

## Review

# Effects of potassium behaviour in soils on crop absorption

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**Potassium (K) is one of the three major elements that play important roles in plants, such as maintaining turgor of cells, promoting activation of enzymes, and improving efficiency of photosynthesis. The types of K in soil may affect the plant absorption of K. K in soils includes K minerals, K in layered silicates (clay minerals), exchangeable K and K in solution. The former two can provide K very slowly through long period and so may be seen as ineffective; the latter two are the major types for K supply to plants. The release of the exchangeable K is basically through ionic exchange reactions. In the farm, soils with weak acidity to neutral conditions and 90% saturation of salt base, has calcium (Ca) as the most important cation among the exchangeable ions, followed sequentially by magnesium (Mg), K and sodium (Na). Ca and Mg are the major competitors of K for the exchangeable sites or locations. The effectiveness of K ions depends on the competitive absorption of Ca and Mg. However, the exchange behaviour of Ca and Mg in soils is quite similar and so they are commonly combined as one cation to simplify theoretical and analytical treatments of the processes. In general, quantity/intensity (Q/I) diagram of K may serve as an index for the strength and quantity of effective K supply to plants in soils. Some parameters such as equilibrium activity ratio ( $AR_e$ ), K selectivity coefficient ( $K_G$ ) and potential buffering capacity (PBC) may provide important information for the K behaviour in soils.  $AR_e$  indicates the amount of K that can be provided by solution instantly in the soil.  $K_G$ , a coefficient for K selectivity, indicates higher K selectivity for the soil when its value is higher. Higher PBC shows higher K buffering capacity of the soil. Therefore, this information may be based as references for K fertilization.**

**Key words:** Potassium (K), quantity/Intensity (Q/I), activity ratio (AR), selectivity coefficient (KG), absorption.

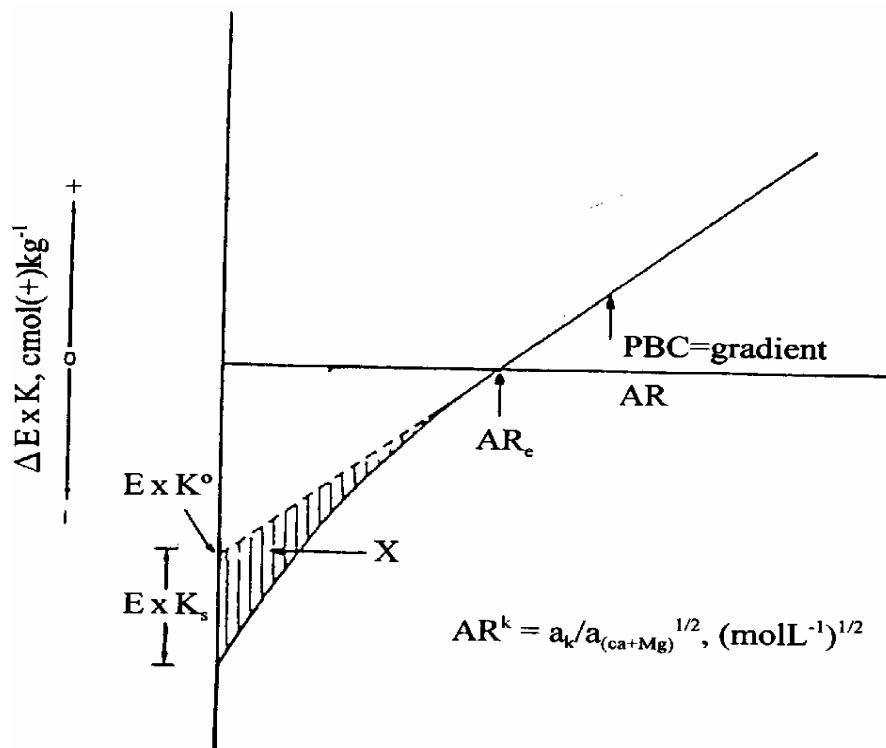
## INTRODUCTION

Potassium (K) is one of the elements required in significant quantity for plants. Plant tissues contain high K that controls physiological functions. These functions include: (1) Maintaining the turgor of cells of promoting plant growth. In general,  $K^+$  and  $Cl^-$  are the most important ions that regulate the osmotic pressure of plant cells. K deficiency would result in lower osmotic pressure, lower turgor and lower water content in plant, which in turn lead to cell expansion and the damage of cells' membrane,

unabling the development of normal metabolism (Mengel and Kirkby, 1982; Makhdom et al., 2007); (2) promoting enzyme activation in plants. K is an activation agent for many plant enzymes and so, it improves many metabolic processes in plants. The enzymes activated by K mainly include synthesized enzyme; (3) improving efficiency of photosynthesis and transport of assimilated products. K may improve the synthesis of chloroplast, regulate the opening and closing of stoma and control the flow of  $CO_2$  and water in plant. It may also improve photosynthesis activities, promote acidification of oxidative phosphorylation and produce ATP. Additionally, K can promote the transport of photosynthetic products and the formation of carbohydrates. As K is important to plants, the types of K in soils and its absorption by plants are closely related.

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**Abbreviations:** Q/I, Quantity/intensity;  $AR_e$ , equilibrium activity ratio;  $K_G$ , potassium selectivity coefficient; PBC, potential buffering capacity; AR, activity ratio; ExK, exchangeable potassium; CEC, cation exchange capacity.



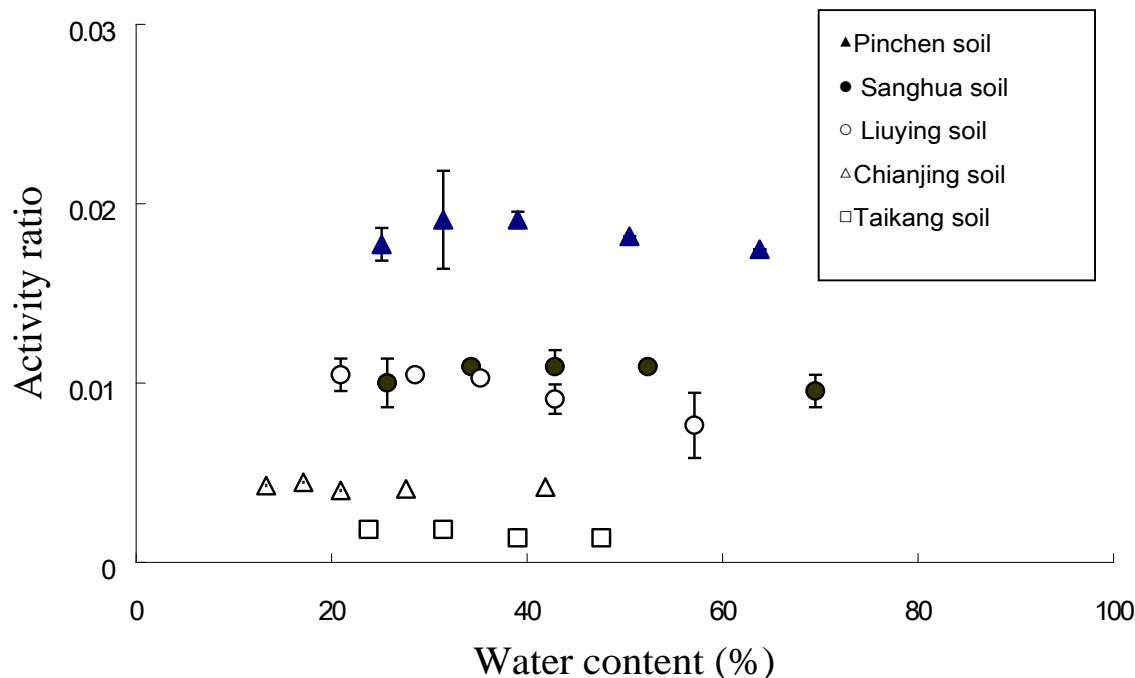
**Figure 1.** The typical Quantity/Intensity (Q/I) plot (Beckett and Nafady, 1967). AR, Activity ratio; I, intensity;  $\Delta ExK$ , quantity (q);  $ExK^0$ , labile K;  $AR_e$ , equilibrium activity ratio;  $ExK_s$ ; potassium specific adsorption; PBC, potential buffering capacity;  $cmol(+)kg^{-1}$ , ion equivalent/kg soil.

## QUANTITY-INTENSITY (Q/I) RELATIONSHIP OF K IN SOILS

Q/I relationship was often used to evaluate direct supply of K from soils to plants in quantity and its buffering capacity (Beckett, 1964a; Kumar et al., 2007). Figure 1 shows a typical Q/I diagram in which Y-axis represents ionic quantity from solid phase, K absorption for positive values and desorption for negative values. X-axis represents the activity ratio of K to Ca + Mg of the solution in soils (Holzmueller et al., 2007). When the K to Ca+Mg activity ratio gradually decreases due to plant absorption of soluble K from the solution in soils, K will be released from soils to make up the deficit for the plant. When the activity ratio (AR) increases in solution, the soil will adsorb K ions. The line intercepted with the Y-axis yields exchangeable K (ExK) value, which can be considered as non-specific absorption of K (Sinclair, 1979; Jalali, 2007). The curve intercepted with the Y-axis represents ExK value of specific absorption of K (Evangelou and Karathanasis, 1986). Non-specific absorption is a plain surface absorption (Sposito, 1989). Specific absorption sites are produced by clay particle crystal lattice margins and wege sites formed by weathered micas (Knibb and Thomas, 1972; Taiwo et al., 2009). Studies have been carried out on Gapon exchange coefficient on K and Ca

in some vertisol clays. Thus, the exchangeable sites were classified into three kinds: 1. Layered margin sites; 2. layered margin split; 3. plain crystal surface sites.

Some important parameter values can be obtained from the Q/I diagram. Equilibrium activity ratio ( $AR_e$ ) is the activity ratio (AR) value where the line crosses the X-axis or the activity ratio at equilibrium. This indicates the degree of K absorption or intensity for plants from the soil instantaneously. The second parameter is the potential buffering capacity (PBC) which indicates the capacity for maintaining the K intensity of the solution in soils. The slope of the line in Figure 2 is the PBC value.  $K_G$  is the selectivity coefficient of K for soils; it indicates the degree of soil preference for K. Hong and Lin (1992) studied the Q/I diagrams for K on four acidic soils in Taiwan and found different Q/I diagrams for different K/Ca concentration ratios with different  $CaCl_2$  concentrations. Based on computer modeling with Gapon's exchange equations, they found similar Q/I diagrams for three different Ca concentrations in prepared solutions. However, the experimental results showed great differences in Q/I diagrams. Similar diagrams are obtained from the solutions at 0.001 M  $CaCl_2$  and 0.004 M  $CaCl_2$  concentrations. When  $CaCl_2$  concentration is increased to 0.01 M, the Q/I diagram is significantly different from the former two diagrams. This indicates that, proper selection



**Figure 2.** The relationship between water content and activity ratio of five important farmland soil series in Taiwan.

of parameters are important from Q/I diagrams.

### EQUILIBRIUM ACTIVITY RATIO ( $AR_e$ )

Different ions in soils exist in proper ratios that are independent of soil moisture. This is the so-called ratio law. It is important to the studies of nutritional elements used for Rothamsted soil to prove that K activity coefficient is independent of moisture by conducting different ion pairs experiments, such as H-Na, H-K, H-Ca, H-Al and H-(Ca + Mg) ion pairs that K ion activity maintains fixed ratios to other ions (mainly Ca and Mg) in soil solution at equilibrium (Schofield and Taylor, 1955; Evangelou and Marsi, 2003). Hough and Lin (1992) studied activity coefficients of five series of acidic form of soils in Taiwan and found that the  $AR_e$  did not vary with their water content. (Figure 2), following the ratio law (Schofield, 1947; Litvinovich et al., 2006). However, Taylor (1958) conducted experiments on four series of Rothamsted soils with K-(Ca + Mg) ion pairs and found two that varied with water contents. In the experiment, Ca + Mg was treated as the same species. Schofield and Taylor (1955) then proposed two conditions to be met for the ratio law to be effective. (1) Almost all K, Ca and Mg ions in unstable state must be kept inside the cation diffusion layer surrounding the negatively charged exchangeable phase on the soil surface; (2) concentrations of K, Ca and Mg ions within the diffusion layer may not be affected by charges of components or concentrations of the solution in soils. Nethsinghe (1958) and Schofield

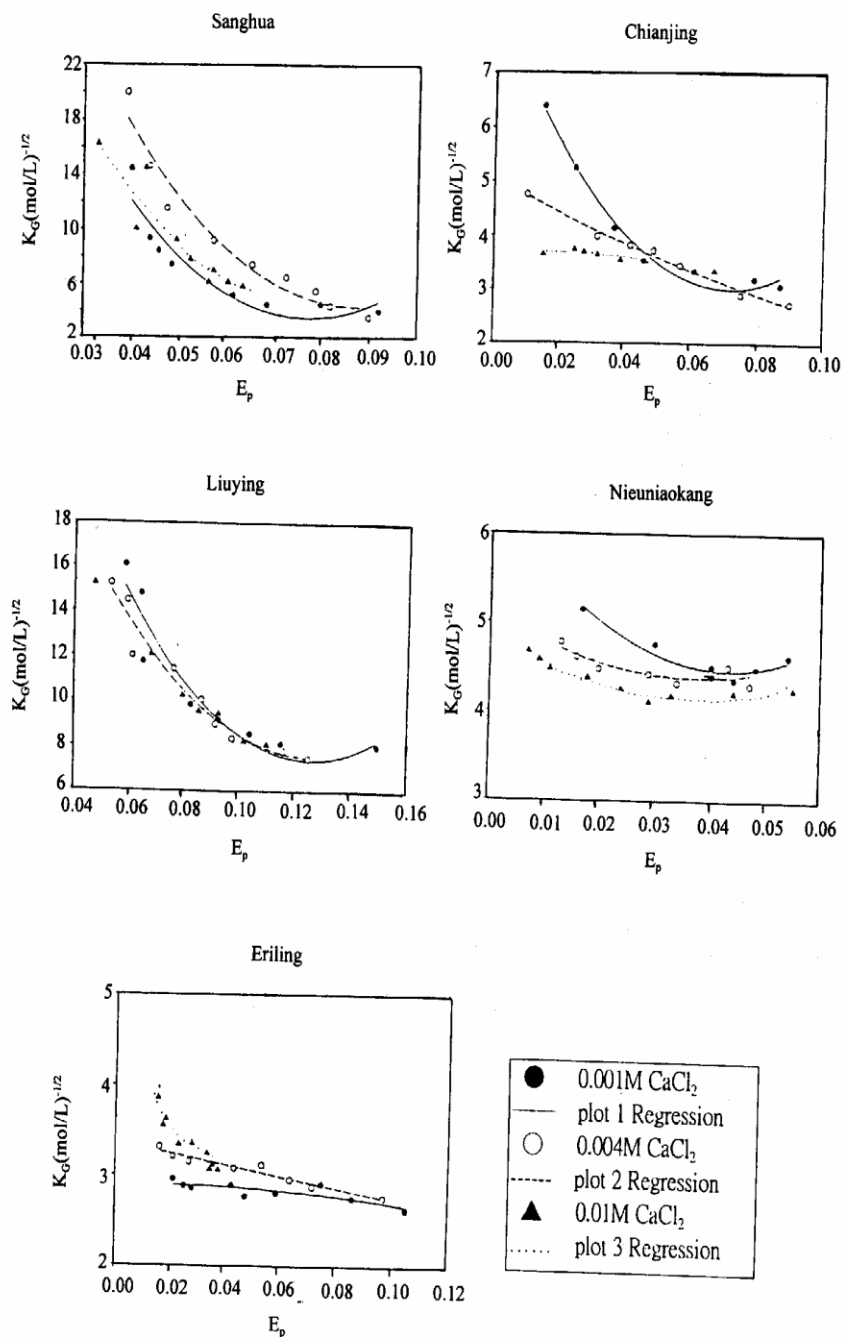
(1947) claimed that the ratio law might not be applicable, if the positive charges are excessive on the exchangeable phase of soil surface.

$AR_e$  is a measurement for the K intensity that the solution in soils may supply directly to plants. Schouwenburg and Schuffelen (1961) suggested that K adsorption remains at marginal sites, if  $AR_e$  is less than 0.001 but it moves to plain sites when  $AR_e$  is greater than 0.01. Jimenez and Para (1991) studied 24 series of Spanish calcareous inceptisols and vertisols and found that, the values range between 0.003 and 0.02. From the Q/I diagram, one can obtain  $AR_e$  as the line intercepts of the X-axis (AR). Higher  $AR_e$  for K indicates greater K supply intensity and so more K may be absorbed by plants instantaneously. If  $AR_e$  of K is the same, the ability to maintain it in various soils is different. Thus, one has to consider the buffering capacity of K in evaluating the effectiveness of K in soils.

### POTASSIUM SELECTIVITY COEFFICIENT ( $K_G$ )

Beckett (1964a) and Woodruff (1955) treated Ca and Mg as a single ion species because it was not significantly different from the real situation. Thus, Ca and Mg were treated as the same single ion species (Beckett, 1964b; LeRoux and Summer, 1968), so that the Gapon equation can be written as (Knibb and Thomas, 1972; Rasnake and Thomas, 1976).

$$K_G = ExK \times [a_{Ca+Mg}]^{1/2} / Ex(Ca+Mg) \times a_K$$



**Figure 3.** The  $K_G$ - $E_p$  relationships between different treatments of  $\text{CaCl}_2$  in five Taiwan farmland soils (Lin and Houg, 1999).

Where,  $K_G$  represents Gapon ion selectivity coefficient in  $(\text{L mol}^{-1})^{1/2}$ ,  $E_x$  is the exchangeable ions in  $\text{cmol (+) kg}^{-1}$  and  $a$  is the activity in  $\text{mol L}^{-1}$ .

Although,  $K_G$  is not a real thermodynamic parameter; it plays an important role in monovalent ionic exchange reactions in soil series. Higher  $K_G$  represents greater efficiency of K for this soil. Under the same cation exchange capacity (CEC) and the same ionic intensity at equilibrium, more K adsorption will result in greater linear

buffering capacity for K. Houg and Lin (1992) also evaluated  $K_G$  values of five farm soils in Taiwan and found the same results. Figure 3 shows  $K_G$  variation with the exchangeable K ratio ( $E_p$ ) under treatments of three Ca concentrations (0.001, 0.004 and 0.01 M). The figure shows a rather high  $K_G$  values at low  $E_p$  values for all three Ca concentrations. As  $E_p$  increases,  $K_G$  decreases

## POTENTIAL BUFFERING CAPACITY (PBC)

Beckett (1964b) proposed that plant absorption of K is related not only to the ionic activity coefficient in solution but also to the capacity of exchangeable K supply. When the K activity ratio gradually decreases due to plant absorption of K from the solution in soils, the exchangeable K in soils will be released. However, if the buffering capacity of exchangeable K is low and K activity ratio in the solution decreases rapidly, then the supply of K released into the solution for plants will be insufficient so, it should be supplemented by K fertilizer. LeRoux and Summer (1968) recognized that PBC is related to  $K_G$ . Evangelou and Karathanasis (1986) obtained  $PBC = K_G \div CEC$  based on Gapon exchange equation. They established a computer model based on these theories to evaluate the relationships among  $K_G$ , CEC and PBC. Rasnake and Thomas (1976) conducted experiments and proved a linear relationship between PBC and the product of CEC and  $K_G$ .  $K_G$  is the K selectivity coefficient for soils.

Higher  $K_G$  represents higher K selection for soils. If CEC of the soils is greater than their adsorption sites will have greater K buffering capacity. Houg and Lin (1992) studied the relationship between PBC and CEC and found that they were poorly related. However, the relationship between PBC and application of K fertilizer also depends on the characteristics of species. For example, rape, peanut, banana, tobacco leaf and mulberry, etc need more application of K fertilizer.  $K_G \cdot CEC$  were good for three different Ca concentrations. Houg and Lin (1992) found that PBC and  $K_G$  were well correlated ( $R^2$  up to 0.99) under the condition of high Ca concentration. Evangelou and Karathanasis (1986) derived the equation  $PBC = K_G \div CEC$  based on the assumption that soils were saturated only with K and Ca (or Ca+Mg), that is,  $CEC = ExK + Ex(Ca + Mg)$ . If the saturation of salt bases is low (e.g. acidic soils) then  $CEC \neq ExK + Ex(Ca + Mg)$  or  $CEC \neq K_G \div CEC$ . Effects of PBC may be evaluated on the basis of CEC and  $K_G$ .

## EFFECTS OF ORGANIC MATTER CONTENT

The author proposed that CEC might be increased due to the accumulation of organic matter in untilled soil (Evangelou and Karathanasis, 1986). However, this increase may not accompany a proportional PBC increase. Salmon (1964) explained that lower K affinity of organic matter caused lower K selectivity coefficient and so PBC was not affected by CEC. Beckett and Nafady (1967) and Sparks and Jardine (1981) recognized that CEC and PBC in soils were related but they noticed that only CEC could affect PBC. We have to consider the sources of negative charges, either from organic matter or mineral. On the other hand, PBC can be affected also by clay mineral contents and different minerals.

## EFFECT OF CLAY MINERALS AND PARTICLE SIZE

The CEC in soils may be affected by clay particle abundance. However, different clay particles may affect soil selectivity of K. The author suggests that higher K selectivity would result from higher content of clay minerals such as illite in soils (Wang et al., 2000). Martin and Sparks (1983) put forward that among the K minerals effective for plant growth, the sequence was *iolite* > *muscovite* > *orthoclase* > *plagioclase*. The clay minerals produced by these minerals generally have higher K contents. Thus, PBC cannot be evaluated only by the contents of clay particles as it is also related to different kind of clay minerals.

## SUITABLE APPLICATION OF K FERTILIZERS

Suitable application of K fertilizer involves consideration of factors such as K content and properties of soils, crop characteristics, K fertilizer properties and application method, etc (Parveen et al., 2007). K fertilization is evaluated mainly based on soil properties in the above discussion. Suitable application of K fertilizer also depends on the kinds of crops and characteristics of species. For example, rape, peanut, banana, coconut, tobacco and mulberry need more application of K fertilizer (Makhdom et al., 2007). Short-stem and high productive rice species will be more effective than long-stem species when K fertilizer is applied. Kinds and properties of K fertilizer may determine effectiveness of the K fertilizer application (Rupa et al., 2003).

Different plants have different tolerance to salts. In K fertilizer, the tolerance is  $KH_2PO_4 > K_2SO_4 > KNO_3 > KCl$ . The apparent interaction of nitrogen (N) and K will occur when fertilizers of K and N are applied together. As absorption of K may affect that of Fe, Mg and Mn, one should pay attention to supply fertilizers of Mg and trace elements when K fertilizer is applied. Some organic fertilizer may contain abundant K that increases K in soils. This is very helpful in supplying K to soils on long-stem basis.

## CONCLUSION

In order to understand the K supply status, one has to know the basic characteristics of soils. If a series of soils has preferential affinity for K, it will adsorb more K that may serve as a reference when K fertilizer is applied. Ratio law proves that the instantaneous supply of K from soils to plants is not affected by the change of water content in soils. It is impossible to base a constant water content in soils at all time. If the instantaneous K supply

varies with the water content, then the soils may be deficient in K at some water content. The ratio law may allow us to avoid such a worry. On the other hand, easy absorption of K from soils by plants (that is, high  $AR_e$ ) does not mean that the soils are not K deficient. If PBC is small then activity ratio for K will drop rapidly following K absorption by plants. This means that, K effectiveness will decrease rapidly. From the view point of providing sufficient effective K on long-term basis, the K buffering capacity in soils is an important factor to consider. In general, if PBC is high, then K fertilization may be done once with a large amount. When PBC of K is low, then K fertilization may be accomplished with a small amount but multiple times so that AR may be maintained at a higher and more stable value.

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