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Potassium in Agriculture

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SUMMARY:

Potassium (K) is an essential plant nutrient and plays a crucial role in many physiological processes vital to growth, production, quality, and stress resistance in all crops. Most of the K in the soil is not available for plant uptake. The element is generally classified into four groups according to its availability: water-soluble, exchangeable, non-exchangeable, and structural forms. Water-soluble K is directly available to plants and microbes and potentially subject to leaching. Exchangeable K is electrostatically bound to the surfaces of clay minerals and humic substances. These two fractions are considered readily available to crops. However, the size of both *pools* is very small. The non-exchangeable and structural forms are considered slow-release or unavailable sources of K to plants. A chemical analysis of the soil is essential for recommending potassium fertilization. K plays the following roles in plants: enzyme activation, protein synthesis, photosynthesis, osmoregulation, phloem transport, energy transfer, and cation-anion balance. Developing plants that are more efficient in terms of mineral nutrition with K is crucial for the development of low-input agriculture, minimizing potassium fertilizer costs, and achieving sustainability. This paper aims to describe the dynamics of K in agriculture, with an emphasis on cotton, peanuts, sesame, castor oil, and sisal.

Keywords: Cotton. Peanut. Sesame. Castor oil plant. Sisal

ABSTRACT:

Potassium (K) is an essential plant nutrient and plays a crucial role in many physiological processes vital to growth, production, quality, and stress resistance in all crops. Most of the K in the soil is not available for plant uptake. The element is generally classified into four groups according to its availability: water-soluble, exchangeable, non-exchangeable, and structural forms. Water-soluble K is directly available to plants and microbes and potentially subject to leaching. Exchangeable K is electrostatically bound to the surfaces of clay minerals and humic substances. These two fractions are considered readily available to crops. However, the size of both pools is very small. The non-exchangeable and structural forms are considered slow-release or unavailable K sources for plants. A chemical analysis of the soil is essential for recommending potassium fertilization. K plays the following roles in plants: enzyme activation, protein synthesis, photosynthesis, osmoregulation, phloem transport, energy transfer, and cation-anion balance. Developing plants that are more efficient in terms of K mineral nutrition is crucial for the development of low-input agriculture, minimizing potassium fertilizer costs, and achieving sustainability. This paper aims to describe the dynamics of K in agriculture, with an emphasis on cotton, peanuts, sesame, beaver beans, and sisal.

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1. INTRODUCTION

Since the 1960s, the world population has almost tripled, from three to more than eight billion people, and this trend will continue in the coming decades. Because of this rapid expansion, a massive increase in the production of food, fiber and energy, to meet the demands of future generations and, at the same time, preserve ecological and energy resources of our planet. Additionally, climate models Current data predict that the incidence and duration of drought and heat stress periods are increasing in many regions, negatively affecting our main agricultural crops and, thus, our food security. Therefore, the main challenges for agriculture are increase crop productivity with more efficient production systems in terms of resources and stabilize development and productivity under conditions of biotic stresses and abiotic (Janni et al., 2024). In this context, among the essential nutrients for plants, potassium (K) plays a crucial role in many physiological processes vital for growth, production, quality and resistance to stress in all crops.

OK constitutes about 2.1% to 2.3% of the Earth's crust, being the seventh or eighth most abundant element. Thus, K reserves in the soil are generally large. However, K is considered unavailable in many agricultural areas around the world, including ¾ of the rice-growing land in China and ÿ of the wheat belt in South Australia (Römheld and Kirkby, 2010). Soils that are naturally poor in K are sandy soils, flooded, saline or acidic. Furthermore, in intensive agricultural production systems, K becomes a limiting nutrient, particularly in those that are coarse-textured or organic. In many cases, when low rates of potassium fertilizers are applied in the context of a unbalanced fertilization can result in significant depletion of K reserves available in the soil and, therefore, in decreasing fertility (Zörb et al., 2014). In relation to fertilizers containing nitrogen (N) and phosphorus (P), potassium is applied at a rate much lower, and less than 50% of the K removed by crops is replaced by fertilization (Shao and He, 2010).

2 THEORETICAL FRAMEWORK

2.1 POTASSIUM IN SOIL

Since mineral soils contain between 0.04% and 3.00% total K, the content of this element in the 0 cm to 20 cm depth layer of most agricultural soils generally ranges from 10 g kg^{-1} to 20 g kg^{-1} . However, most of the K in the soil (90% to 98%) is incorporated

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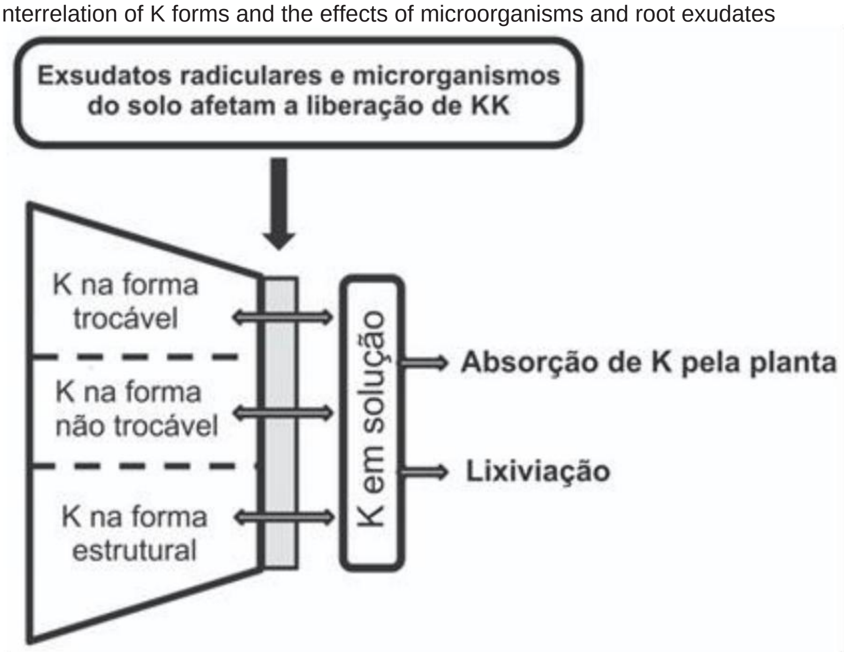
to the crystal structure of metals and thus not directly available for absorption by plant. K availability differs greatly between different soil types and is affected by its physicochemical properties. Simplifying the complex dynamics of K in soil, the element is generally classified into four groups according to its availability to plants: water-soluble, exchangeable, non-exchangeable and structural forms (Figure 1).

Water-soluble OK is directly available to plants and microbes, and potentially subject to leaching. Exchangeable OK is electrostatically bound, like a complex of external spheres, to the surfaces of clay minerals and humic substances. These two fractions are often considered readily available to crops. However, the size of both *pools* is very small. Together, they make up only about 0.1% to 0.2% and 1.0% to 2.0%, respectively, of the total K in the soil. The non-exchangeable and structural are considered slow or unavailable K sources for plants. However, these *"pools"* can also contribute significantly to the supply of plants in the long term. The amounts of K in the soil, available and unavailable to plants, vary greatly between soil types and the dynamic equilibrium reactions that exist between the different *"pools"* of this element. Thus, the physical and chemical properties of the soil, plant-soil interactions and biological activity affect K fixation and release (Zörb et al., 2014).

Figure 1 - Interrelation of K forms and the effects of microorganisms and root exudates



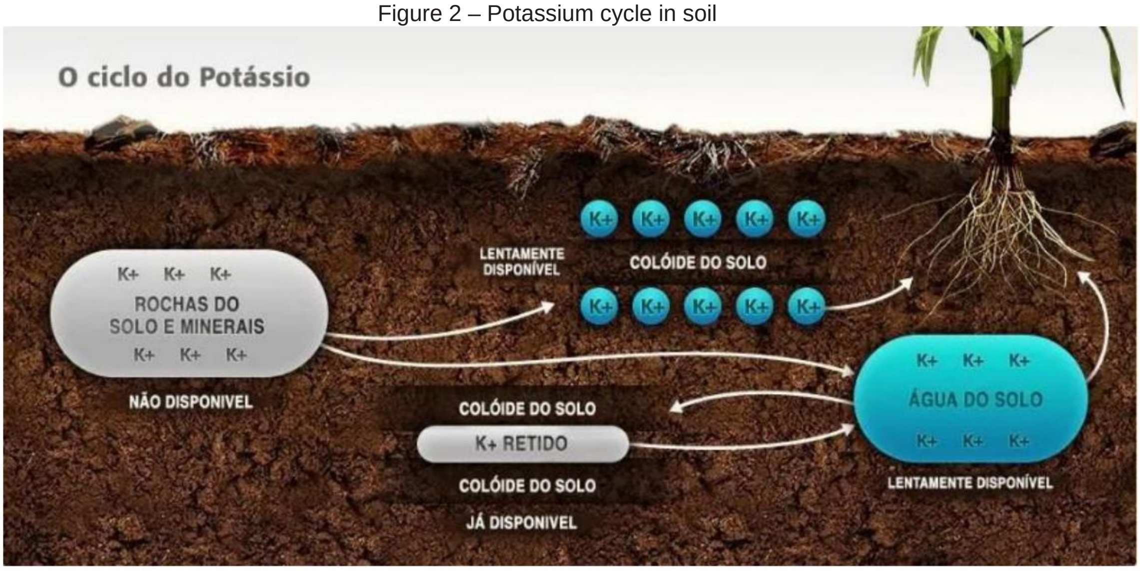
Source: Zörb et al. (2014)
Layout: Sérgio Cobel da Silva

Most of the K in soil is in structural form, composed primarily of primary minerals containing the element, such as muscovite, biotite, and feldspars. The feldspars can release K directly into the soil solution, while the K contained between the mica layers are held firmly together by electrostatic forces. Weathering of feldspars and micas from soil parent materials produce minerals secondary elements that represent the potential source of K available to plants. OK in micas trioctahedral (such as biotite and phlogopite) is the most easily released by weathering. This Thus, the application of biotite to K-deficient soils can increase the content of this nutrient available to plants (Öborn et al., 2005).

The formation of 2:1 dioctahedral expandable minerals from biotite is a form to increase the amount of K in the soil solution. However, the weathering of minerals K-containing primary sources is very slow. Therefore, applying only biotite as a K source can be detrimental plant growth, especially when compared to soluble fertilizers. However, the addition of potassium rock powder (primary minerals containing K) can increase long-term soil fertility in relation to potassium, as it increases the K deposited in the system. Plant species effective in K uptake and microbial populations solubilizers of this element may be two other key factors controlling the release of K from soil minerals (Zörb et al., 2014).

Figure 2 below illustrates the K cycle in soil.

Figure 2 – Potassium cycle in soil



Source: Duarte (2024)

Some soil microorganisms (e.g., Pseudomonas spp., Burkholderia spp., Acidothiobacillicus ferrooxidans, Bacillus mucilaginosus, Bacillus edaphicus, Bacillus

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megaterium) are capable of releasing K from the minerals that contain them by excreting acids organic acids. These acids directly dissolve K from the rock (primary K-containing minerals) or chelate the silicon ions of the primary mineral to bring the K into solution. Therefore, inoculation of K-solubilizing microorganisms together with the application of rock dust potassium to the soil have recently gained much attention. The exudates of these microorganisms can effectively increase the release of K from clay minerals. The application to the soil of micas and/or feldspars inoculated with solubilizing microorganisms K can increase the solubility of the element in the solution as well as its absorption by the roots of plants (Sharma et al., 2024).

The use of non-exchangeable K sources is an important factor for the efficiency of nutrient uptake by plants. Plant species or genotypes within species differ among themselves in relation to their ability to use these sources. The difference between cultures in potassium absorption is generally attributed not only to absorption efficiency but also to the mobilization of non-exchangeable K by root exudates. The main compounds released are organic acids such as citric, oxalic, tartaric and malic acids. Also, amino acids found in root exudates increase the release of K from minerals of clay. When K depletion in the rhizosphere falls below a threshold level (10µM – 20µM), a key signal occurs to activate the molecular mechanisms that culminate in the production of root exudates (Schneider et al., 2013).

Organic acids are known to facilitate the weathering of soil minerals through the formation of metal-organic compound complexes and by increasing the exchange of H^+ by K^+. A better understanding of the mechanisms involved in the release of K from minerals in the soil is key to developing new approaches to sustainable agriculture.
However, the origin of K absorbed by crops and the contribution of non-exchangeable K are extremely difficult to estimate due to the lack of suitable methods under conditions of field or even in laboratory experiments. But we can conclude that crops have differences between them in the transformation of non-exchangeable K into soluble forms. Thus, in areas where K is limited, the selection of species and varieties that are efficient in solubilizing K via exudates has great potential to increase the efficiency of this nutrient use (Zörb et al., 2014).

In addition to releasing K, soil minerals can also fix it, affecting significantly increase its availability. Fixation is related to the adsorption of K^+ ions in intermediate layers between weathered silicate layers, such as illite and vermiculite. The degree of K fixation in soils depends on the type of clay mineral and its bulk density.

charges, soil moisture, competition between ions and soil pH. Montmorillonite, weathered mica vermiculite are the main clay minerals that tend to fix the K. In addition, soil moistening and drying also significantly affect fixation. of K, by expanding and contracting, respectively, the clays. The process of fixing this element is relatively fast, whereas the release of fixed K is very slow due to the strong force binding between K and clay minerals. The fixation or release of this nutrient in the soil is highly dependent on the concentration of K in the solution. In addition to organic acids, concentration of H+ in soil solution (via soil pH) appears to play a key role in the release of K from clay minerals. Therefore, optimizing soil pH can be a way to increase K release. To optimize fertilizer management practices potassium, it is crucial to understand the factors that regulate the release of K from the non-exchangeable *pool* soil (Portela et al., 2019).

There is no doubt about K's ability to impact soil structure as well as increase water retention. The application of potassium mineral fertilizers improves structural stability of sandy soils in particular. This effect is due to an increase in concentration of electrolytes in the soil solution, causing flocculation and precipitation of salts crystallized. Also, a higher concentration of K in the soil solution can cause a increase in microshear strength, which may explain the change in retention of water. However, Mg2+ and Ca2+ are more effective cations for stabilizing soil structure, since the flocculating powers of K+, Mg2+ and Ca2+ are, respectively, 1.7, 27.0 and 43.0, respectively. Greater water retention means a guarantee of soil productivity in areas with water limitations. Therefore, more information is needed to understand the effect of K fertilization on the physical properties and water retention capacity of the soil (Raghavendra et al., 2021).

2.2 POTASSIUM FERTILIZATION

In agricultural production, fertilization is done not only to ensure, but also to sustain an adequate supply of soluble K to crops. However, the rates and periods of application of organic and inorganic fertilizers are often based on the optimum supply of N and not in the requirements of K. This can lead to an excess or a decrease in K, depending on the crop and soil characteristics (Xu et al., 2020).

Therefore, monitoring soil K reserves is extremely important for make potassium fertilization recommendations accurate.

For potassium fertilization recommendations, chemical analysis of the soil is essential, the sampling process is of great importance, as it must guarantee representativeness of the general condition of K of the area. An error in this process can compromise the following steps to define the amounts of fertilizer applied to the crop. The sampling depth, for most cultivated plants, it should be at least 0 to 20 cm. In the cultivation of fruit and forestry, the 20 to 40 cm deep layer should also be sampled. The The area to be sampled must be divided into strata, plots or blocks of no more than 10 hectares, homogeneous in relation to the following aspects: color, topography, texture, drainage, degree of erosion, type of vegetation or previous crop, history of use, management and productivity agricultural. For each homogeneous plot and depth, a sample must be formed composite (Figure 3), consisting of simple samples collected separately, walking randomly in a zigzag pattern (Figure 4). Afterwards, they must be mixed to form the composite sample, which will be sent to the laboratory. The number of simple samples does not must be less than 10 points per homogeneous plot. It is worth remembering that the higher the number of simple samples, the greater the representativeness of the composite sample (Borges and Accioly, 2020).

Figure 3 – Division of the heterogeneous area into three homogeneous plots

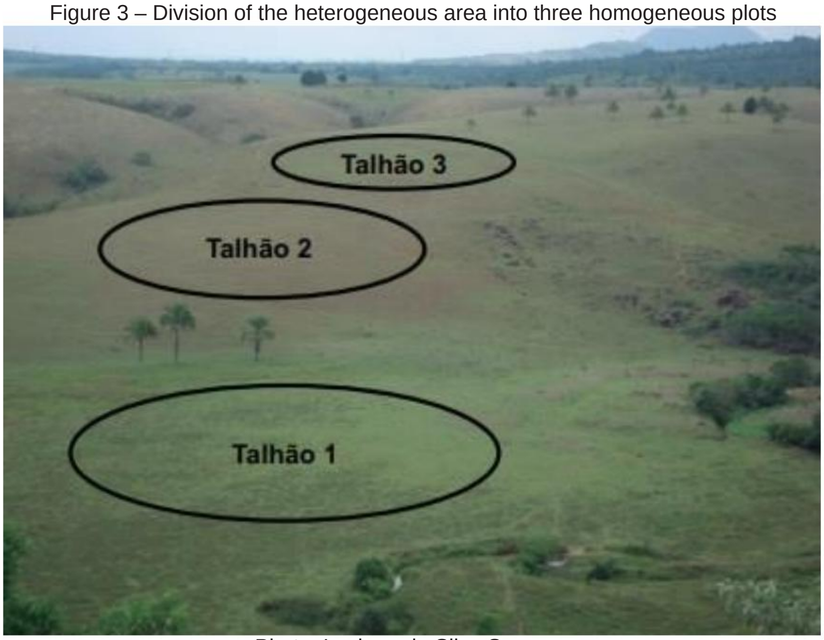

Photo: Luciano da Silva Souza

Source: Borges and Accioly (2020)

Figure 4 – Collection of simple zigzag samples in two homogeneous plots

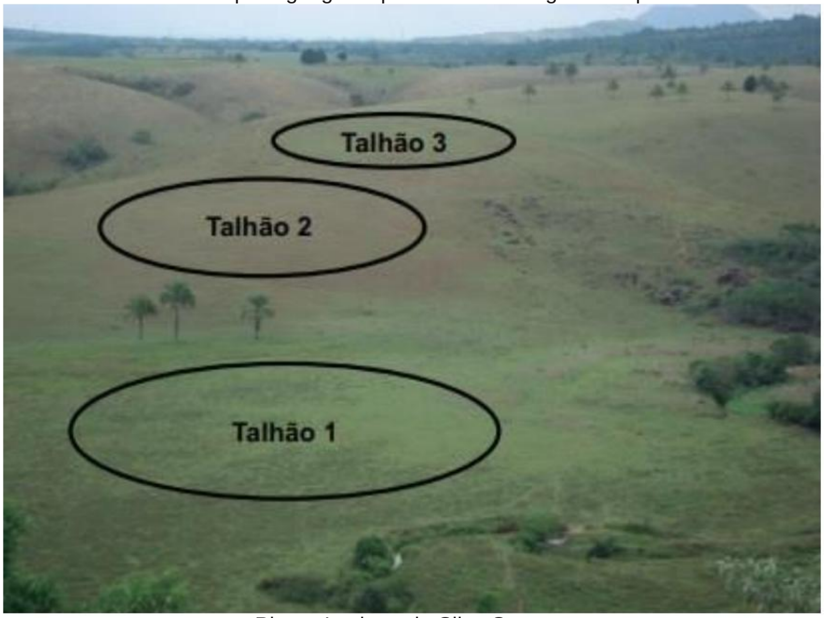

Photo: Luciano da Silva Souza

Source: Borges and Accioly (2020)

The precision and accuracy of sampling must be such that subsequently, we can say, with as little doubt as possible, how much potassium fertilizer is necessary to apply.

> Simple soil extraction methods for measuring exchangeable K are widely used to estimate a crop's potassium fertilizer demand. Estimating soil exchangeable K with ammonium acetate, ammonium chloride, calcium chloride, or ammonium fluoride (Mehlich 3) from air- or oven-dried soil samples is the most widely used soil test for K and provides the basis for most potassium fertilizer recommendations worldwide (Zörb et al., 2014).
>
> In this case, the preparation procedure involves drying soil samples at a maximum of 40° C and grinding them to pass through a 2 mm sieve to provide a homogeneous mixture for analysis. However, it is widely recognized that drying soil samples can influence the amount of K extracted by traditional extractors. Extractable K may increase after drying (Zebec et al., 2017).

Also, it is postulated that soils with high exchangeable K contents tend to fix the element and soils with low exchangeable K levels tend to release it after drying (Steiner et al., 2015). The impact of sample drying on K extracted by tests that estimate exchangeable K depends on the change in the concentration of the element in equilibrium at the time of sampling and soil mineralogy. Illite-rich soils tend to release K during drying while soils rich in vermiculite and montmorillonite tend to fix it (Zörb et al., 2014).

Another method of K extraction, called the wet extraction method (extraction with ammonium acetate in wet field soils), presents a better correlation between the production and K absorbed by the crop than methods of extracting K from dry soils

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air. Wet extraction K tests have a superior ability to predict responses of crops to potassium fertilization when compared to the commonly used extraction method dry. However, few laboratories have adopted wet extraction methods due to the impractical procedures, such as sifting wet soils (Barbagelata and Mallarino, 2012).

The extraction methods discussed above provide sufficient information to Fertilization recommendations for light-textured soils that do not contain clay minerals type 2:1. In soils containing these minerals, however, the non-exchangeable K *pool* generally contributes largely, sometimes more than 50%, to the K supply to crops (Mengel and Kirkby, 2001).

The measure of plant-available soil K that is released from non-exchangeable reserves, is very difficult due to the complexity of the dynamic balance between the various forms of element during the plant cycle. Therefore, there are no routine methods available for to measure this variable. However, several methods have been established to evaluate K in soil slowly or potentially available. For example: extraction with 1 M HCl, boiling in HNO_3 0.5 M or 1.0 M, electroultrafiltration, exchange resins, Jackson test (tetraphenylborate sodium, NaTPB) and field balances (Zörb et al., 2014).

However, common acid extraction methods remove only a proportion of K reserves in the non-exchangeable *pool* . In light-textured soils, boiling the soil with 0.5 M HNO_3 better predicts the K available for uptake by plant roots than other acid extraction methods. On the other hand, boiling with 1.0 M HNO_3 extracts more K than than that available to crops (Øgaard and Krogstad, 2005).

Potassium fertilizers are formed from saline geological deposits, being materials with a high concentration of K_2O, soluble in water and fast acting (Reetz, 2017).

- Potassium chloride (KCl) or muriate of potash (MOP): Most deposits of K occurs as KCl (sylvite) or mixed with NaCl (halite) in the mineral sylvinite, usually in ancient marine deposits buried deep below the Earth's surface. In processing, the mineral is ground and KCl plus NaCl are separated. KCl has 60% to 63% K_2O (50% to 52% K and 45% to 47% Cl). It is usually broadcast on the surface before plowing, or applied in furrows, close to the seed line. Because of the high salt content, KCl should not be placed in direct contact with the seed. It dissolves readily in the soil solution releasing K^+ and Cl^- . K^+ binds to the cation exchange sites of clays and organic matter. Most KCl fertilizer is white, but some materials may be reddish due to the presence of small amounts of iron oxide; but both are identical for agricultural use. Pure forms of KCl can be dissolved for use as fluid fertilizer or application in irrigation water.

- Potassium sulfate (K_2SO_4) or sulfate of potash (SOP): Has 48% to 53% K_2O and 17% to 18% S. Potassium sulfate is found in mineral deposits mixed with other substances. The components are separated by washing with water. OK of sulfate potassium works similarly to KCl, but is also an important source of sulfur where the soil is deficient in this nutrient. Potassium sulfate is less soluble than chloride of potassium. Therefore, it is not commonly used in irrigation water. But potassium sulfate Potassium is sometimes applied as a foliar spray if both K and S are needed. It is also used to supply K to Cl-sensitive plants.

- Potassium and magnesium sulfate ($K_2SO_4.2MgSO_4$): It is also called langbeinite, potassium sulfate and magnesia or commercially sulpomag. Langbeinite is a mineral found in few places in the world. It comes from underground mines near Carlsbad (Germany) and New Mexico (USA). Langbeinite has 21% to 22% K_2O, 10% to 11% Mg, and 21% to 22% S. It is a popular fertilizer where all three nutrients are needed. It is soluble in water, but dissolves slowly, unlike other fertilizers containing Mg and S. It has a neutral effect on soil pH.

- Potassium nitrate (KNO_3) or potassium saltpeter: It is a popular fertilizer for high-value crops that require N in the form of nitrate and also K. It is especially popular as a source of K for crops that are sensitive to Cl. It has 13% N and 44% to 46% K_2O. It can be applied to the soil or as a foliar treatment to stimulate fruit development when root activity is declining. It is also a common source of nutrients. for fertigation.

- Various industrial wastes containing K (e.g., filter dust) have been developed for use as slow-acting forms, especially where it is desired to avoid losses by leaching.

Potassium fertilizers should generally be applied at planting time. K^+ ions are adsorbed in the soil, remaining available and largely protected from leaching. However, splitting applications is recommended for some crops in soils and climates where high rates of leaching losses are expected.
Some immobilization within the structural layers of certain clays reduces availability, but strong fixation of completely unavailable forms is restricted to a few special soil types. The utilization rate of K in fertilizers is about 50% to 60% (Reetz, 2017).

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2.3 POTASSIUM IN PLANTS

K concentrations in plants vary widely with location, year, species planted and the type of fertilizer used. They are found in a range from 0.4% to 4.3% (Askegaard et al., 2004). The concentration of K in the cytoplasm is kept relatively constant in the range of 50 mM to 150 mM, while the concentration in the vacuole varies widely from according to the *"status"* of the plant in K. Together with the accompanying anions (NO_3^-, Cl^-, malate, citrate), vacuolar K largely determines the osmotic potential of cell sap. High K concentrations in crops have often been linked to "luxury consumption". However, as will be seen, the accumulation of K by crops during growth plant can be considered as a "security strategy" to enable it to survive better during sudden environmental stress (Zörb et al., 2014).

Plant species differ in their requirements for K and in their abilities to absorb this element. Differences in K absorption among different plant species are attributed to variations in root structure, such as root density, depth of rooting and root hair length. There are positive correlations between K absorption efficiency and length of root hairs or root systems more dense. These two morphological variables can deplete K in larger volumes of solution from the soil, and this depletion can initiate the release of non-exchangeable K (Shin, 2014).

OK performs the following functions in the plant (Rengel et al., 2023):

> Enzyme Activation: K^+ is considered essential for the functioning of more than 50 enzymes, acting as a cofactor or allosteric effector. Enzymes such as synthetases and kinases depend on K^+ for their normal activity. K^+ is related to changes in the conformation of molecules, which increases the exposure of active sites for substrate binding. In general, K^+-induced conformational changes in enzymes they increase the rate of catalytic reactions (Vmax) and/or the affinity for the substrate (Km).
> Protein Synthesis: OK is critical for the structure and function of ribosomes. Ribosomal RNA (rRNA), which catalyzes and regulates protein synthesis, depends on metal ions, including K, for its proper function. Declines in cytosolic K concentration due to K deficiency in the soil can significantly inhibit protein synthesis. In green leaves, the chloroplast contains about half of all RNA and protein in the cell. In C3 species, the majority of chloroplast proteins are rubisco. Consequently, the synthesis of this enzyme is particularly impaired under K deficiency, responding rapidly to its restoration. Under K deficiency, plant tissues accumulate soluble nitrogen compounds (amino acids, amides, and nitrate).
>
> Photosynthesis: K influences photosynthesis anatomically, physiologically, and biochemically. It plays a fundamental role in CO_2 conductance in the mesophyll, chloroplast structure, Rubisco activity, and the transport of photoassimilates via the phloem. The effect of K on CO_2 fixation was initially demonstrated in isolated chloroplasts, where an increase in the external concentration of this element to 100 mM stimulated CO_2 fixation threefold. Under illumination, additional K influx from the cytosol is required to maintain a high pH in the stroma, necessary for optimal Rubisco activity.

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As the main inorganic osmolyte of the cell, K is critical for regulating guard cell turgor and, thus, for stomatal movement and CO_2 diffusion .
K deficiency often results in decreased stomatal conductance, which can negatively impact photosynthesis. These changes are commonly associated with changes in leaf anatomy, such as decreased leaf thickness, smaller mesophyll cells, and reduced internal leaf air space.

Photorespiration decreases in response to K deficiency. This may be due to CO_2 depletion at the catalytic sites of Rubisco. Conversely, dark respiration increases under K deficiency, which may reflect greater substrate (sugar) availability.

Photosynthetic activity is influenced by the transport and utilization of photoassimilates. Increased sucrose accumulation in the leaves of K-deficient plants may exert negative *feedback* on CO_2 assimilation by limiting its uptake by mesophyll cells and decreasing rubisco activity.

The increase in atmospheric CO_2 content improves the photosynthetic activity of plants, especially C_3 plants. However, when plants suffer from K deficiency, the expected positive impact on the increase in atmospheric CO_2 is significantly impaired.

Osmoregulation: A high osmotic potential in the root stele is a prerequisite for solute transport driven by turgor pressure in the xylem and for plant water balance, with K being a fundamental element in these processes.
- Cell Extension: Cell extension involves the formation of a large central vacuole occupying between 80% and 90% of the cell volume. There are three main requirements for cell extension: (1) cell extensibility (reorganization or loosening of the cell wall), (2) synthesis and deposition of newly formed cell wall components,
formed) and (3) accumulation of solutes to create the internal osmotic potential necessary for turgor pressure. In most cases, cell extension is due to the accumulation of K in the cells, which is required to stabilize the pH in the apoplast and cytoplasm and to lower the osmotic potential in the vacuoles. A decrease in apoplastic pH is necessary to activate the enzymes involved in cell wall loosening.

Cell extension in leaves and roots is positively correlated with K content. K deficiency reduces turgor, cell size, and leaf area. Furthermore, a reduced rate of leaf expansion is a highly sensitive indicator of K deficiency in crop plants. Sugars and other low-molecular-weight organic solutes also contribute to osmotic potential and turgor-driven cell expansion. However, this contribution depends on the plant's K nutritional status. After cell expansion is complete, K^+ can be replaced, to maintain turgor in the vacuoles, by other solutes such as Na^+ or reducing sugars.
- Stomatal Movement: In most plant species, K^+ and yours
Accompanying counterions play a key role in guard cell turgor changes during stomatal opening and closing. An increase in guard cell K concentration results in a decrease in osmotic potential and, thus, in the water uptake of adjacent cells, resulting in an increase in guard cell turgor and, consequently, in stomatal opening.

Stomatal closure is induced by darkness, plant dehydration, and the phytohormone ABA, and is associated with the rapid efflux of K and its accompanying anions from the guard cells. Unlike stomatal opening, which is driven by active transport, stomatal closure is due to the release of solutes along a concentration gradient. Stomatal closure is associated with a sharp increase in K and Cl concentrations in the apoplast of the guard cells.

- Photonastic and Seismonastic Movements: In the leaves of many plants, particularly in Fabaceae, leaves reorient their lamina photonastically in response to a light signal, either nondirectional (circadian rhythm; e.g., leaf blades folding in the dark and unfolding in the light) or directional (e.g., reorienting toward a light source). These photonastic responses increase light interception or prevent damage from excess light.

Leaf and leaflet movements are caused by reversible changes in the turgor of specialized tissues (motor organs or pulvini). Turgor changes cause shrinkage and swelling in the cells (extensor and flexor, respectively) of the motor organ. The main solutes involved in osmoregulation are K^+, Cl^-, and malate, inducing water flow across the plasma membrane, particularly through aquaporins, followed by volume change and leaflet movement. The principles of the mechanism responsible for stomatal movement also apply to movement in leaves and leaflets.

Although similar mechanisms are responsible for the movement of leaves and other plant parts in response to light and mechanical stimuli, there are differences in the speed of response to seismic signals. In *Mimosa pudica,* leaflets fold in a few seconds and reopen after about 30 minutes. This turgor-regulated response is correlated with the redistribution of K within the motor organ and the sudden release of sucrose from the phloem. In seismic reactions, there is also rapid long-distance transport of the "signal" from the touched leaflet to other leaflets. This "signal" is an action potential, which is carried in the phloem to the motor organs at a high velocity, inducing the discharge of sucrose from the phloem to the motor organ.

Phloem Transport: K plays important roles in sucrose loading and the rate of mass-flow-driven solute transport in the phloem sieve tubes. These K functions are related to (1) the need to maintain a high pH in the sieve tubes for sucrose loading and (2) K's contribution to the osmotic potential in the sieve tubes and, therefore, to the rate of photoassimilate transport from source to sink. The role of K in phloem loading and photoassimilate partitioning is evident by comparing the relative distribution of carbohydrates between the shoots and roots of K-sufficient and K-deficient plants. Photoassimilate transport to the roots is greatly reduced in K-deficient plants.

Reduced transport of assimilates to sinks results in reduced root growth in K-deficient plants. Compared to K-deficient plants, root nodules of legumes with adequate K supply have more sugars, which increases their rate of N_2 fixation and the export of nitrogen compounds.

Phloem amino acid transport is affected by both sucrose loading and osmotic pressure (mass flow) in the sieve tubes. Therefore, any impairment in sucrose loading or phloem mass flow due to K deficiency causes a corresponding decline in phloem amino acid transport. Thus, one of the positive effects of adequate potassium nutrition on plants is an increase in seed protein content, which is related to increased amino acid transport.

Energy Transfer: In addition to its role in the transport of assimilates, K circulation in the phloem can serve as a decentralized energy store that can be used in a specific location in the plant where it is needed, such as in a shaded area. In this case, K is uptaken and subsequently released into the phloem, followed by loading and unloading under energy-limiting conditions.

Cation-Anion Balance: K plays a fundamental role in the balance of anion charges in various organelles such as chloroplasts and vacuoles, as well as in xylem and phloem. The role of K^+ in the cation-anion balance is important in nitrate metabolism (NO_3^-), where K^+ is often the dominant counterion to this anion in long-distance transport in the xylem, as well as for its storage in the vacuoles. As NO_3^- is reduced in the leaves, K^+ remaining requires the stoichiometric synthesis of organic acid anions for charge balance; thus, K^+ and malate can be transported to the roots for subsequent utilization of K^+ as a counterion to NO_3^- for transport through the xylem. In nodulated legumes, this recirculation of K^+ may have a similar function in the transport of amino acids in the xylem.

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2.4 SYMPTOMS OF POTASSIUM DEFICIENCY

Figure 5 below shows symptoms of K deficiency in corn.

Figure 5 – Symptoms of potassium (K) deficiency in corn plants: detail of tip and margin necrosis of older leaves

Photos: Magna Maria Macedo Nunes Costa
Source: Adapted from Ferreira (2012)

Symptoms of K deficiency in corn begin to appear when the plants are still are young and occur initially in older leaves because K is an easily absorbed nutrient mobile in the phloem (Ferreira, 2012). The characteristic symptom is a necrosis that appears in the leaf tips evolving downwards, at the edges of the blade (Figure 5). As at the tips and edges of the leaf blade are the ends of the xylem vessels, the deficient plant in K there will be a lack of this element in this part of the leaf, preventing K from performing normally its functions such as enzyme activation, protein synthesis, photosynthesis and osmoregulation, becoming dry (dead). This necrosis can progress to the central vein.

Figure 6 below shows symptoms of K deficiency in cowpea.

Figure 6 – Symptoms of potassium (K) deficiency in cowpea plants: brown spots spread throughout the leaf blade

Photos: Magna Maria Macedo Nunes Costa

Symptoms of K deficiency in cowpea initially occur in the younger leaves. old because K is a nutrient that is easily mobile in the phloem (Ferreira, 2012). The symptom characteristic are brown spots that spread throughout the leaf blade. As as the leaves age, these spots evolve into necrosis. These symptoms are related with the functions already discussed that K performs in plants – enzyme activation, synthesis of proteins, osmoregulation, phloem transport, energy transfer and cation-balance anion.

Figure 7 below shows symptoms of K deficiency in sweet sorghum.

Figure 7 – Symptoms of potassium (K) deficiency in sweet sorghum leaves. Dark reddish spots and rectilinear necrosis.

Photos: Oscar Fontão de Lima Filho

Source: Lima Filho (2014)

Initially, on older leaves, there is the occurrence of dark reddish spots and rectilinear necrosis along the secondary veins and edges, starting from the ends to the main vein, in addition to drying of the leaf tip. It also occurs, partial curling of the edge towards the center in the upper third of the sheet and stoppage of the growth of the internodes, giving the plant the appearance of a fan, with the leaf sheaths overlapping (Figure 7).

In Figure 8, the symptoms of K deficiency in jatropha can be seen.

Figure 8 – Symptoms of potassium (K) deficiency in jatropha plants. Spots and pits, initially chlorotic and then necrotic, starting on the margins of older leaves.

Photos: Oscar Fontão de Lima Filho

Source: Lima Filho (2014)

Symptoms of K deficiency in Jatropha curcas initially occur in the younger leaves. old because K is a nutrient that is easily mobile in the phloem (Ferreira, 2012). Symptoms Characteristic are spots and punctuations, initially chlorotic and then necrotic (Figure 8). Subsequently, wilting may occur (Lima Filho, 2020).

Figure 9 below shows symptoms of K deficiency in cotton (Borin et al., 2013).

Figure 9 – Symptoms of potassium (K) deficiency in cotton plants. Photo on the left: Evolution of potassium deficiency symptoms in cotton leaves (from left to right). Photo on the right: Traditional symptom of potassium deficiency in older leaves of the cotton plant.

Photos: Gilvan Barbosa Ferreira

Source: Adapted from Borin et al. (2013)

2.5 SYMPTOMS OF EXCESS POTASSIUM

Although cultivated plants have a luxury consumption of potassium (Kaminski et al., 2007), there is no characteristic symptom of excess of this nutrient.

> Sometimes, symptoms of excess potassium are confused with damage caused by soil salinity due to the solubility of potassium fertilizers. High levels of potassium in the soil can induce symptoms of calcium and magnesium deficiency in plants (Mengel and Kirkby, 2001).

2.6 EFFECT OF POTASSIUM ON COTTON, PEANUT, AND VEGETABLE CROPS SESAME, CASTOR BEAN AND SISAL

Cotton *(Gossypium hirsutum* L.) is the most important crop in the international *commodities market.* The performance of the 2023/2024 cotton harvest, with a harvest of over 3.7 million tons, elevated Brazil to the position of world's largest producer. The country also officially became, for the first time in history, the world's largest cotton exporter, surpassing the United States (Silva, 2024).

This result was achieved thanks to research and innovations in the areas of improvement genetic, biological control, biotechnology, agricultural mechanization, plant health and systems production, enabling the increase in cotton productivity at the small, medium and large cotton growers in Brazil.

Fertilization is one of the most important steps in the production system. Plants that are well-nourished, both quantitatively and proportionally, have a greater potential to withstand biotic and abiotic stresses. N is the second most-required nutrient in cotton crops, behind only N. It is essential for ensuring high yields, good fiber quality, and resistance to pests and diseases.
Participating in various functions in plants, such as enzyme activation, protein synthesis, phloem transport, and osmoregulation, K is crucial for mitigating biotic and abiotic stresses. In environments where there is water stress, K helps cotton plants reduce water loss through transpiration. This is particularly important in semiarid regions, where cotton is often grown. K increases cellulose deposition in the inner fiber walls, improving the Micronaire index, a key indicator of fiber size, strength, and quality. It also has a positive effect on fiber uniformity, increasing its commercial value in the textile industry, which requires high-quality raw materials.

Therefore, it is important that cotton farmers prioritize potassium fertilization (Borin et al., 2013).
Cotton is a very responsive crop to K in terms of productivity and fiber quality, especially under adequate soil moisture, high temperatures, and high light intensity. Despite this, it has a relatively low daily water consumption rate (approximately 6.5 mm day-1). , in the (phase of greatest transpiration demand), even in hot climates with adequate soil water supply. In early varieties, water consumption during the growing season does not exceed 450 mm. In modern varieties, K deficiency is common at the end of the growing season, as it coincides with periods of lower rainfall. Since most of the K depends on water to be transported close to the roots, a nutrient deficiency can occur at the end of the plant's growing season (Oliveira et al., 2004).

In general, cotton does not stand out as a plant with high root density when compared to, for example, corn, soybeans, and peanuts. The K depletion rate in the rhizosphere is around 30% and generally does not exceed 5 to 10 mm from the root, a very short distance compared to other cultivated plants. The rate of K uptake by cotton roots depends on the density, length, and surface area of the roots, characteristics strongly influenced by the nutrient content in the medium and its interactions with soil structure, pH, and moisture. These factors become especially important during boll filling (Rosolem et al., 2003).

The cotton plant extracts K from the soil at rates of up to 5.6 kg ha-1 day-1 during the flowering and fruiting stages. For each kilogram of fiber produced, 0.13 kg of K must be absorbed, so a high-yielding cotton crop can extract more than 250 kg ha-1 of K from the soil. The cotton boll, including its husk, is the sink.

K deficiency in the plant. K deficiency causes losses in fiber production and quality. The plant has a shorter cycle, with earlier maturation and decreased fruit, fiber, and seed production. As the deficiency becomes more severe, there is a reduction in flower bud and fruit retention, in addition to premature leaf drop (Rosolem and Witacker, 2007).

A study was conducted by El-Gayed and Bashandy (2018) to study the response of cotton to soil and foliar K fertilization. The results showed that this nutrient increased plant height, the number of reproductive branches per plant, the number of flowers per plant, seed cotton yield, earliness, seed weight, and foliar contents of N, K, chlorophylls *a* and b, especially under adequate soil moisture conditions.

Sarhan and El Gayed (2022) demonstrated that cotton, when subjected to water stress, significantly reduces nutrient uptake, leaf pigment formation, vegetative growth, and variables related to cotton production. However, this negative effect can be offset by the application of K; that is, this nutrient increases cotton's drought tolerance, likely due to its effect on the continuation of stomatal opening when plants are subjected to this adverse condition.

The peanut *(Arachis hypogaea* L.) belongs to the Fabaceae family and is considered an important legume consumed worldwide due to its richness in calories, oils, proteins, and vitamins. It is native to South America and was cultivated by indigenous populations before the arrival of European colonizers. It is consumed *raw,* roasted, cooked, or processed. Its byproducts—oil, flour, and bran—are widely used due to their high protein content (Sousa and Ferrarezi Junior, 2022).

In Brazil, peanut productivity in the 2021/2022 harvest was 744 thousand tons, 24.6% more than in the previous harvest, with São Paulo as the state with the largest cultivated area, with 179 thousand hectares (CONAB, 2022).

One of the most important stages of the production system is fertilization. Well-fertilized plants nourished quantitatively and proportionally have greater potential to face stresses biotic and abiotic. OK is the second most required nutrient in quantity by the crop peanut, second only to N. Being important in stomatal conductance and transport of carbohydrates, when well supplied with K, peanut plants are more drought tolerant, use water more efficiently and are more productive.

In Brazil, according to Cordeiro et al. (2023), the K recommendation for runner peanuts is 116 kg haÿ1 , in soil with a low content of the element, but farmers apply 25 kg haÿ1 of K at planting and do not perform topdressing.

Peanuts remove a lot of K from the soil at harvest, resulting in depletion of this nutrient, which leads to the need to constantly renew potassium fertilization. Furthermore, in sandy soils, which are the most used for planting this crop, it occurs leaching, especially under irrigation or in areas with high rainfall.

According to Meneghette et al. (2017), fertilization and potassium nutrition of peanuts are debatable issues, since, despite the great capacity of this plant species to extract K from the soil, the responses to fertilization criteria applied to it cannot yet be generalized, mainly due to the great potential for utilization of previous fertilizations.

A study was carried out by Almeida et al. (2015) to evaluate the effect of K on the nutritional status and productivity of peanut grains. The treatments consisted of the application of 30, 60, 90 and 120 kg ha-1 of K_2O and a control (without

K) in the Runner. OK variety resulted in a significant increase in the number of leaves and height, K levels (50 - 70 g kg-1) and grain yield, obtaining 2,790 kg ha-[1] at a dose of 120 kg ha-1·

Another experiment was conducted by Zoz et al. (2018) to maximize peanut yield through potassium fertilization. Doses of 0, 30, and 60 kg ha-1 of K2O were tested at sowing of the Runner variety. K fertilization promoted increases of approximately 38% and 49%, respectively, in pod and grain yield.

Sesame *(Sesamum indicum* L.) is an annual herbaceous plant native to the African continent, belonging to the Pedaliaceae family. It is cultivated in approximately 71 countries, primarily in Asia and Africa. India and China account for 70% of the world's seed production of this oilseed, which is estimated at 3.6 million tons, grown on 7.5 million hectares, with an average productivity of 478.2 kg ha-1.

. Brazil produces around 16 thousand tons, produced on 25 thousand hectares and with a yield of around 650 kg ha-1 (Pontes et al., 2021).

OK is an essential element for the growth, development and quality of capsules in sesame plants. However, if applied in excess, it can interfere negatively in the absorption of Ca and Mg, making the plant deficient in these elements.

Arriel et al. (2007), the extraction of K from the soil by sesame depends on production, nutritional status, and the variety used. In general, the plant requires 60 kg ha-1 of K2O to produce 1,000 kg ha-1 of seeds. Of this total, the fruits can account for up to 60% of the K extracted. To ensure productivity in subsequent plantings, this amount must be replenished with potassium fertilization.

Sesame plants absorb little K until the thirtieth day after planting. From that date, the plant's requirement for this nutrient increases rapidly until the end of the cycle (Arriel et al., 2007).

Potassium fertilization can be done at the time of planting together with phosphate or in installments. twice as much as nitrogen, according to the soil's leaching capacity.

Anjos et al. (2024), studying the response of three sesame cultivars (BRS Anahí, BRS Morena and BRS Seda) to increasing doses of K2O (40, 60, 80 and 100 kg ha-1), found that doses of 60 to 80 kg ha-1 were those that provided the best results.

Castor bean *(Ricinus communis* L.) is a species belonging to the Euphorbiaceae family and is considered a toxic plant. Originally from Ethiopia, it has spread throughout the Middle East, India, and China. The main producing countries are India, Mozambique, China, Brazil, Myanmar, and Ethiopia, accounting for 97% of global cultivation. Castor bean has great potential for use in a variety of ecological conditions. Its cultivation is mostly for oil production (Ergun, 2022).

Castor bean nutrition and fertilization are crucial to the production process. While fertilizers are highly needed, fertilizer costs are high, making it increasingly necessary to optimize the use of these inputs to achieve higher yields at the lowest possible cost. With the expected productivity increases, it is possible to repay the technological investment financed with the crop and increase the producer's net income. Mineral fertilizer application at 120 kg ha-1

of phosphorus increases seed productivity by 62.5% (Sofiatti et al., 2010).

Mineral fertilization with 150 kg ha-1 of K2O significantly increased the weight of seeds per plant in the castor bean BRS Nordestina (Mesquita et al., 2011).

Studying the influence of K on the castor bean lineage UFRB 222, Cavalcante et al. (2020) found that the application of this nutrient increased leaf area, number of seeds and oil production, and the best dose was 300 kg ha-1 . Hussien et al. (2012) found that foliar fertilization with K increased the foliar concentrations of K, Ca, Mg, Zn, Fe and Mn, in addition to increasing the dry mass of the stem, leaves and the entire plant; the height of the plants; the number of leaves and productivity.

> Agave *sisalana* Perrine, popularly known as sisal, is a monocotyledonous herbaceous plant belonging to the Agave genus. This genus is native to Central and North America and currently occurs in tropical and subtropical countries such as Brazil, Tanzania, Kenya, Madagascar, China, and Mexico. The fiber from its leaves is used to produce carpets, ropes, and yarn, while other parts of the plant are used in the production of cellulose, animal feed, and even fiberglass. Sisal has a high capacity to withstand dry environmental conditions due to its ability to conserve water in its leaves. Therefore, agave cultivation occupies a large area in the semiarid region of the Northeast. Brazil leads the world in sisal production and export, and approximately 80% of Brazilian production is exported. Planting is concentrated in the state of Bahia, which accounts for 94.2% of the country's cultivated area (Leite et al., 2023).

Agaves are perennial plants that have a production cycle of between 8 and 12 years, xerophytes; their anatomy and metabolism are adapted to efficiently utilize water and, therefore, they are able to live in arid and semi-arid conditions (Queiroga, 2021). To produce one ton of fiber, the agave needs to remove 70 kg ha-1 of K_2O from the soil (Miranda, 2011).

2.6 GENETIC IMPROVEMENT TO INCREASE EFFICIENT POTASSIUM USE

> Developing plants that are more efficient in terms of mineral nutrition is crucial for the development of low-input agriculture, minimizing fertilizer costs, and achieving sustainability. Nutritionally efficient genotypes in K may have specific physiological mechanisms or traits to acquire sufficient amounts of this nutrient (uptake efficiency) and/or to utilize absorbed K more effectively (utilization efficiency). Looking ahead, using K-efficient genotypes in combination with optimized soil fertilization is the ideal strategy for developing stable and sustainable agricultural systems (Zörb et al., 2014).
>
> There are eight areas in which breeders can intervene: root morphology, root hair formation, root exudates, ability to release K from non-exchangeable *pools* , K uptake kinetics, K translocation, K replacement, and harvest. The first five traits are related to K uptake efficiency, while the last three determine nutrient utilization efficiency (Rengel and Damon, 2008).
>
> The effect of K on cell growth is the factor that justifies plant breeding efforts to increase the absorption of this nutrient. K is the driving force behind increased cell volume because it controls the plant's water relations. For example, breeding to increase K channel activity contributes to increased cell turgor, leading to cell elongation during root hair growth, which improves crop performance under water stress or soil salinity (Taiz and Zeiger, 2016).

FINAL CONSIDERATIONS

Considering that K is a macronutrient that performs important functions in plants, such as enzyme activation, protein synthesis, photosynthesis, osmoregulation, transport in the phloem, energy transfer and cation-anion balance, it is important that institutions of agricultural research emphasizes scientific investigations related to this nutrient in agricultural systems. There is a wide variety of themes to be developed to increase the nutritional efficiency of K sources. In this context, topics such as better methods of application for the most diverse crops, interaction of K with other nutrients in the soil, bioinputs such as K sources, phosphate nutrition and plant resistance to phytopathogens, use of conventional breeding and biotechnology for the development of materials that have greater nutritional efficiency for this element and K management in ecological and/or family-based production systems are currently relevant for environmental, social and economic sustainability.

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