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Potassium in agriculture – Status and perspectives

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ABSTRACT

In this review we summarize factors determining the plant availability of soil potassium (K), the role of K in crop yield formation and product quality, and the dependence of crop stress resistance on K nutrition. Average soil reserves of K are generally large, but most of it is not plant-available. Therefore, crops need to be supplied with soluble K fertilizers, the demand of which is expected to increase significantly, particularly in developing regions of the world. Recent investigations have shown that organic exudates of some bacteria and plant roots play a key role in releasing otherwise unavailable K from K-bearing minerals. Thus, breeding for genotypes that have improved mechanisms to gain access to this fixed K will contribute toward more sustainable agriculture, particularly in cropping systems that do not have access to fertilizer K. In K-deficient crops, the supply of sink organs with photosynthates is impaired, and sugars accumulate in source leaves. This not only affects yield formation, but also quality parameters, for example in wheat, potato and grape. As K has beneficial effects on human health, its concentration in the harvest product is a quality parameter in itself. Owing to its fundamental roles in turgor generation, primary metabolism, and long-distance transport, K plays a prominent role in crop resistance to drought, salinity, high light, or cold as well as resistance to pests and pathogens. Despite the abundance of vital roles of K in crop production, an improvement of K uptake and use efficiency has not been a major focus of conventional or transgenic breeding in the past. In addition, current soil analysis methods for K are insufficient for some common soils, posing the risk of imbalanced fertilization. A stronger prioritization of these areas of research is needed to counter declines in soil fertility and to improve food security.
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Potassium availability in the soil and its relevance for crop production

The global potassium demand for agriculture

Since the 1960s, the world population has doubled from three to seven billion, and this trend will persist in the coming decades. Because of this rapid expansion, a massive increase in crop production is required to meet the food and energy demands of future generations, while also preserving the ecological and energy-related resources of our planet. Additionally, recent climate models predict that incidences and duration of drought and heat stress periods are increasing in many regions, negatively affecting our major crops, and thus our food security. Therefore, major challenges for agriculture are to enhance crop yields in more resource-efficient systems and to stabilize plant development and yield formation under biotic and abiotic stress conditions (Reynolds et al., 2011). In this context, among the many plant nutrients, potassium (K) plays a particularly crucial role in a number of physiological processes vital to growth, yield, quality, and stress resistance of all crops.

K constitutes about 2.1–2.3% of the earth's crust and thus is the seventh or eighth most abundant element (Schroeder, 1978; Wedepohl, 1995). Therefore, soil K reserves are generally large (Schroeder, 1978). However, large agricultural areas of the world are reported to be deficient in K availability, including ¾ of the paddy soils of China, and ⅔ of the wheat belt of Southern Australia (Mengel and Kirkby, 2001; Römheld and Kirkby, 2010). Soils inherently low in K are often sandy, waterlogged, saline, or acidic. Additionally, in intensive agricultural production systems, K has become a limiting element, in particular in coarse-textured or organic soils (Goulding and Loveland, 1986). In many cases, lower fertilizer K application in the context of unbalanced fertilization may result in a significant depletion of available soil K reserves, and thus in decreased soil fertility. Smil (1999) reported that, in contrast to nitrogen (N) and phosphorus (P), K fertilizers are applied at a much lower rate, and less than 50% of the K removed by crops

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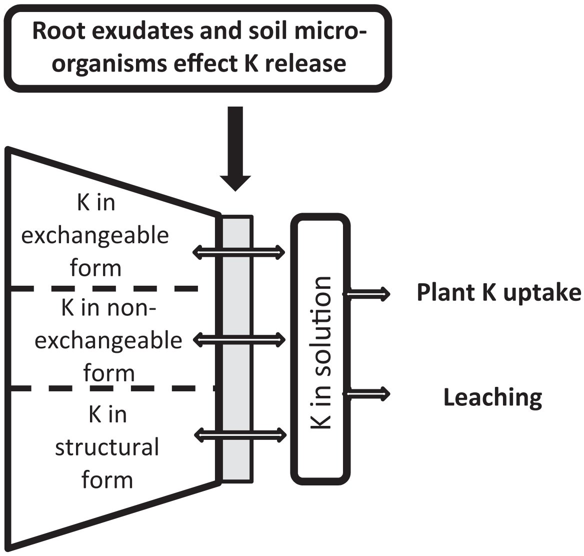

Fig. 1. Interrelationship of K forms in the soil and the effects of soil microorganisms and root exudates (after Sparks and Huang, 1985).

is replenished. An analysis of the nutrient balance of six Asian countries (China, Indonesia, Malaysia, the Philippines, Thailand and Vietnam) from 1961 to 1998 also indicated an overall annual K deficit of about 11 Mt, which is 250% more than their current K fertilizer use (Syers et al., 2001).

Potassium in soils

As mineral soils contain 0.04–3% K, the total K content of the upper 0.2 m of most agricultural soils generally ranges between 10 and 20 g kg^{-1} (Jackson, 1964; Sparks, 1987). However, most of the soil K (90–98%) is incorporated in the crystal lattice structure of minerals and thus not directly available for plant uptake. The availability of K differs greatly with soil type and is affected by physico-chemical properties of the soil. To simplify the complex K dynamics in soil, K in soil is often classified into four groups depending on its availability to plants: water-soluble, exchangeable, non-exchangeable and structural forms (Fig. 1). Water-soluble K is directly available for plants and microbes, and potentially subjected to leaching. Exchangeable K is electrostatically bound as an outer-sphere complex to the surfaces of clay minerals and humic substances (Barre et al., 2008). Both fractions are often considered to be easily available for crops. However, the size of both pools is very small. They make up only about 0.1–0.2% and 1–2% of the total K in soil, respectively (Sparks, 1987). Non-exchangeable and structural forms are considered to be slowly- or non-available K sources for plants. However, these pools may also contribute significantly to the plant supply in the long term (Pal et al., 2001). The quantities of plant-available and non-available K in the soil vary greatly among soil types, and dynamic equilibrium reactions exist between the different pools of soil K. Thus, a number of soil physical and chemical properties as well as plant-soil interactions and soil microbial activities affect the fixation and release of K in soils.

Most of the K in soil is in the structural form, mainly comprised of K-bearing primary minerals such as muscovite, biotite and feldspars. K-feldspars may directly release K to the soil solution, whereas interlayer K of micas is held tightly by electrostatic forces. Weathering of K-feldspars and micas inherited from soil parent materials produces secondary soil minerals which represent the potential sources of plant-available K in soils (Singh and Goulding, 1997). The K in trioctahedral micas (such as biotite and phlogopite) is reported to be more readily released by weathering, and it has been suggested that application of biotite to K-deficient soils may enhance the plant-available K content of soil (Öborn et al., 2005). Formation of dioctahedral expansible 2:1 minerals from biotite is a distinct possibility that may enhance the amount of K in soil solution. It should be noted that weathering of K-containing primary minerals is very slow. Therefore, their sole addition to soil may not be beneficial for crop growth, especially when compared to soluble K fertilizers. Nevertheless, a number of recent investigations suggest that addition of rock K (K-containing primary minerals) materials may increase the long-term fertility of the soil by increasing the K depots (Sheng, 2005; Basak and Biswas, 2009). Plant species effective in K uptake and K-solubilizing microbial populations may be two further key factors that control the K release from soil minerals.

Effect of potassium-solubilizing bacteria on potassium availability in soils

Some soil microorganisms (*e.g.*, Pseudomonas spp., Burkholderia spp., *Acidothiobacillicus ferrooxidans*, *Bacillus mucilaginosus*, *Bacillus edaphicus*, *Bacillus megaterium*) are able to release K from K-bearing minerals by excreting organic acids (Sheng et al., 2002). These organic acids either directly dissolve rock K (K-containing primary minerals) or chelate the primary mineral's silicon ions to bring the K into solution (Bennett et al., 1998; Basak and Biswas, 2009). Therefore, inoculation of K-solubilizing microorganisms in conjunction with application of rock-K to soil has recently gained a great deal of attention. Beneficial effects of inoculated-mica application to soil on plant K uptake have been reported in cotton, oilseed rape, pepper, cucumber, and sudan grass (Sheng et al., 2002; Han and Lee, 2005; Han and Supanjani Lee, 2006). This indicates that exudates of these microorganisms can effectively enhance the release of K from clay minerals. Similarly, a number of incubation trials have shown that application of inoculated feldspars into soil enhances about 40–60% of K solubility and plant K uptake (Han and Supanjani Lee, 2006; Basak and Biswas, 2009; Abou-el-Seoud and Abdel-Megeed, 2012). However, most of these incubation experiments were carried out in the laboratory. Currently, little information is available on the field application of such methods, which is most likely due to difficulties in soil inoculation under field conditions. In order to evaluate the potential of such applications for agricultural production systems, we need more field studies that evaluate their effect on both soil properties and crop growth.

Effect of root exudates on potassium availability in soils

The utilization of non-exchangeable K sources is an important factor for the K uptake efficiency of crops (Claassen and Steingrobe, 1999), and plant species or genotypes within species have been reported to differ in their capacity to use this resource (Wang et al., 2011). For example, ryegrass and sugar beet are more efficient in mobilizing K than wheat and barley. El Dessougi et al. (2002) reported that sugar beet took up 3–6 times more K per unit of root length than wheat and barley grown on K-fixing soils. Crop differences in K uptake are generally attributed not only to the efficiency in absorption, but also to the mobilization of non-exchangeable K by root exudates. Major compounds released are organic acids such as: citric and oxalic acids by maize (Kraffczyk et al., 1984), tartaric acid by pak-choi and radish (Chen et al., 2000), and malic acid by oilseed rape (Zhang et al., 1997). Similarly, amino acids detected in root exudates of wheat and sugar beet were found to enhance the release of K from clay minerals (Rengel and Damon, 2008). The depletion of K in rhizosphere soil solution below a threshold level (10–20 μM) has been reported to be a key signal to activate the root exudation mechanism (Hosseinpur et al., 2012; Schneider et al.,

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