



Role of Potassium for Improving Nutrient Use Efficiency in Agriculture

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Abstract

There is a growing need to improve the agronomic efficiency of plant nutrients, which has been declining over the years. Although the demand for nitrogen (N) fertilizers is increasing, there is a considerable reduction in yield increase per unit of N (nutrient use efficiency, NUE). Improving the NUE of N is of great importance, both for economic and environmental reasons. Insufficient applications of potassium (K), combined with excess N applications, is an increasingly serious problem for modern intensive agricultural systems. This often leads to great N losses, pollution of the environment, and low NUE. Recently, balanced nutrition –mainly N and K balanced nutrition and touching the subject of N and K synergistic effect–has been increasingly identified as an important strategy to improve NUE. Several studies demonstrate the positive effects of the interaction between N and K, particularly for crop productivity and economics, but balanced nutrition is not implemented correctly in various areas around the world. The application of K has been neglected in many developing countries, including India for example, resulting in soil K exhaustion and declining crop yields and quality. Optimal N: K nutritional ratios can reverse this trend by increasing yields and crop quality. Many long-term field trials have demonstrated how K application can also improve the NUE of phosphorus (P) and other nutrients like sulphur (S). Studies have also shown that K can mitigate the adverse effects of excessive N on disease and insect-pest incidences, thereby improving crop yields and health, thus, in turn, improving the NUE of N.

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Abbreviations

Al	Aluminum
Ca	Calcium
Cu	Copper
DM	Dry matter
Fe	Iron
K	Potassium
KUE	Potassium use efficiency
KSB	K solubilizing bacteria.
Mg	Magnesium
Mn	Manganese
N	Nitrogen
Na	Sodium
NR	Nitrate reductase
NUE	Nutrient use efficiency
P	Phosphorus

13.1 Introduction

Agriculture is currently under immense pressure to feed an increasing global population (Grzebisz et al. 2012). Not only does the sector face the serious challenge of growing enough healthy food to feed the expanding global population (FAO 2013), but this challenge is also deepening the constraint on global base resources (land, water, and air). Increasing yield per unit area is needed to help increase food production (Baligar and Fageria 2015). FAO (2013) estimates that about 1.54 billion ha of land globally is in use for cropping. The majority of land that is suitable for cropping is already being used, with the exception of some areas in sub-Saharan Africa and South America, but these areas are too brittle to cultivate due to soil degradation.

Soil degradation, caused by intensive cultivations and inappropriate management, combined with increased abiotic and biotic stress events poses a serious challenge to attaining reasonably good annual and perennial crop yields worldwide (Baligar and Fageria 2015). Sufficient nutrients supply (applied through fertilizers) together with superior genetic cultivars and genotypes, are essential to attain higher yields and high-quality food. Essential nutrient scarcity affects many of the world's soils, but high fertilizers application to reach higher crop yields might contain toxic elements as well (Dudal 1976; Clark 1982; Baligar et al. 2001). Various factors, including

salinity, acidity, alkalinity, the nature of farming anthropogenic processes, and erosion, cause soil degradation and decrease soil fertility. About 4 billion ha of the world's land suffers from soil acidity and about 950 million ha of land is salinized. To cultivate some of these areas requires costly inputs including irrigation, soil amendments, and fertilizers. Adding fertilizers to degraded and infertile soils is crucial for appropriate nutrient supply and attaining higher yields (Baligar and Fageria 2015). Nitrogen (N), phosphorus (P), and potassium (K) are the three main essential nutrients plants require in relatively large amounts for their metabolism and growth. A deficiency in any of these nutrients results in a significant reduction of crop yields (Mitra 2017). The reservoir of N, P, and K in cultivated soils is not sufficient to meet the needs of crops grown in the same area annually, so to reach optimum yields N, P, and K should be added every year through fertilizers.

World consumption of NPK fertilizers reached 186.67 million tons in 2016, up by 1.4% from 2015. Between 2015 and 2020, the demand for N, P, and K fertilizers were estimated to have grown annually on average by 1.5, 2.2, and 2.4%, respectively. The global demand for fertilizer production, intermediates, and raw materials is also expected to increase (Roy et al. 2006). Chemical fertilizers are one of the more costly inputs farmers use to increase their yields. About 12 million tons of N, two million tons of P, and four million tons of K are applied every year by farmers in North America (Baligar et al. 2001). About 18 million tons of N, 6.9 million tons of P_2O_5 , and 2.5 million tons of K_2O were applied in India during 2018–2019 (FAI 2019). Global K_2O consumption since 1973 can be seen in Fig. 13.1. Despite fertilizer use increasing, plants being grown in many soils take up very little nutrients from applied inorganic fertilizers. Estimations of the overall efficiency of applied fertilizers have been about 50% or lower for N, less than 10% for P, and about 40% for K (Baligar and Bennett 1986a, b). The efficiency of these nutrients under flood irrigated rice systems in Asia is even lower. Significant nutrient losses through leaching, runoff, gaseous emissions, and fixation by soil all contribute to low efficiencies. Nutrient losses may also contribute to soil and water quality degradation, ultimately leading to environmental degradation (Baligar et al. 2001). These reasons emphasize the need to improve nutrient use efficiency (NUE).

Blair (1993) defined NUE as the genotype's ability to uptake nutrients from a growth medium and to integrate or utilize them in shoot and root biomass production or functional plant materials such as seeds, grains, fruits, and forage. NUE usually is defined as the nutrient output or the crop output per unit of nutrient input (Meena et al. 2020; Naeem et al. 2017). Improved NUE of plants can reduce the rate of nutrient losses and fertilizer input costs and increase crop yields (Baligar et al. 2001). Various factors influence NUE: the plant's genetics, soil, fertilizers, agronomic management, biotic, and abiotic stresses. This chapter looks at the effect of K fertilization on NUE. Additional factors that can improve NUE can be seen in Fig. 13.2.

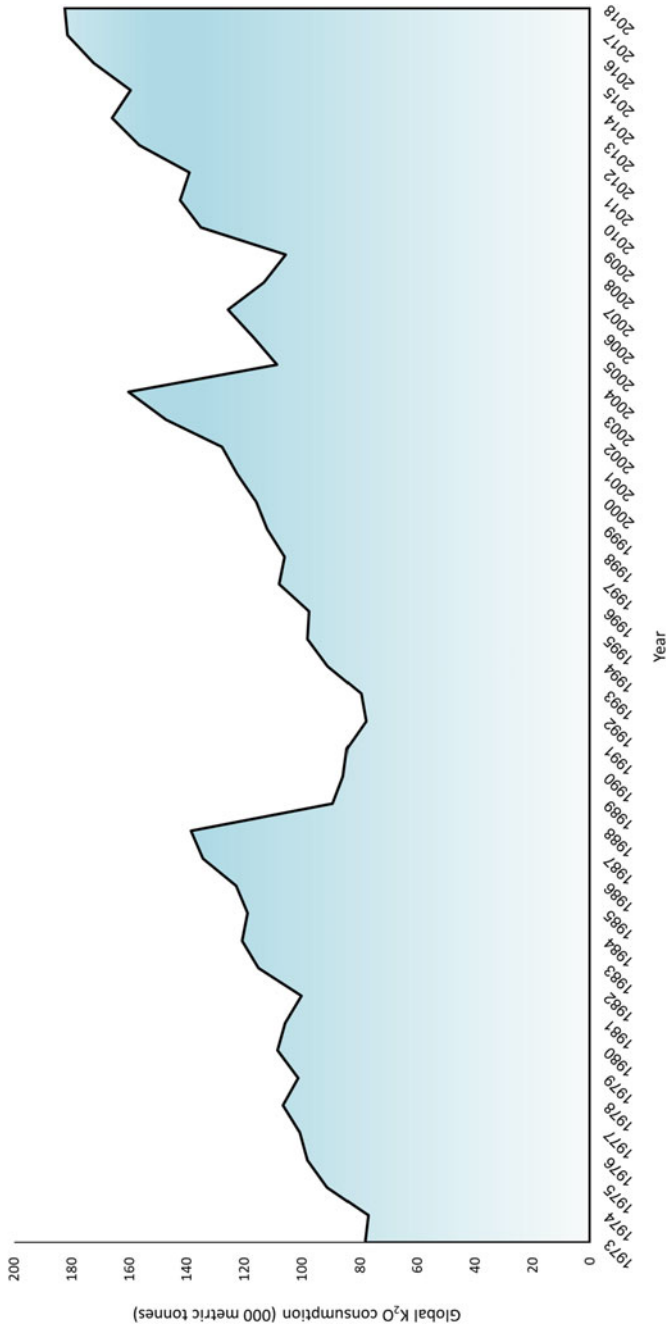


Fig. 13.1 Global K₂O fertilizer consumption, from 1972 to 2018 (adopted from IFA 2021)

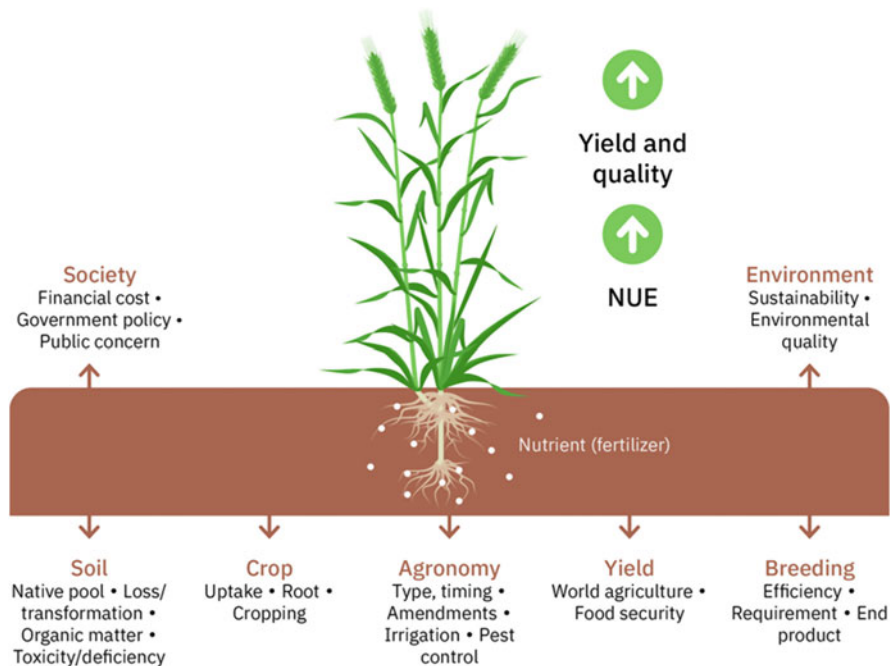


Fig. 13.2 Factors that can improve NUE, adopted from Mathur and Goel (2017)

13.1.1 The Role of K in Plants

K^+ is an essential mineral and the most plentiful cation in plants. K^+ is also unique as it occurs solely in the free ion form (Römheld and Kirkby 2010). In sufficiently supplied plants, K^+ can compose ~6% of plant dry matter (DM) or in ~200 mM concentrations (Leigh and Wyn Jones 1984). The highest K^+ concentrations can be found in young developing tissues and reproductive organs, which can indicate its key role in growth and cell metabolism. K^+ activates several enzymes, some are involved in protein synthesis, energy metabolism, and solute transport (Mengel and Kirkby 2001; Amtmann et al. 2008). Other processes where K^+ is found to be involved include stomatal movement, osmoregulation, and cell extension, phloem loading, photosynthesis, and transport and uptake (Römheld and Kirkby 2010). K^+ is needed by plant cells to maintain transmembrane voltage potential for homeostasis of cytoplasmic pH and transporting inorganic anions and metabolites (White and Karley 2010). K^+ is the main cation in long-distance transport inside the xylem and phloem, participating in neutralizing anions, giving its high mobility through the whole plant (Jeschke et al. 1997). K^+ up-taking and accumulating by plant cells is the main driving force for cells' osmotic expansion (Uchida 2000; Mengel and Kirkby 2001).

The most common symptom of K^+ deficiency is chlorosis along leaf edges, which is also known as leaf margin scorching (Fig. 13.3). Chlorosis occurs first in older

Fig. 13.3 Potassium deficiency in soybean (IPI website)



leaves, due to the high rate of K^+ allocation from mature to developing tissues. First, the growth rate decreases (known as hidden hunger), and then later chlorosis and necrosis appear in the older leaves. Because K^+ is required in photosynthesis and protein synthesis, K^+ deficient plants will have slow and stunted growth. In some crops, stems become weak, and lodging incidences increase. The size and production quantity of seeds and fruits size and their production quantity are also reduced. Plants with K^+ deficiency demonstrate turgor decrease and become flaccid under water stress, especially during the middle of the day (Uchida 2000; Mengel and Kirkby 2001). K^+ also contributes to plants survival under various abiotic stresses (Wang et al. 2013), as well as environmental stress conditions and many physiological processes. These include protein synthesis, energy transfer, enzyme activation, photosynthesis and translocation of photosynthates into sink organs, osmoregulation, stomatal movement, phloem transport, cation–anion balance, and stress resistance, and decreasing excess uptake of ions like sodium (Na) and iron (Fe) in flooded and saline soils (Mengel and Kirkby 2001; Marschner 2011).

13.1.2 Potassium Uptake by Plants

K content in soils ranges between 0.5–2.5% and about 2–10% of a plant's dry weight is made up of K (Gierth and Mäser 2007). K is highly important for plants, as shown by the sophisticated mechanisms of K uptake, redistribution, and homeostasis, and is a component in numerous cell wall and membrane protein families (Hirsch et al. 1998; Armengaud et al. 2004; Szczerba et al. 2009; Pyo et al. 2010). Numerous regulatory mechanisms have been identified for K transporters. These transporters are activated by different environmental factors, including K^+ , Na^+ , and Ca^{2+} concentrations in the soil and water availability. Many proteins in the plant are involved in K^+ transportation (Mitra 2017).

There are two K transport systems: (1) a low-affinity transport system, which is channel-mediated that acts when external K concentrations are high and is iso-thermodynamically passive (Leigh 2001; Szczerba et al. 2009) and, (2) a high-affinity transport system, a system that can reach saturation, which accelerates the thermodynamically active K uptake when external K concentrations are low (< 1 mM) (Schachtman and Schroeder 1994; Szczerba et al. 2009; Cuéllar et al. 2010). The capacity of a plant to uptake K and maintain internal homeostatic properties is ruled by genetic expression mechanisms (Hirsch et al. 1998; Yin et al. 2011; El-Mesbahi et al. 2012). Furthermore, K uptake is closely associated with water budget (Sardans and Peñuelas 2015). K and water transmembrane channels are probably co-regulated and their function is synchronized to maintain proper cytosolic osmolarity (Patrick et al. 2001; Liu et al. 2006; Osakabe et al. 2013).

13.1.3 Potassium Use Efficiency (KUE)

Information about KUE is inadequate compared with N and P (Mathur and Goel 2017). K^+ is one of the most abundant minerals in the earth's crust. The lithosphere contains approximately 2.5% of K^+ . K soil concentrations for mineral soils differs broadly, between 0.04 and 3.0% (Sparks 1987). Various rocks are a source for K, including igneous rocks like granites and syenites ($46\text{--}54$ g K kg^{-1}), basalts (7 g K kg^{-1}), and periodotites (2 g K kg^{-1}), sedimentary rocks such as clayey shales (30 g K kg^{-1}), and limestone (6 g K kg^{-1}) (Malavolta 1985). Even though plants can uptake K^+ from the soil solution, most K^+ in soil is unavailable as it is fixed and in lattice forms (Syers 1998; Ashley et al. 2006). Soil K (Fig. 13.4) can be divided into four categories: (1) K in the soil solution (2) exchangeable K, (3) non-exchangeable-K, and (4) structural K (Syers 2003; Moody and Bell 2006). Exchangeable K can be released rapidly from soil particles to enter the soil solution, but K release from the other three forms is much slower and so will not be as readily available. The portion of available K in soil solution is 0.1–0.2% of total soil K, exchangeable K is 1–2%, non-exchangeable K is 1–2% (fixed in 2:1 clays), and soil-unavailable K is 96–99% (Sparks 1987; Wang et al. 2010; Britzke et al. 2012; Sardans and Peñuelas 2015).

On top of the issue of restricted K^+ availability, other soil components also interfere with K^+ uptake, e.g. high concentrations of NH_4^+ and Na^+ disturb plant roots K^+ uptake (Qi and Spalding 2004; Ashley et al. 2006). K availability differs with soil types and is largely affected by the soil's physical (type and amount of clay and organic matter), biological, and chemical properties. Soil K is also influenced by the parent material's nature, weathering degree, the addition of manures and fertilizers, leaching, erosion, and crop removal (Dhillon et al. 2019). Another factor influencing the efficiency of K^+ uptake in plants is soil moisture (Shin 2014; Meena et al. 2020).

There are a couple of mechanisms that enable plants to adjust and survive limited K^+ conditions. As soon as plants sense a shortage of K^+ , root volume is increased, which enables increased K^+ to uptake from the soil, and the high-affinity K^+ uptake system is activated. When plants cannot adjust and raise K^+ uptake and available K^+

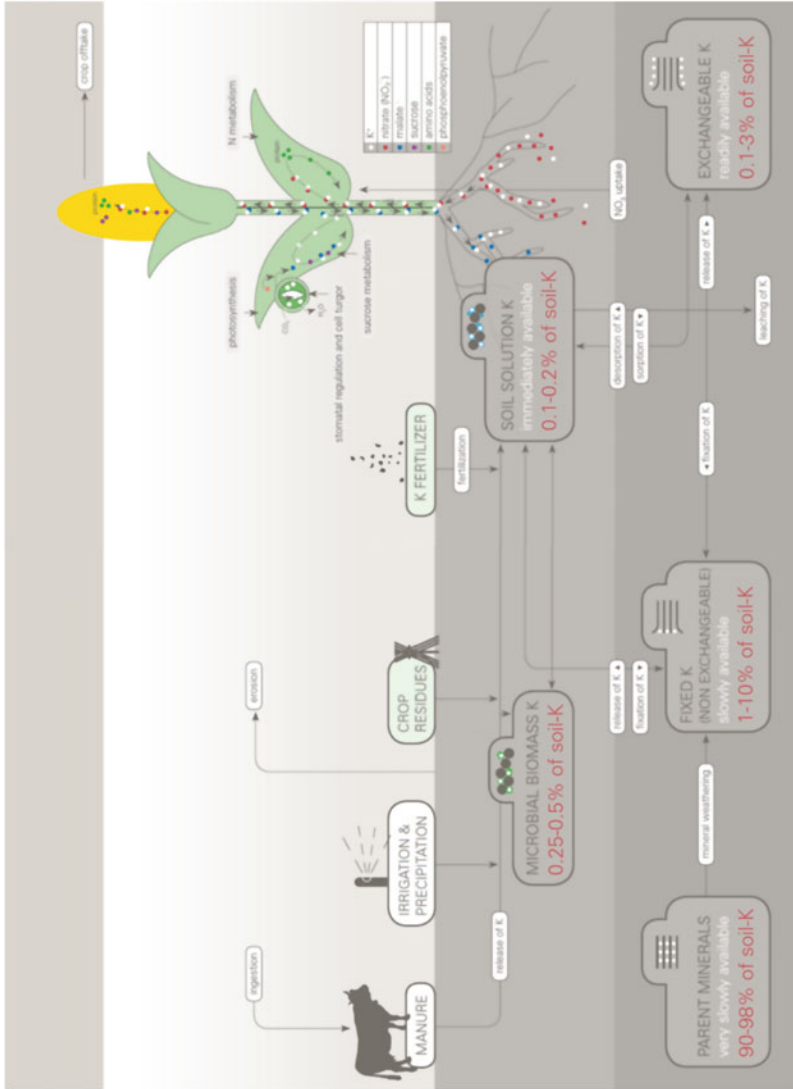


Fig. 13.4 The potassium cycle in soil (IPI website)

relocation internally, their metabolism rate decreases, and ultimately the plant stops growing. In agricultural crops, K^+ limitation results in reduced yields, but one solution is to either increase fertilizers usage or improve the efficiency of K^+ uptake, transport, and utilization (Shin 2014). Calculating KUE is based on the relationship between the amount of fertilizer consumed by a certain crop and the amount of K removed by the plant. To determine global KUE for crops, the following equation (adapted from Raun and Johnson 1999; Dhillon et al. 2017) can be used:

$$KUE = \frac{\text{Crop yield } K \text{ uptake} - K \text{ removed from soil}}{K \text{ applied as fertilizer to the crop}} \times 100 \quad (13.1)$$

13.1.4 Nutrient Use Efficiency Estimation in Plants

A plant NUE is greatly affected by its physiological and genetic makeup, which impacts a plant's capability to uptake and employ nutrients under several environmental conditions. To determine NUE, it can be beneficial to distinguish plant species genotypes and cultivars by their nutrient uptake and assimilation abilities for maximizing DM production and yields. Three efficiency mechanisms determine NUE:

1. Uptake efficiency: which is affected by absorption from the soil, influx kinetics and influx rate into the roots, radial transport (based on root parameters per length or weight). Uptake is correlated as well to particular amounts of nutrients that are already present in the soil or were applied.
2. Incorporation efficiency: refers to nutrient transport to the plant upper organs, based on shoot parameters.
3. Utilization efficiency: which is based on remobilization and whole plant parameters.

Plant NUE can be characterized as the maximum economic yield, or DM produced per unit of an applied nutrient or a unit of that nutrient that was taken up (Baligar and Fageria 2015). Figure 13.5 presents the different yield responses to nutrient levels.

13.2 Potassium for Improving Nutrient Use Efficiency

The average amount of available K in most soils globally is not sufficient to meet the nutritional needs of sensitive and high-yield crops (Gaj and Górski 2014). Intensive cropping, combined with unbalanced fertilization, causes K depletion in soils (Igras and Kopyński 2009). K deficiency, particularly in crop production, is usually caused by increasing applications of N and P fertilizer while neglecting K fertilization (Ju et al. 2005). K deficiency is a problem globally (Dobermann et al. 1998), and

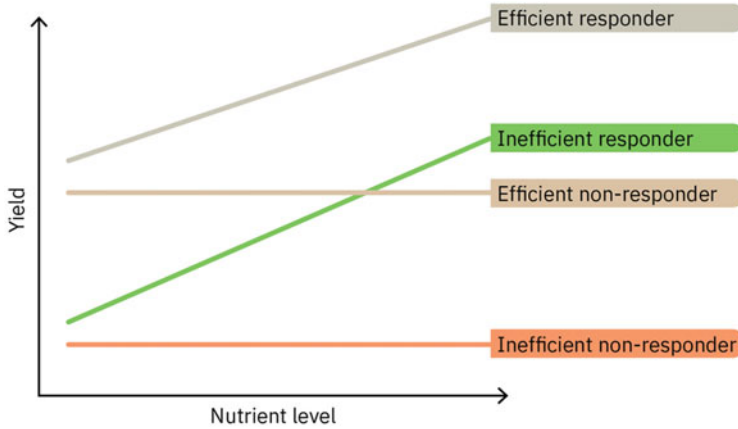


Fig. 13.5 Plant classes, relative to yield responses and nutrient level in the growth medium (adopted from Gerloff 1987; Blair 1993)

levels of K are decreasing in cultivated soils in Africa, Asia, Europe, and North America (Tan et al. 2012). Unbalanced K and P fertilization is a common cause for low N utilization, due to competition on absorption sites for example (Gaj and Rebarz 2014; Yadav et al. 2020). The efficiency of fertilizer use is also low as a result of current global N management strategies for crop productions systems (Cassman et al. 2002; Fageria and Baligar 2005), where N is often being applied in excess on the count of other nutrients. The relationship between nutrient uptake and yield is reflected as NUE and is expressed through economic products, such as grains (van Duivenbooden et al. 1996). To maximize NUE from mineral fertilizers, an analysis of the amount of nutrient applied, and its uptake is required, in addition to determining the factors limiting nutrient use (Gaj and Rebarz 2014).

In crops, nutrient interactions happen when one nutrient supply affects the absorption and employment of other nutrients. This occurs when one nutrient is in excess concentrations in the substrate (Fageria et al. 1997). Nutrient interactions happen at the root surface and inside the plant and can be divided into two main categories:

1. Interactions between ions when they are capable of forming a chemical bond. In this class, interactions are due to precipitates or complex formation. For instance, this interaction type happens when liming acid soils reduce the concentration of the majority of micronutrients (Fageria 2001), by reducing the soil pH and their availability to plants.
2. Interactions between ions with chemical properties are similar enough that they compete for transport, adsorption sites, and function on the root's surface or inside plant tissues. These kinds of interactions are more likely to occur between nutrients with a similar charge, size, coordination geometry, and electronic

configuration (Robson and Pitman 1983). This is common for Ca^{2+} , Mg^{2+} , K^+ , and Na^+ , for example.

13.2.1 Potassium and Nitrogen Use Efficiency

Interactions between K and N have been well documented, with the first experiments starting in 1852 at Rothamsted Station, UK (Ranade-Malvi 2011). Some of the interactions that affect crop response to a nutrient like K are due to factors such as fertilizer form, method, and date of application, and the variety of crops. Occurrence of such K and N interactions may lead to changes in the ways of using K fertilizers (e.g. changing N:K ration when fertilizing). The most important variables are qualitative, such as the level of other nutrients applied, irrigation rate, spacing between plants, etc.

The interaction of K with other nutrients, particularly with N, is the most important variable (Loue 1980). K application, for example, could improve N metabolism enzyme activity (Hu et al. 2016; Zahoor et al. 2017). N and K interactions are important for crop production. The importance of N-K interactions and how best to manage this is increasing due to demand for higher crop yields globally, increasing cropping intensity, and considerable K depletion in cultivated soils (Aulakh and Malhi 2005). Crops with high K requirements often show strong N-K interactions (Loue 1980; Singh 1992). Plants uptake N either in a cationic (NH_4^+) or anionic (NO_3^-) form. This creates unique anion-cation and cation-cation interactions with K. The majority of current research findings have revealed that K does not compete with NH_4^+ for uptake but increases NH_4^+ assimilation in the plants and prevents possible NH_4^+ toxicity (Aulakh and Malhi 2005). Mengel et al. (1976) determined that it is improbable for K to compete with NH_4^+ for selective binding sites during the uptake process. The relationship of K and N use efficiency, and its effect on yield, is shown in Fig. 13.6 and Table 13.1.

Ranade-Malvi (2011) was observed that crop response to N fertilizer applications was reduced when exchangeable K content in the soil was below optimal levels. Mengel et al. (1976) reported that while a higher K supply caused a decrease in Na^+ , Mg^{2+} , and Ca^{2+} uptake by the shoots, NH_4^+ uptake was increased. Mengel et al. (1976) reported that higher K concentrations in the solution were favoring the labeled N translocation from roots to shoots. In certain cases, higher K levels also enhanced the labeled N transfer rate from the soluble to the insoluble N fraction. On the other hand, increasing Mg^{2+} levels in the uptake solution had no effect on the uptake of labeled NH_4^+ . Steineck (1974) revealed (through his nutrient solution technique) that there is a close relationship between N and K in their physiological functions and the main effect of K is improving N utilization efficiency. Increased K uptake led to increased N uptake and vice versa: plants take up the amount of K required for full N utilization (Steineck 1974). The effects of both nutrients on plant composition and yield have an important impact on the nutrient cycle, especially when crops with high K uptake (like forage crops) are concerned (Loue 1980). Figure 13.7 provides an example of potato response to increasing K concentrations.

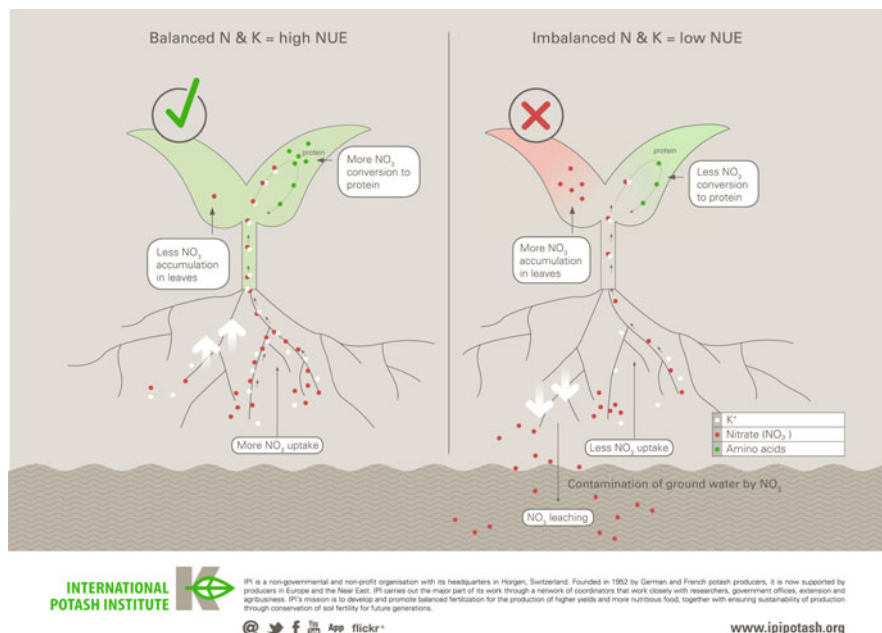


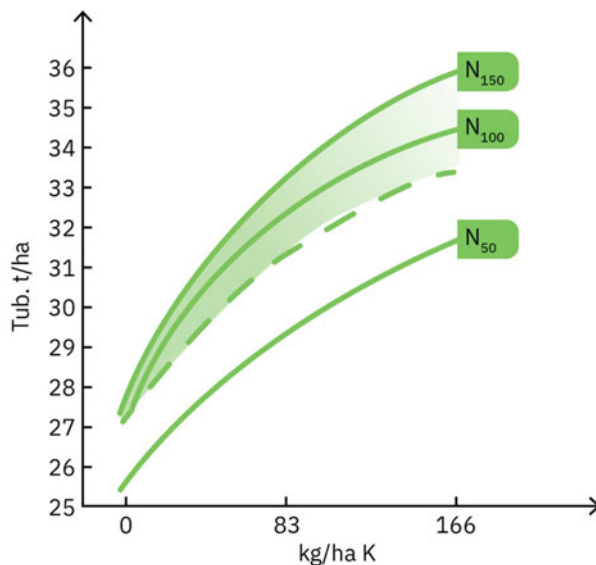
Fig. 13.6 Potassium and nitrogen use efficiency (IPI)

Table 13.1 Increase in yield and NUE achieved in IPI on-farm experiments. Adopted from *e-ipc* No. 13, 9/2007. IPI

Crop	Country	Parameter	N rates (kg/ha)	K rates (kg/ha)	Yield increase (kg/ha)	NUE increase (%)
Maize	India	Grain	125	30–90	200–1300	6–29
Maize	China	Grain	150–300	75–180	200–1800	5–29
Maize	Ukraine	Grain	30	30	720	15.5
Rice	Bangladesh	Grain	100	33–66	690–900	23–30
Rape seed	China	Seeds	180	113–188	142–704	35–53
Sugarcane	India	Cane	240–340	85–200	2200	70
Sunflower	Hungary	Seeds	80	100–200	200–1100	10–30
Sunflower	India	Seeds	60	30–690	400	18
Wheat	China	Grain	180–300	75–150	200–1370	2–26
Winter rye	Belarus	Grain	90	60–120	230–610	10–23

Ajayi et al. (1970) reported that when tomato plants were given a continuous supply of N in the form of NH_4^+ , severe stem injuries were observed unless K^+ was added at equivalent rates. Leaf injuries were seen to be a result of NH_3 toxicity when plants were treated with NH_4^+ , but when plants received higher K rates, the injuries

Fig. 13.7 Response to increasing K at 50, 100, and 150 kg/ha N in potato crops. The shaded area shows how the response to N increases as the K level is raised (mean of 17 years) (adopted from Loue 1980)



did not appear. Their conclusion was that K^+ boosted NH_4^+ assimilation in the plant, which avoided NH_3 toxicity, and that K^+ uptake did not compete with NH_4^+ uptake. Similar phenomena were observed in corn plants, where injuries appeared when NH_4^+ and NO_3^- were applied at low K^+ concentrations (Dibb and Welch 1976). Based on their work on rice, Mengel et al. (1976) also concluded that it was improbable that K^+ competed with NH_4^+ for selective binding sites in their uptake process. In fact, increased N and K uptake, combined with higher K rates, indicates a possible complementary uptake effect amid NH_4^+ and K^+ (Dibb and Thompson 1985).

Translating a plant's genetic code to produce proteins and enzymes is impossible without adequate K. Although N is fundamental for producing proteins, K-deficient plants will not produce proteins even with high levels of available N. This is because the enzyme nitrate reductase (NR) which catalyzes protein formation is influenced by K (Ranade-Malvi 2011). K does not activate NR but was found to be the most effective monovalent cation in its synthesis (Nitso and Evans 1969). In maize, NR activity was enhanced with increased K, therefore, it is likely that K ions influence NR synthesis (Khanna-Chopra et al. 1980). Starch synthetase was also found to be affected by K. Nitso and Evans (1969) found that K is needed for starch synthetase in sweetcorn. Starch synthetase showed optimum activity in the presence of 0.05–0.1 M of K, while other monovalent cations were not so efficient. Lower amounts of starch mean that less starch is moving from source to sink, leading to a poor-quality end product. One practical implication of the N-K interaction is that applications of large amounts of N when there is insufficient exchangeable K in the soil are not beneficial. That is because N is not used efficiently and is expressed as a financial cost to the grower (Ranade-Malvi 2011).

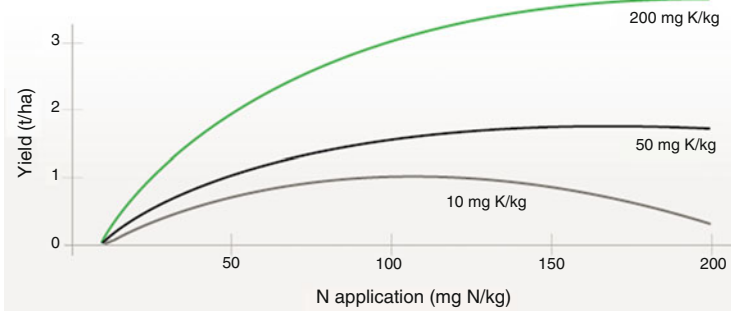


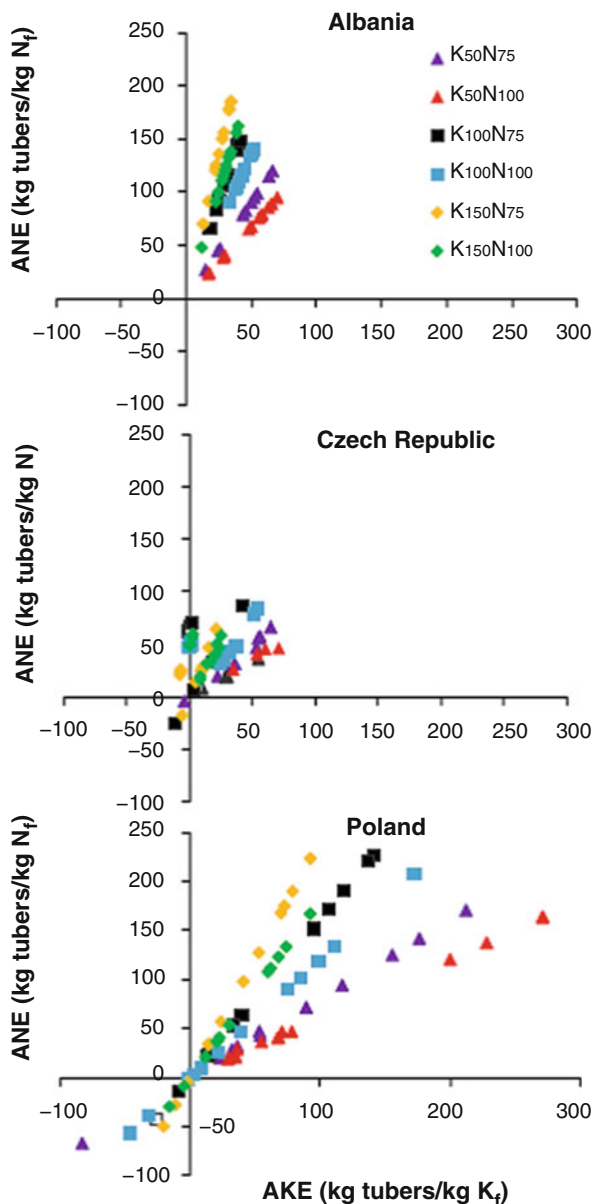
Fig. 13.8 Effect of N and K interaction on barley yield in hydroponic culture, adapted from (Macleod 1969)

One of the main reasons for a low potato yield is the low efficiency of applied N fertilizer (Singh and Lal 2012; Grzebisz et al. 2017). Current mineral nutrition management in potato production is N-oriented and overlooks other minerals like K and P. Consequently, harvested yields are very variable year-to-year (Grzebisz et al. 2010). Increasing K levels above current recommendation levels improve N use efficiency in potatoes, which also allows N application to be reduced below recommended levels and increase tuber yields (Grzebisz et al. 2017). Trials in pigeon pea (*Cajanuscajan L. Millsp.*) showed that P and K application significantly increased grain and protein yield (Brar and Imas 2014). Increasing K level has been shown to not only increase grain yield but also improve N use efficiency by 6–29% in maize, 18% in sunflower, and up to 70% in sugarcane (IPI 2007).

Macleod (1969) reported that a plant's response to N was dependent on both P and K, increasing K levels improved barley responses to N fertilization, meaning that with high K levels less N can be applied to obtain a high yield (Fig. 13.8). Mondal (1982) identified a positive N-K interaction in rice. A low increase in yields was recorded when N levels were high and K applications levels were low, but yields increased with higher K application levels, meaning that there is a better utilization of applied N when N and K application levels are balanced. Muthuswamy and Chiranjivi (1980) reported that in Tamil Nadu (India), the optimal rate for fertilizer application for cassava was found to be 50 kg N/ha and 250 kg K₂O/ha. The N-K interaction resulted in very low yields when N was applied without K applications. The yield increased remarkably with increased levels of applied K. K application ensured N utilization and carbohydrate storage in cassava roots, thus improving N use efficiency. The impact of KUE on N use efficiency can be seen in Fig. 13.9.

Duan and Shi (2014) reported that adding K to N and NP fertilizers resulted in significantly higher N use efficiency both in rice and wheat. They concluded that there is a great potential for improving N use efficiency in China by adding K to NP fertilization. Hou et al. (2019) revealed that N and K combined applications increased rice grain yields by 42.2%, 62.9%, and 39.0% compared with treatments without NK fertilizers over 3 years. A suitable N and K combination improved grain yields and reduced the rates of N applications. Dong et al. (2010) also demonstrated

Fig. 13.9 Impact of the apparent potassium efficiency (AKE) on the apparent nitrogen efficiency (ANE) at six different N combinations (75% and 100% of the recommended rate) and K (50, 100, and 150% of the recommended rate) application levels (Grzebisz et al. 2017)



that N inputs can be reduced when combined with K without causing yield reduction. N supply with growing K rates increased grain yields and promoted the uptake of N and K. Other research has shown that the response of grain yields to N applications was higher with higher K rates than lower K rates: 120 and 180 kg K_2O ha^{-1} vs. 0 and 60 kg K_2O ha^{-1} (Hou et al. 2019). K has been found to promote

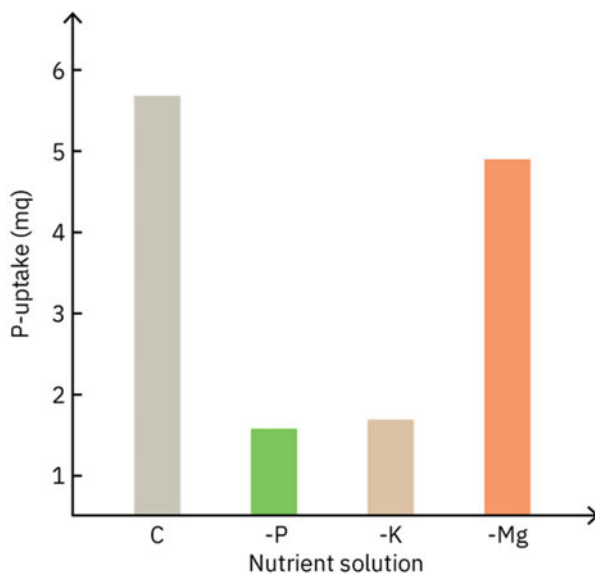
higher root growth in rice, and to activate plant enzymes involved in assimilating ammonium and amino acid transport, causing increased N uptake and hence improved N use efficiency (Li et al. 2012). Improved N use efficiency contributes to farmer's profitability and can also decrease undesirable environmental effects (Jing et al. 2007).

13.2.2 Potassium and Other Nutrient's Use Efficiency

P is regularly applied to meet a crop's nutritional needs since sub-optimal P application can cause yield losses of 10–15% compared with maximum yields (Shenoy and Kalagudi 2005). Enriching soils with P do come with the risk of polluting surrounding water systems, which has become a growing environmental concern (Liu et al. 2011). Recovery of P by plants, through applied fertilizers, has been shown to be low—about 10% (Johnston 2000; Shenoy and Kalagudi 2005). Consequently, most applied P stays in the soil and is prone to be lost during the post-harvest season. Losses of P are affected by the application rates of P fertilizers and by the uptake of P by plants (Leinweber et al. 1999). Generally, the long-term build-up of soil P through the addition of levels of P higher than crop demand increases the risk of P losses (Liu et al. 2011). P-K interactions have less impact than N-K interactions and have attracted less attention. It appears that there is no close connection between the functions of P and K in plant nutrition. While N and K are taken up by plants in large amounts, P uptake is relatively small. It seems that P-K interactions are only noticeable when soils are supplied with insufficient P and K (Loue 1980). P movement in the soil and plant P uptake is usually associated with water content (Liu et al. 2011). Nevertheless, P and K are vital for enzyme and energy-driven reactions, photosynthesis, stress tolerance, seed formation, and quality, and crop maturity.

Robertson et al. (1954) reported that the effect of P on increasing vegetative growth in maize was significantly lower when P was applied as a starter fertilizer without N and K, compared with when P was applied with N and K. Applications of P only led to increasing grain yields when K and N were also applied. Fageria et al. (1990) found that fertilization with K significantly affected N, P, and K concentrations in the plant tops in lowland rice cultivars. K application both increased N concentrations in rice cultivars and increased P concentrations in plant tissues. Khangahi et al. (2018) found that inoculating rice with K solubilizing bacteria (KSB), not only increased grains and straw K uptake but also improved N and P concentrations in the grain and straw, particularly when they were combined with half K chemical fertilizer (47.5 Kg/ha) application. Adequate K levels have been found to be necessary to achieve maximum crop response to added P. Wagner (1979) stressed the importance of P-K interactions in maximum yield production. Jones et al. (1977) reported on the need for balanced P-K application to achieve high soybean yields. Welch et al. (1981) showed a similar positive P-K interaction on bermudagrass yield. Adepetu and Akapa (1977) discovered a potential P-K interaction in the uptake stage. They proposed that since K^+ deficiency caused a significant

Fig. 13.10 Effects of potassium and magnesium on root potassium uptake of HI 13-4 cowpea grown in a nutrient solution (adopted from Adepetu and Akapa 1977)



reduction in P uptake, even with sufficient P levels in the solution, K^+ activates a specific P ion absorption site, and adding Mg^{2+} to the solution did not activate the P absorption site (Fig. 13.10).

Magnesium (Mg) and Calcium (Ca) usually have a negative correlation when applied with K concentrations, probably due to competition for absorbing sites (Loue 1980). Nevertheless, it seems that the negative effect of K on Mg uptake is concentration depended. Fageria (1983) reported that Mg uptake increased with increasing K concentrations up to 511 μ M, but when K concentrations further increased a decrease in Mg uptake was observed. This depressing effect of K on Mg uptake at higher concentrations may be as a result of competition for metabolically produced binding compounds (Omar and Kobbia 1966).

A physiological relationship was found to exist between iron (Fe^{2+}), K^+ and organic N in sorghum grains (Matocha and Thomas 1969). Soil and foliar Fe applications increased grain yields and were linked to amplified tissue K^+ concentrations. K applications without Fe^{2+} reduced yields, while the uppermost yields were reached with Fe^{2+} and K^+ applied together. Added K^+ was reported to reduce mild Fe^{2+} deficiency symptoms in potatoes (Bolle-Jones 1955). The effect of K^+ on Fe^{2+} toxicity in rice was evaluated. Roots of K^+ deficient plants decreased Fe^{2+} excluding power; therefore, Fe^{2+} toxicity is increased. Plant roots which received sufficient K^+ had more metabolic activity in the roots and a higher rate of Fe^{2+} excluding, consequently reducing Fe^{2+} toxicity (Tanaka and Tadano 1972).

Synergetic effects of K and manganese (Mn) interaction have been reported in several studies (Stukenholtz et al. 1966; Smith 1975; Leggett et al. 1977). P, Ca, and Mg has a key role in Mn absorption regulation by plants (Ramani and Kannan

1974). P, Ca, and Mg was shown to decrease Mn uptake when Mn concentrations were in large and potentially toxic amounts. On the other hand, they elevated Mn absorption when its concentration was low. K has been found to increase Mn concentration in alfalfa but had no effect on Fe or aluminum (Al) accumulation (Smith 1975). An increase in Mn content was detected in burley tobacco leaf when K applications were increased (Leggett et al. 1977). When high levels of P and k were applied, total Mn accumulation was nearly tripled in corn plants (Stukenholtz et al. 1966). K application also caused an increase in copper (Cu) content in bent-grass (Waddington et al. 1971), and amplified K and Cu concentrations in blue-joint grass but only when P was present (Laughlin 1969). Responses to additional K applications have included higher forage yield and DM production, accompanied by higher Cu concentrations.

13.3 Conclusions

The need to improve fertilizer use efficiently (to achieve a higher NUE), especially when it comes to N fertilizers, is greater than ever before. The constant increasing demand for food is resulting in greater N fertilizer usage, yet this is having a negative impact on the environment. Balanced fertilization can reduce excess N usage, which results in N cascading into the environment. For example: without sufficient K levels, NO_3 will accumulate in the roots, then further NO_3 uptake will be stopped by a feedback mechanism in the root cells. As a result, NO_3 stays in the soil and can be lost to the atmosphere as N gas or nitrous oxide, a greenhouse gas. Adequate supply of K not only increases yields but also increases N concentrations in the crop, resulting in smaller quantities of NO_3 left in the soil at harvest. When residual N is lower, contamination groundwater potential risk is decreased. Sufficient K soil reserves are therefore crucial for achieving an optimal response to N and increasing maximum N use efficiency. Where K reserves have been exhausted due to lack of K applications, applying larger N amounts is not economically viable and will leave a large amount of nitrate that risks being lost by leaching, and damaging the environment.

To conclude, improving NUE by supplying enough K can be beneficial in several aspects:

- Fertilizer dose reduction (especially N) is more economical for farmers.
- Obtain higher yield potentials due to synergistic nutrient interactions.
- Increase plant tolerance to damage caused by pests and diseases and possibly increase resilience to drought.
- Positively influence crop quality and biochemical components of the final product, e.g. proteins, oil, fatty acids, etc.
- Reduce the amount of residual nutrients left in the soil after harvest, consequently reducing the potential for environmental damage caused by leaching and emissions of greenhouse gases.

Further research should be carried out on genetic improvements (breeding, genetic engineering) to improve crop NUE, estimating crop K requirements based on location and crops physiology, and using modern tools to study K interactions with other nutrients.

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