricultural conditions, including the occurrence of
176 Oxisol exerted problems with KCl use (Sanz-Scovino and Rowell 1988; Wang et al.2000).Initial

177 soil K status also influenced the effectiveness of the minerals and their application is quite
178 effective particularly in K deficient soil.

179 Few field trials were also conducted in order to work out the efficiency of the mineral as source
180 of K for crop growth. For example, feldspar was tested as a source of K using okra (Abdel-
181 Mouty and El-Greadly 2008), legumes (Sanz-Scovino and Rowell 1988) and tomato (Badr 2006)
182 cultivation. These studies showed that okra and tomato yield increased by 39.3 and 40%,
183 respectively, with feldspar application whereas legumes did not show any response. Application
184 of K bearing minerals like biotite, microcline, orthoclase and waste mica increased plant biomass
185 yield and K uptake in spring barley (Madaras et al. 2013) and leek (Mohammed et al. 2013) as
186 well. The mineral source of K was effective in some long duration crops like grape, coffee and
187 olive. Berry yield K content in grape increased when biotite was used as a source of K in
188 vineyard (Stamford et al. 2011), while phonolite was as effective as KCl in increasing fruit yield
189 in coffee (Mancuso et al. 2014). These studies indicated that plant species along with their growth
190 pattern also could facilitate the release of K from K bearing minerals.

191 Although crushed rock materials were promoted as nutrient sources for some time, this was
192 largely confined in alternative or organic farming sectors (Lisle 1994; Walters 1975). The use of
193 K bearing minerals as such or silicate rock fertilizers in traditional agricultural practices was
194 found poor because of low solubility of silicate rocks, subsequent low availability of nutrients to
195 plants, and the practicality of applying large amounts of ground rock to agricultural land
196 (Hinsinger et al. 1996; Bolland and Baker 2000; Harley and Gilkes 2000). So, only crushed rock
197 materials as such were not sufficient to supply K to plant as compared with conventional soluble
198 K sources. However, several biological means, particularly the use of K mobilizing
199 microorganisms, can mobilize K from rocks and minerals and thus can increase K availability to

200 plants. So, the use of rock powders in combination with some suitable biological modification
201 can be an alternative source of K for crop production, especially with the gradual growth in
202 popularity of organic farming.

203

204 **4. Bio-intervention of silicate minerals and K availability**

205 Applications of silicate minerals as such are not as effective as commercial K fertilizers. So,
206 some interventions are needed to speed up the K release rate. Release of K in soil from K bearing
207 minerals is influenced by many factors, especially by the microbial activity in the rhizosphere
208 region. Microbial activity releases K directly from the mineral structure as well as from the non-
209 exchangeable reserve. Many microorganisms hold a primary catabolic role in the degradation of
210 silicate mineral structure, which contributes to the release of K in soils. These microorganisms
211 are able to solubilize the unavailable forms of K from K-bearing minerals, such as micas, illite
212 and orthoclase, by excreting organic acids which either directly dissolves the rock K or chelates
213 the silicon ions to bring the K into solution (Friedrich et al. 1991; Vandevivere et al. 1994;
214 Ullman et al. 1996; Bennett et al. 1998; Biswas and Basak 2013). These microorganisms are
215 commonly known as K solubilizing microorganisms (KSM). In China and South Korea the K
216 dissolving bacteria are known as ‘biological K fertilizer’ (BPF) and used for bio-activation of
217 soil K- reserves so as to alleviate the shortage of K-fertilizers (Lin et al. 2002; Sheng et al. 2002;
218 Han and Lee 2005; Han et al. 2006). On the other hand, blending of K-bearing minerals during
219 composting is an alternative and viable technology to release K from minerals (Badr 2006;
220 Nishanth and Biswas 2008; Zhu et al. 2013). Therefore, biological modification or bio-
221 intervention (microbial intervention and composting) can turn out to be an important and
222 effective means to mobilize K from K-bearing minerals for plant nutrition. Such bio-intervention

223 strategies (Figure 3) provide fewer chances for pollution and consume less energy in improving
224 available K assimilation by plants.

225

226 **5. Mechanisms of potassium mobilization from silicate minerals**

227 **5.1. Dissolution by organic acids**

228 The principal mechanism of K solubilization from K-bearing minerals is the action of organic
229 acids synthesized by the soil microorganisms (Table 3) (Huang and Keller 1972; Huang and
230 Kiang 1972; Leyval and Berthelin 1989). The protons associated with the organic acid molecules
231 decrease the pH of the solution, and therefore, induce the releasing capacity of cations such as
232 Fe, K and Mg. Microbial respiration and degradation of particulate and dissolved organic carbon
233 can elevate the carbonic acid concentration at mineral surfaces, in soils and in ground water
234 (Barker et al. 1998; Calvaruso et al. 2006), which can lead to an increase in the rates of mineral
235 weathering by a proton-promoted dissolution mechanism. Experiments revealed that species of
236 *Bacillus* increased the soluble K content in the culture medium (Sheng et al., 2002; Han et al.
237 2006). It was also proposed that *Bacillus mucilaginosus* increased the dissolution rate of silicate
238 and aluminosilicate minerals and released the K^+ and SiO_2 from the crystal lattice primarily by
239 generating organic acids like oxalic, citric, tartaric, fumaric, glycolic, etc. Among these acids,
240 oxalic and citric acids were the most common and present in a relatively larger quantities. In
241 addition to production of carboxylic acids (citric, tartaric and oxalic acids), microorganisms
242 could also produce some intermediate and high molecular weight organic molecules like
243 mannuronic and guluronic acids. Like the low molecular weight organic acids, the high
244 molecular weight acids could also increase the extent of mineral weathering presumably by
245 complexing with the ions in solution, thereby lowering the solution saturation state (Welch and

246 Vandevivere 1994; Welch et al. 2002). It was found that the exopolysaccharides produced by
247 microorganisms strongly adsorbed to organic acids and thus assisted in their attachment to the
248 mineral surface, resulting in an area of high concentration of organic acids near the mineral (Liu
249 et al. 2006). The EPS adsorbed SiO_2 and thus affected the equilibrium between the mineral and
250 fluid phases and directed the reaction towards SiO_2 and K solubilization. Bacteria might also
251 increase the release rates by creating and maintaining microenvironments where metabolite
252 concentrations, such as extracellular polymer, primarily proteins and polysaccharides, were
253 higher than in the bulk solution (Malinovskaya et al. 1990; Ullman et al. 1996). Organic acid
254 molecules have a triple action on mineral weathering: (i) they adhere to the mineral surface and
255 extract nutrients from the mineral particles by electron transfer reaction; (ii) they break the
256 oxygen links; and (iii) they chelate ions present in solution through their carboxyl and hydroxyl
257 groups. The third mechanism indirectly accelerates the dissolution rate by creating gradient
258 between cation and anion concentrations in the solution (Welch et al. 2002).

259

260 **5.2. Metal complexing ligands**

261 Another possible mechanism of K mobilization by microorganisms is the production of metal-
262 complexing ligands. In addition to producing a variety of organic acids, microbes also produce
263 high molecular weight polymers and organic ligands (mannuronic acid, guluronic acid and
264 alginates). Ligands can complex with ions on the mineral surface and can weaken the metal-
265 oxygen bonds. Alternatively, ligands directly affect the reactions by forming complexes with
266 ions in solution, thereby decreasing solution saturation state. The high molecular weight
267 polymers can accelerate the ions diffusion away from the mineral surface by producing slime
268 layer around the mineral surface, which increases the contact time between water and the mineral

269 (Banfield et al.1999). For example,the production of capsular polysaccharide or extracellular
270 polysaccharides (EPS) and enzymes by K solubilizing microorganisms' viz., *Bacillus*
271 *mucilaginosus* and *Bacillus edaphicus* (Richards and Bates1989; Lin et al. 2002; Banfield et al.
272 1999) may accelerate the dissolution of a variety of silicates. The capsular polysaccharide
273 produced by *Bacillus edaphicus* contained functional groups (—COO—) that complexed with
274 mineral ions, lowering solution saturation state, and thereby enhanced dissolution (Sheng et al.
275 2002).

276 In addition to many simple and complex organic acids, microbially produced organic ligands
277 might include metabolic by-products, extracellular enzymes and chelates, which would help in
278 the dissolution of K-minerals by decreasing the pH of the environment. Chelating molecules
279 might increase the dissolution rates of cations by forming strong bonds with them or with
280 mineral surfaces (Welch et al. 2002). Mixture of polymers and low molecular weight ligands
281 produced by *Bacillus mucilaginosus* had a beneficial effect on silicate mineral (biotite and
282 muscovite) weathering (Malinovskaya et al.1990). Bacteria might also increase the release rate
283 of K by creating and maintaining microenvironments where metabolite concentrations are higher
284 than in the bulk solution (Ullman et al.1996). Thus, the production and release of extracellular
285 polymers, primarily proteins and polysaccharides into surrounding environment increase the
286 release of K from silicate mineral structure.

287

288 **5.3. Formation of biofilm**

289 An additional hypothesized mechanism of mobilization of mineral K is by the formation of
290 biofilm on the rhizospheric mineral surfaces by certain bacterial strains (Balogh-Brunstad et al.
291 2008). Biofilm was defined as a microbial community concentrated on the root-hypha-mineral

292 interface and was protected by extracellular polymers produced by themselves utilizing plant and
293 fungal exudates in soils (Banfield et al. 1999; Gadd 2007). These bacteria were remarkable for
294 their tremendous phylogenetic and metabolic diversity and for their ability to adapt and colonize
295 extreme environments which were not tolerated by other organisms. In such a microenvironment,
296 bacteria extracted inorganic nutrients and energy directly from the mineral matrix and thereby
297 helped in mineral weathering. Extracellular polymers, primarily proteins and polysaccharides
298 produced by the microorganism served as catalyst and thereby induced the K release from
299 silicate mineral structure.

300 It was also reported that ectomycorrhizal hyphal networks and root hairs of non-ectomycorrhizal
301 trees could embed in biofilms and transfer nutrients to the host. It suggested that the presence of
302 biofilms accelerated the weathering of biotite and anorthite, and thereby increased the mineral
303 uptake by plants (Adey et al. 1993; Shi et al. 2014).

304

305 **6. Bio-approaches for K mobilization from silicate minerals**

306 **6.1. Microbial intervention**

307 Potassium solubilizing microorganisms (KSM) include mainly bacteria and some fungi, but
308 bacteria are the most dominant members. They are also known as potassium solubilizing bacteria
309 (KSB) or potassium dissolving bacteria or silicate dissolving bacteria (SDB). A wide range of
310 KSMs including bacteria (*Bacillus mucilaginosus*, *Bacillus edaphicus*, *Bacillus circulans*,
311 *Acidithiobacillus ferrooxidans*), fungi (*Aspergillus niger*, *Aspergillus fumigatus*, *Aspergillus*
312 *terreus*) and some arbuscular mycorrhizal fungi (AMF) were reported to release K from K
313 bearing minerals in plant available form (Lian et al. 2002; Wu et al. 2005; Sheng et al. 2008;
314 GeetaSingh et al. 2010; Liu et al. 2011; Biswas and Basak 2013; Prajapati et al. 2012; Rajawat et

315 al. 2012). Apart from the above mentioned microorganisms, some rhizospheric microorganisms
316 were also reported as K solubilizers. These include *Enterobacter hormaechei* (KSB-8) (Prajapati
317 et al. 2012), *Arthrobacter sp.* (Zarjani et al. 2013), *Paenibacillus mucilaginosus* (Liu et al. 2011;
318 Hu et al. 2006), *P. frequentans*, *Cladosporium* (Argelis et al. 1993), *Aminobacter*,
319 *Sphingomonas*, *Burkholderia* (Uroz et al. 2007), *Paenibacillus glu-canolyticus* (Sangeeth et al.
320 2012), etc. But the strains like *B. mucilaginosus* and *B. Edaphicus* were the most efficient in their
321 action (Zhao et al.2008; Sheng 2005; Lian et al. 2002; Li et al. 2006; Li 2003). Table 4
322 summarizes several examples where K-release from minerals was augmented by bio-intervention
323 (microbial and composting).

324

325 6.1.1. Potassium solubilizing bacteria

326 Potassium solubilizing bacteria, particularly the genus *Bacillus*, enhances K availability through
327 solubilization of the insoluble K from silicate minerals during the process of biodegradation of
328 silicate minerals (Han et al. 2006; Liu et al. 2006). The results of such activity involve both
329 geochemical and structural changes in the rocks and silicate minerals. The metabolic diversity of
330 *Bacillus spp* .i.e., the various types of *Bacillus* strains and their mutants, has led to the fact that
331 many representatives of this group are being used as K biofertilizers (Sheng et al.2003; Sheng
332 and He 2006). It was found in several experiments that species of K solubilizing bacteria
333 increased the soluble K⁺ content when cultured with media containing K bearing minerals under
334 *in-vitro* laboratory conditions (Sheng et al. 2002; Han et al. 2006). The K solubilization capacity
335 was also governed by the type of bacterial strains. For example, local bacterial strain (K-81)
336 solubilized 2.6, 2.0 and 4.6 times more K from biotite, muscovite and hydromuscovite,
337 respectively, than K-31 strain under same laboratory conditions (Mikhailouskaya and Tchernysh

338 2005). On the other hand, the amount of K solubilization was found to differ from mineral to
339 mineral by the same bacterial strain (Liu et al. 2006; Sheng and He 2006). K released by *Bacillus*
340 *mucilaginosus* was observed as 4.29 mg L⁻¹, 1.26 mg L⁻¹ and 0.85 mg L⁻¹ from mica, microcline
341 and orthoclase, respectively (Sugumaran and Janarthanam 2007). Thus, both the types of silicate
342 minerals and the associated bacterial strains could play an equally significant role in K
343 solubilization.

344

345 6.1.2. Potassium solubilizing fungi

346 Like KSB, some fungi (*Aspergillus niger*, *A. fumigatus*, *A. awamori*, *Penicillium* sp) and yeast
347 (*Torulaspora globosa*) could release K from K bearing minerals (Lian et al. 2008; Prajapati et al.
348 2012; Song et al. 2014), and they are known as potassium solubilizing fungi (KSF). Among the
349 KSFs, *Aspergillus niger*, *A. fumigatus*, and *A. terreus* were able to release significant amount of
350 K from insoluble source of K under laboratory conditions within a short period of time (Lian et
351 al. 2008; Prajapati et al. 2012). *Penicillium purpurogenum* and *Torulaspora globosa* were able to
352 release 30 and 38% of the total K, respectively, from a silicate rock powder within 15 days under
353 laboratory conditions. So, KSF could be a potential bio-agent for improving K release from
354 silicate minerals as well as a promising K biofertilizer.

355

356 6.1.3. Arbuscular mycorrhizal fungi

357 Arbuscular mycorrhizal fungi (AMF) could also release nutrient elements including K from the
358 mineral structure by releasing protons, CO₂ and organic acids in surrounding environment (Jones
359 et al. 2009; Veresoglou et al. 2011; Yousefi et al. 2011). The AM fungi, which are well known to

360 improve P nutrition of plants (Bolan 1991), were also able to solubilize K, Fe, Mg and Al from
361 apatite, phlogopite, biotite, feldspars and other silicates rock powders, and promote plant growth
362 under nutrient-limiting conditions (Leyval and Berthelin 1989; 1991; Paris et al. 1995; Jongmans
363 et al. 1997; Wallander and Wickman 1999; Hoffland et al. 2003; Balogh-Brunstad et al. 2008).
364 But the K release rate was very slow and only occurred when surrounding environment was
365 deficient in K. So, the AM fungi could be a promising K biofertilizer for long duration crops
366 (plantation and fruit) where slow but continuous supply of the nutrient is required.

367

368 **6.2. Composting**

369 Composting of organic matter with K-minerals can release K and improve the K availability in
370 the system. The silicate structure of K-minerals could be disintegrated during the composting
371 process because of the production of organic acids and CO₂, which rendered low pH
372 environment in the system. Carbonic acid produced from CO₂ is assumed to play an important
373 role in weathering of minerals through suppression of pH and the known impact of increased
374 proton activity to accelerate the weathering of primary silicate minerals (Banwart and Berg
375 1999). This mode of action is similar to low molecular weight organic acid produced by the
376 microorganisms. Similarly, vermicomposting (with the introduction of earth worms) accelerated
377 the K release from silicate minerals due to the low pH, high microbial population and improved
378 enzymatic action in the earthworm intestine (Liu et al. 2011). There are only few evidences
379 available in the literature which demonstrated enhanced K release from silicate minerals through
380 composting process (Badr 2006; Nishanth and Biswas 2008; Biswas et al. 2009). For example,
381 concentration of available K releasing from feldspar increased markedly through composting
382 process and the maximum increase was observed with 40% feldspar addition in the total compost

383 dry weight (w/w) (Badr 2006). In another study, a significant amount of K released from waste
384 mica when composted with rice straw and cow dung slurry for 120 days (Nishanth and Biswas
385 2008). Addition of low-grade rock phosphate along with waste mica to crop residue during
386 composting improved the quality of the compost in terms of its total N, P and K contents which
387 helped to enhance the mobilization of unavailable K in waste mica into plant available forms
388 (Biswas et al. 2009). Significant release of K was observed when K bearing mineral powder
389 (PBMP) was composted in the presence of earthworm (*Eisenia foetida*), which increased the
390 available and effective K content in the final compost (Zhu et al. 2013). The amount of acids
391 which are produced during the composting process is presumably much higher than an individual
392 microorganism because composting often involves a heterogeneous microbial strain. In case of
393 vermicomposting, the K release from silicate minerals might be accelerated by both the chemical
394 and physical actions of earthworms. These actions come from the enhanced enzymatic activities
395 and the grinding of minerals within the earthworm's gut. Hence, composting process could
396 significantly contribute to the K mobilization from rocks and minerals and become available
397 option for the production of K-enriched organic fertilizer.

398

399 7. Structural changes of silicate minerals due to bio-intervention

400 Bio-intervention of silicate minerals leads to the release of K either by direct K dissolution from
401 the mineral structure or by chelation of Si and Al ions with organic molecules. Both the
402 processes might lead to some structural alternation of the mineral species. As the Si and Al ions
403 are the main structural frame work of silicate minerals, there is a significant possibility of their
404 structural change or breakdown. For example, soil microorganisms were able to transform biotite
405 minerals following the release of K and other ions (Boyle and Voigt 1973). Microbial destruction

406 of feldspar was evident due to an accelerated weathering by ligand excretion and release of
407 limiting nutrient from the mineral structure (Bennett et al. 1998). The structural degradation of
408 silicate minerals (e.g., mica and feldspar) by *Bacillus mucilaginosus* occurred as a result of the
409 release of K^+ and SiO_2 under laboratory conditions (Liu et al. 2006). Significant changes of full-
410 width at half maximum (FWHM) in the X-ray diffraction (XRD) reflection of mica was observed
411 when inoculated with *B. mucilaginosus* under both the laboratory and pot culture conditions
412 (Basak and Biswas 2009; Biswas and Basak 2014). The same bacterial strain was found to alter a
413 montmorillonite structure under laboratory conditions (Yang et al. 2016). These alterations also
414 led to the structural degradation of the mineral and reduced the water retention capacity of
415 montmorillonite, which might raise a question about the long term sustainability of the
416 technology (Yang et al. 2016). However, further research is needed in order to unravel the
417 microstructural changes of minerals due to bio-intervention and its possible environmental
418 impacts. Advanced instrumental techniques like scanning electron microscopy (SEM),
419 transmission electron microscopy (TEM), XRD, neutron scattering, and also synchrotron based
420 methods could be used to pin point the specific change or alteration of minerals occurred due to
421 the microbial intervention.

422

423 **8. Plant growth and K nutrition on bio-intervened silicate minerals**

424 Application of silicate rocks alone as the source of K has yielded varying results, and sometimes
425 was not very effective in increasing the crop growth and nutrition. But an integrated application
426 of silicate minerals with K mobilizing microorganisms was found promising in increasing the
427 crop growth and yield under both pot culture and field experiments using a range of K-bearing
428 silicate minerals in combination with either different species of KSM or composting.

429

430 8.1 Pot trials

431 Reports on the bio-intervention of silicate minerals as a source of K under pot culture
432 experiments are listed in Table 5. Significant amount of K uptake was reported from biotite and
433 microcline by *Pinus sylvestris* colonized by two ectomycorrhizal fungi, *Paxillus involutus* and
434 *Suillus variegatus* (Wallander and Wickman 1999). Slime-forming bacteria (*Bacillus*
435 *mucilaginosus*, *Bacillus edaphicus* and *Bacillus cereus*) isolated from soils, rock surface and
436 earthworm intestine could dissolve silicate minerals. This helped in improving yield and K
437 uptake in tomato, cotton, rape, mustard, groundnut, wheat, sorghum and sudan grass by
438 supplying K to K-deficient soils (Lin et al. 2002; Sheng 2005; Sheng and He 2006; Badr et al.
439 2006; Sugumaran and Janarthanam 2007; Basak and Biswas 2009). Inoculation of these bacterial
440 strain could improve the yield by 21% in rape, 24% in cotton, 125% in tomato, 58% in sorghum
441 and 125% in groundnut while K uptake increased by 31% in rape, 34% cotton and 71% in
442 sorghum (Lin et al. 2002; Sheng 2005; Badr et al. 2006; Sugumaran and Janarthanam 2007).
443 Application of enriched vermicompost prepared from gneiss and steatite powder also resulted in
444 a higher growth and yield than plants grown in Oxisol with non-enriched vermicompost. Further,
445 vermicompost enriched with steatite powder increased the dry matter yield of maize by 21.5% in
446 comparison to applying non-enriched vermicompost and steatite alone to the soil (de Souza et al.
447 2013). Apart from improving plant growth parameters, soil K content was also improved by
448 inoculation of bacterial strain. The available K content increased from 3.63 mg kg⁻¹ in non-
449 rhizosphere soil to 5.73 mg kg⁻¹ in rhizosphere soil when plant root was inoculated with *Bacillus*
450 *mucilaginosus* strain (Lin et al. 2002).

451 Sometimes co-inoculation with other bacteria like plant growth promoting rhizobacteria (PGPR),
452 phosphate solubilizing bacteria (PSB) and N-fixing bacteria may improve the performance of
453 individual inoculants due to synergistic effects on each other. The use of PGPR including PSB
454 and KSB as biofertilizers was suggested as a sustainable solution to improve plant nutrition and
455 production (Alexander1977; Park et al.2003; Vessey2003). Synergistic effects of soil fertilization
456 with rock P and K materials and co-inoculation with phosphate solubilizing bacteria (PSB)
457 *Bacillus megatherium* and potassium solubilizing bacteria (KSB) *Bacillus mucilaginosus* KCTC
458 3870 on the improvement of P and K uptake by eggplant (*Solanum torvum* L. NIVOT) grown
459 under limited P and K soil in greenhouse was reported (Han and Lee 2005).Although individual
460 inoculation did not increase the yield and uptake of N, P and K by eggplant, co-inoculation with
461 both bacteria and fertilized with rock P and K materials increased the yield as well as N, P and K
462 uptake by shoot (14, 22 and 14%, respectively) and roots (11, 14 and 21%)(Han and Lee 2005).
463 Similarly co-inoculation of biofertilizer containing N-fixer (*Azotobacter chroococcum*), P-
464 solubilizer (*Bacillus megatherium*) and K-solubilizer (*Bacillus mucilaginosus*) and AM fungi
465 (*Glomus mosseae* and *G. intradices*) had beneficial effect on soil properties and maize growth.
466 The study also indicated that half the amount of biofertilizer applications had similar effects
467 when compared with organic fertilizer or chemical fertilizer treatments. Microbial inoculums not
468 only increased the nutritional assimilation total N, P and K in plants, but also improved soil
469 properties (Wu et al. 2005). The potential of co-inoculation with phosphate solubilizing bacteria
470 (PSB) *Bacillus megatherium* var. *phosphaticum* and potassium solubilizing bacteria (KSB)
471 *Bacillus mucilaginosus* on mobilization of P and K from rock minerals and their effect on
472 nutrient uptake and growth of pepper and cucumber was also studied in Korea (Han et al. 2006).
473 The integrated use of co-inoculation with two bacterial strains and insoluble rock P and K

474 materials resulted in higher yield and nutrient uptake by pepper and cucumber as well as 36 and
475 31% increase in P and K availability in soils, respectively, as compared to the control (Han et
476 al.2006). Similarly waste mica (K source) co-inoculated with K solubilizing (*Bacillus*
477 *mucilaginosus*) and nitrogen fixing (*Azotobacter chroococcum* A-41) bacteria was found to be
478 effective in increasing the biomass yield and N and K uptake in Sudan grass grown under K
479 limiting soil (Basak and Biswas 2010). Soil fertilization with apatite (P source), feldspar and
480 illite powders in combination with P and K solubilizing bacteria (*Bacillus megaterium* var.
481 phosphaticum) and KDB (*Bacillus mucilaginosus* and *B. subtilis*) significantly improved P and K
482 uptake, P and K availability and growth of maize plant grown under P and K limited calcareous
483 soil (Abou-el-Seoud and Abdel-Megeed 2012).

484 Therefore, bio-intervention of silicate mineral was found to be effective as a source of K and
485 could be an alternative to commercial K fertilizer. These results of pot and green house studies
486 are quite promising, but still need to be replicated the success under in field conditions for better
487 acceptance of this technology in sustainable faming system.

488

489 8.1. Field trials

490 The effectiveness of integrated application of K-bearing minerals and KSMs have already been
491 established, but through a fewer number of field trials (Table 6). Application of K bearing
492 minerals (feldspar, illite, muscovite and biotite) inoculated with KSB strains (*Bacillus cereus*,
493 *Bacillus mucilaginosus* and *Bacillus pasteurii*) significantly improved the yield and K uptake in
494 wheat, tomato, hot pepper, peanut and sesame under field conditions (Mikhailouskaya and
495 Tchernysh 2005; Badr 2006; Supanjani et al. 2006; Youssef et al. 2010). Soil inoculated with K
496 solubilizing fungi (*Pseudomonas putida*) was found quite effective in plantation crops like tea

497 and tobacco, and could supplement 25% of the chemical fertilizer (Bhagyalakshmi et al.2012;
498 Subhashini 2015). Similarly, potassium enriched compost prepared from waste mica was quite
499 effective as the source of K in potato-soybean cropping system (Biswas 2011). However, other
500 mineral ions such as Si and Mg contained in the rock powder might have also contributed
501 towards the yield. Application of enriched compost to the first crop resulted in a significant
502 increase in soybean yield grown on residual fertility which could supplement 50% of the total K
503 requirement of soybean crop (Meena and Biswas 2013).The application of bacterial strains (K-31
504 and K-81) with K mineral (hydromuscovite, muscovite and biotite) effectively improved the
505 available K content in sandy loam soil (Luvisol) andindicated the effectiveness of K mobilizing
506 bacteria in a K deficient situation (Mikhailouskaya and Tchernysh 2005). These results clearly
507 indicated that both the microbes and composting process mobilized K from K bearing minerals
508 which acted as a continuous source of K throughout the cropping system.

509 The result of field studies indicated that bio-intervention of silicate mineral could be a viable
510 option of crop growth in place of costly commercial K fertilizer. In most of the cases, this
511 technology performed better than control as well as application of silicate mineral alone. In some
512 cases bio-intervention of silicate mineral was as effective as commercial K fertilizers or even
513 better than that. So, more systematic study is needed to standardize this technology in large scale
514 which can effectively supplement the costly K fertilizer while maintaining yield and quality of
515 crops.

516

517 **9. Conclusions and future prospect**

518 This review highlighted the contribution of bio-intervention of naturally available K-bearing
519 minerals as a possible alternative of K fertilizer for sustaining crop production and maintaining

520 soil K level. Investigations on the possible use of silicate rocks for K supply through bio-
521 intervention (K mobilizing microbes and composting) yielded promising results. The benefit of
522 this approach was however confined mostly within laboratory or green house scale studies. The
523 validity and possibility of sustaining agronomic performance and reduce the cost of cultivation
524 through the use of cheap natural sources is highly important. Thus, combined application of
525 different kind of bio-agent like KSB, KSF, AM fungi, yeast and earthworm in different
526 combination could provide a faster and continuous supply of K from low cost mineral powder.
527 Currently, there is a lack of consistency in terms of the design of individual trials, limiting
528 comparison and extrapolation. Performance of this technology under different soil types and
529 properties are rarely reported. The relative impact of this technology on the mineral-weathering
530 process is still poorly understood. Further research is highly justified due to a continuously
531 increasing price of conventional K fertilizers worldwide.

532 In further study, emphasis should be given to find out the best combination of different factors
533 which can be suitable alternative of conventional potash fertilizers. There is a huge scope for
534 careful selection of the silicate rock as K sources. On the basis of dissolution rate, priority should
535 be given to rocks that are enriched with bioavailable K. It is appropriate to consider the use of
536 commonly abundant K bearing minerals such as feldspars and mica (muscovite, biotite, etc.) for
537 field crop trials. The best KSM strain can be selected on the basis of their ability to dissolve
538 silicate minerals or release K from the minerals. There is also an opportunity to isolate
539 indigenous KSM strains which may be more suitable in local agro-ecological conditions in
540 comparison to an alien species. Composting process would enhance the dissolution of K from
541 indigenous mineral which is very promising, but more systematic approaches are needed in order
542 to explore their efficacy. It is essential that scientists from both biology and mineralogy

543 disciplines effectively collaborate in conducting this research. Future studies should more
544 concentrate to test this potential technology under field conditions.

545

546 **Acknowledgements**

547 This work was made possible by an Endeavour Research Fellowship awarded to senior author by
548 the Australian Federal Government. It was also supported by the Indian Council of Agricultural
549 Research (ICAR), New Delhi.

550

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840 **Table 1** Chemical formula and potassium contents (expressed as element and oxide) for potash
 841 ore/ minerals and for common potassium silicate rock forming minerals

Mineral	Formula	Weight % K	Weight % K ₂ O
<i>Potash ore/minerals</i>			
Sylvite	KCl	52.35	63.09
Carnallite	MgCl ₂ ·KCl·6H ₂ O	14.05	16.94
Kainite	KMgSO ₄ Cl·3H ₂ O	15.69	18.91
Langbeinite	2MgSO ₄ ·K ₂ SO ₄	18.84	22.71
<i>Silicate minerals</i>			
Potassium Feldspar	KAlSi ₃ O ₈	14.03	16.91
Leucite	KAlSi ₂ O ₆	17.89	21.56
Nepheline	(Na,K)AlSiO ₄	13.00	15.67
Kalsilite	KAlSiO ₂	24.68	29.75
Muscovite	KAl ₃ Si ₃ O ₁₀ (OH) ₂	9.03	10.88
Biotite	K ₂ Fe ₆ Si ₆ Al ₂ O ₂₀ (OH) ₂	7.62	9.18
Phlogopite	K ₂ Mg ₆ Si ₆ Al ₂ O ₂₀ (OH) ₄	9.39	11.30

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843 *Source:* Manning (2009)

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845 **Table 2** Summary of crop trials with direct application of silicate minerals used as K fertilizer

Crop	Minerals	Trial type	Agronomic benefit	Reference
Legume	Feldspar	Field	Insignificant	Sanz-Scovino and Rowell, 1988
Rice	Phlogopite	Pot culture	Increased grain yield	Weerasuriya et al, 1993
Wheat	Granite	Pot culture	Increased biomass and grain yield	Hinsinger et al, 1996
Wheat	Diorite	Pot culture	Insignificant	Hinsinger et al, 1996
Ryegrass	Granite	Pot culture	Increased in biomass yield and K uptake	Coroneos et al, 1996
Pearl millet	Glauconitic sandstone	Sand culture	Dry matter yield K content significantly increased	Rao and Subba Rao, 1999
Alfalfa	Gneiss	Pot culture	Insignificant	Wang et al, 2000
Italian Ryegrass	Gneiss	Pot culture	Significant increase in K content in biomass	Wang et al, 2000
Perennial Ryegrass	Gneiss	Pot culture	Significant increase in K content in biomass	Wang et al, 2000

Maize	Gneiss	Pot culture	Significant increase in K content in biomass	Wang et al, 2000
Clover	Granite	Pot/Field	Insignificant	Bolland and Barker, 2000
Chinese Cabbage	Fused potassium silicate	Sand and soil culture	Significant increase in K uptake	Yao et al, 2003
Tomato	Feldspar	Field	Increased biomass and fruit yield	Badr, 2006
Okra	Feldspar	Field	Increased pod yield	Abdel-Mouty and Greadily, 2008
Grape	Biotite	Field	Increase berry yield and K content	Stamford et al. 2011
Olive	Glauconitic sandstone	Hydroponics	Effect as slow release K fertilizer	Karimi et al. 2012
Italian Ryegrass	Granite powder	Green house	Significant increase in plant biomass yield	Silva et al. 2013
Spring Barley	Zinnwalidite, waste mica & orthoclase	Sand culture	Plant biomass and K uptake increased in the order of Zinnwalidite> waste mica > orthoclase	Madaras et al. 2013

Leek	Biotite, microcline and nephelinesynite	Pot culture	Biotite found most effective and readily available source of K	Mohammed et al. 2014
Arabica coffee	Phonolite	Field	Increased fruit yield similar to KCl application	Mancuso et al. 2014

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848 **Table 3** Potassium solubilizing microbes (KSMs) involve in solubilization K from minerals

Microbes	Predominant acid produce	Reference
Bacteria		
<i>Bacillus mucilaginsus</i>	Oxalic and Citric	Liu et al.2006
<i>Bacillus edaphicus</i>	Oxalic and Tartaric	Sheng and He 2006
<i>Bacillus globiospora</i>	Gluconic, Acetic and Tartaric	Sheng et al. 2008
<i>Paenibacillismucilaginosus</i>	Tartaric, Citric, Oxalic	Liu et al. 2012; Hu et al. 2006
Fungi		
<i>Aspergillusniger</i>	Citric, Glycolic and Succinic	Sperberg1958
<i>Torulasporaglobosa</i>	Acetic acid	Vora and Shelat1998
<i>Aspergillusterreus</i>	Itaconic	Magnuson and Lasure2004
<i>Aspergillusfumigatus</i>	Succinic and Acetic	Song et al. 2014
<i>Penicilliumperpurogenum</i>	Oxalic	Song et al. 2014
AMF		
<i>Glomusmosseae</i>	Citric, Malic and Oxalic	Yousefi et al. 2011
<i>Glomusintraradices</i>	Citric, Malic and Oxalic	Yousefi et al. 2011

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851 **Table 4** Summary of experiment of mobilization of K from silicate minerals through bio-intervention

Type of mineral experiment/condition	Mineral	Microbial strain/bioagent	Outcome	Reference
Laboratory study/In vitro	Muscovite and Biotite	Local rhizobacterial strain (K-31, K-81)	Significantly improved K release from minerals	MikhailouskayaTchernysh 2005
Laboratory study	Feldspar	<i>Bacillus cereus</i>	Increased K release from feldspar	Badr et al. 2006
Composting	Feldspar	<i>Bacillus cereus</i>	Significant mobilization from feldspar	K Badr 2006
Laboratory study	Mica and Feldspar	<i>Bacillus mucilaginsus</i>	K release increased by 66% from mica	Liu et al. 2006
Laboratory study	Muscovite mica, Microcline and Orthoclase	<i>Bacillus mucilaginsus</i>	Significant amount of potassium released from different minerals	Sugumaran and Janarthanam 2007

Laboratory study	Mica and Feldspar	<i>Bacillus</i> strain	Increased soluble K content	Girgis et al. 2008
Laboratory study	Feldspar and Illite	<i>Aspergillusfumigatus</i>	Drastically increased K release from the K minerals	Lian et al. 2008
Composting	Waste mica	<i>Aspergillusawamori</i>	Sharp increase in water soluble K after 120 days	Nishanth and Biswas 2008
Laboratory study	Feldspar and Potas-sium aluminum silicate	<i>Aspergillusterreus</i> and <i>Aspergillusnigerwere</i>	Higher K released by <i>A. terreus</i> from both the mineral	Prajapati et al. 2012
Composting	Quartz powder	Earthworm (<i>Eiseniafoetida</i>)	Significantly increased available K content	Zhu et al. 2013
Laboratory study	Alkaline ultramafic rock powder	Yeast (<i>Torulasporaglobose</i>)	38% of total K released from rock powder	Rosa-Magri et al. 2012

Laboratory study	Waste mica	<i>Bacillus mucilaginsus</i>	About 34% increase in available K content after 28 days	Biswas and Basak 2014
Laboratory study	Muscovite	<i>Penicilliumpurpurogenum</i>	30% K dissolved from muscovite	Song et al. 2015

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855 **Table 5** Summary of the pot experiment: Improved plant nutrition through bio intervention of silicate minerals

Rock/mineral	Bio intervention (KSMs and composting)	Crop/plant	Salient outcomes	Reference
Biotite and Microcline	<i>Paxillus involutus</i> & <i>Suillus variegatus</i>	Pine	Mycorrhizal fungi improved K uptake by releasing K from mineral structure	Wallander and Wickman 1999
Illite powder	<i>Bacillus edaphicus</i> NBT	Cotton and Rape	Dry matter yield and K content increased	Sheng 2005
Illite and rock phosphate powder	Co-inoculation of <i>Bacillus mucilaginosus</i> (KSB) and <i>Bacillus megatherium</i> (PSB)	Eggplant	Enhanced plant growth and NPK uptake as well as soil availability of P & K	Han and Lee 2005
Feldspar	<i>Bacillus cereus</i>	Sorghum	Yield and K uptake	Badr et al. 2006

				increased while K status in soil improved	
Feldspar and Illite	<i>Bacillus edaphicus</i> wild strain (MPs series)	Wheat	Crop growth and K content increased	Sheng and He 2006	
Illite and rock phosphate powder	Co-inoculation of <i>Bacillus mucilaginsus</i> (KSB) and <i>Bacillus megatherium</i> var <i>phosphaticum</i> (PSB)	Pepper and Cucumber	Increased availability of P & K in soil and uptake by plants	Han et al. 2006	
Microcline, Orthoclase and Muscovite mica	<i>Bacillus mucilaginsus</i>	Groundnut	Yield and oil content increased while K status in soil improved.	Sugumaran and Janarthanam 2007	
Waste Mica	<i>Bacillus mucilaginsus</i>	Sudan grass	Improved biomass yield and K uptake	Basak and Biswas 2009	

			by Sudan grass as well as soil K status	
Waste Mica	Co-inoculation of <i>Bacillus mucilaginsus</i> (KSB) and <i>Azotobacterchroocccum</i> (N-fixer)	Sudan grass	Biomass yield, K and N uptake increased	Basak and Biswas 2010
Feldspar	<i>Bacillus mucilaginsus</i>	Maize	Plant growth and K uptake increased	Abou-el-Seoud and Abdel-Megeed 2012
Gneiss and steatite	Earthworms (<i>Eiseniaandrei</i>)	Maize	Steatite charged vermicompost increased 21.5 % dry matter yield over non-enriched vermicompost	de Souza et al. 2013

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858 **Table 6** Summary of the field experiments: Improved plant nutrition through bio intervention of silicate minerals

Rock/mineral	Bio intervention (KSMs and composting)	Crop/plant	Salient outcomes	Reference
Muscovite and Biotite	Local rhizobacterial strain (K-31, K-81)	Wheat	Improved grain yield and K status of soil	Mikhailouskaya and Tchernysh 2005
Feldspar	<i>Bacillus cereus</i>	Tomato	More fruit yield and potassium use efficiency (KUE) as compared to K ₂ SO ₄	Badr 2006
Potassium (Illite) powder	<i>Bacillus mucilaginosus</i> strain (KCTC3870)	Hot pepper	Improved biomass and fruit yield as well as K availability in soil	Supanjani et al. 2006
Waste mica	Composting with <i>Aspergillus awamori</i>	Potato-Soybean	Mica enriched compost significantly increased yield K uptake by both the	Biswas 2011

				crops	
Feldspar	<i>Bacillus pasteurii</i> (Biopotash)	Peanut	and	Increased K uptake by	Youssef et al. 2010
		Sesame		maize and wheat	
Muriate of potash	<i>Pseudomonas putida</i>	Tea		Improved leaf yield and	Bhagyalakshmi et al.2012
				quality as well as nutrient	
				uptake	
Waste mica	Composting	with Soybean		Mica charged compost	Meena and Biswas 2013
	<i>Aspergillusawamori</i>			improved Soybean yield	
				and K uptake as compared	
				to ordinary compost	
Sulphate of potash	<i>Frateuriaaurantia</i>	Tobacco		Potassium content in	Subhashini 2015
				tobacco leaf increased	
				39% when soil inoculated	
				with bacterial strain	

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861 **Figures**

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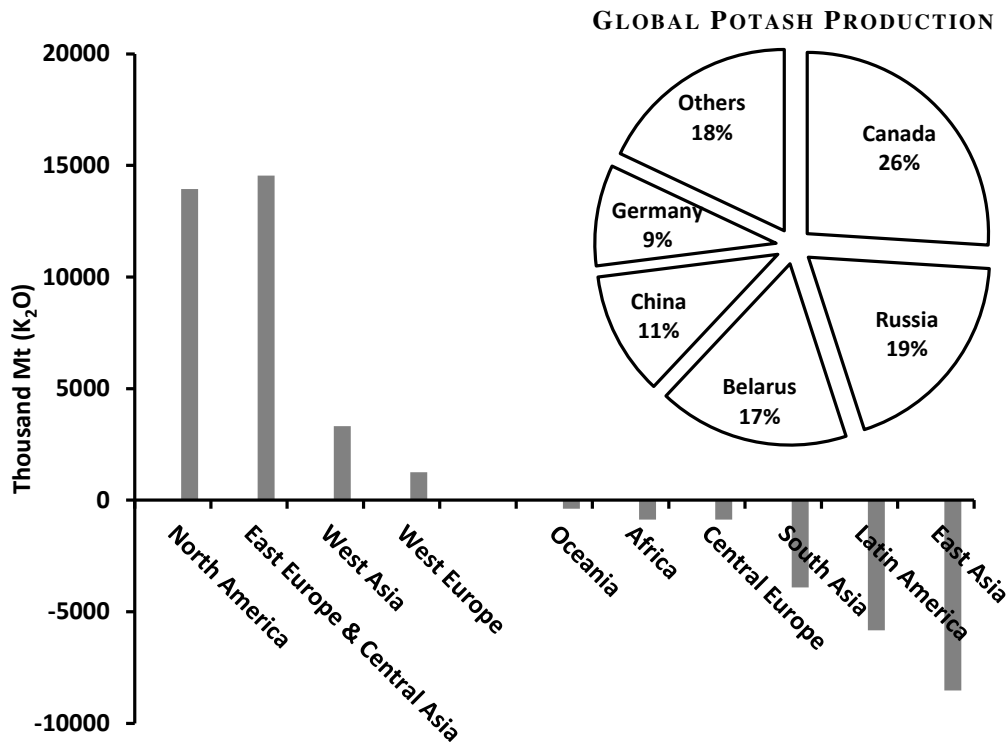
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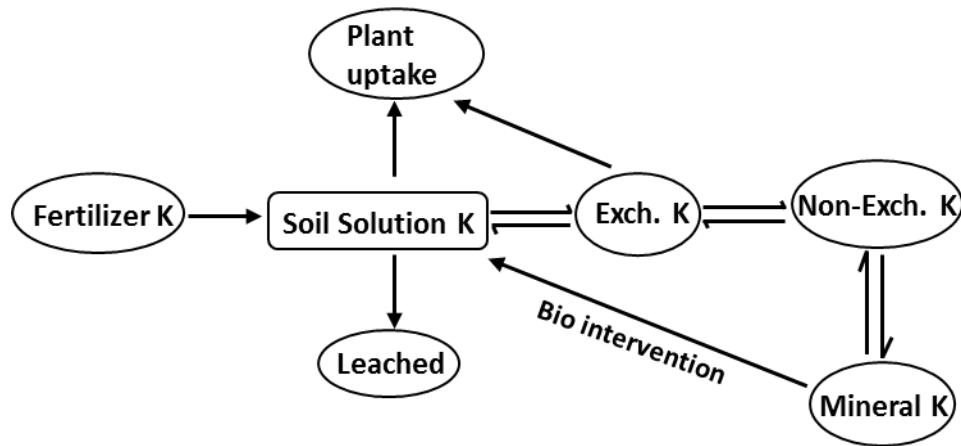
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872 *Source: World fertilizer outlook (FAO, 2015)*

873 Figure 1: Projection of regional potash balance according to FAO for 2018 in thousand metric
874 tonnes K₂O equivalent

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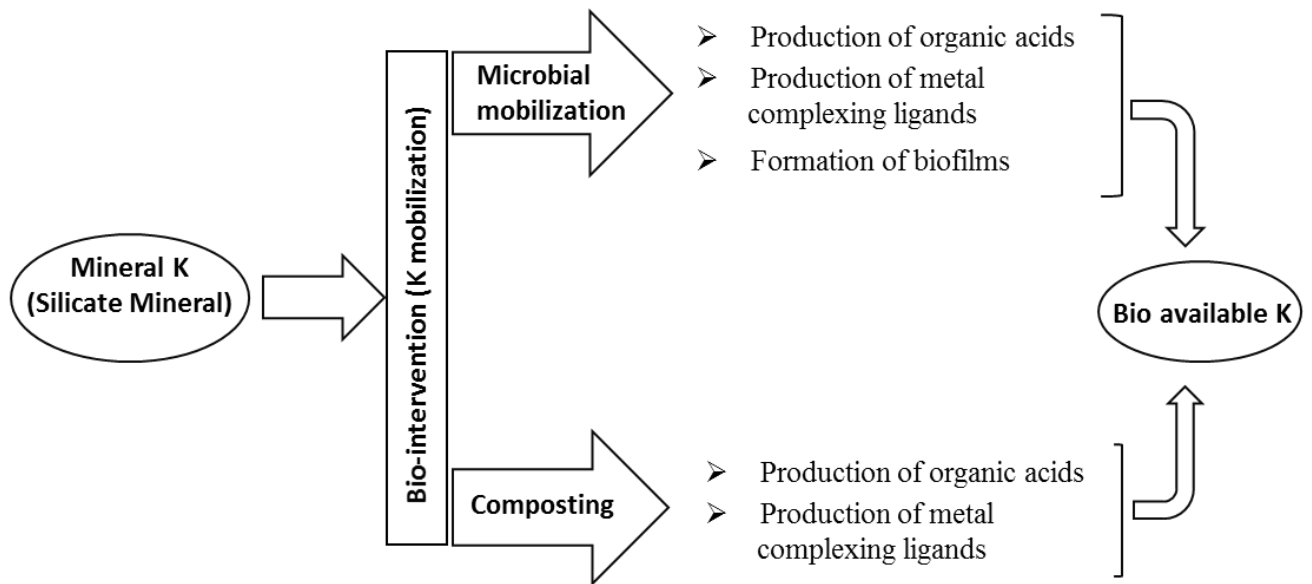




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877 Figure 2: Scope of bio intervention for direct mobilization of potassium from mineral under
 878 dynamic pools of soil potassium

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881 Figure 3: Brief mechanisms of potassium mobilization from silicate minerals through bio-
 882 interventions

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