Chapter 3

Potassium Nutrition in Fruits and Vegetables and Food Safety through Hydroponic System

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Additional information is available at the end of the chapter

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Abstract

Although it is not an element with structural function in plants, potassium (K) is demanded in considerable quantities by plants due to multifunctional role in plant physiology and metabolism. Nevertheless, the interface of plant mineral nutrition and food safety evidences needs for a better understanding of functional mechanisms of this nutrient in plants, taking into account its management in hydroponic cultivation and food production with nutritional quality. Thus, the nutritional content of K in vegetables is indicative of post-harvest and nutritional quality. This fact is important considering that modern life has induced increased consumption of processed foods whose preparation implies reduction of K levels and increase of Na levels, with the consequent low K intake and appearance of diseases related to insufficient intake. Therefore, the present chapter aimed to address main nutritional, physiological, and biochemical aspects of K in a context of hydroponic plant production and importance of potassium nutrition to human health.

Keywords: K, plant nutrition, transport of K, food, metabolism

1. Introduction

The term "potash" describes a variety of extracted and manufactured salts containing chemical element potassium (K) in water-soluble form. It is one of three primary nutrients for plants, along with nitrogen and phosphorus, with about 90% potash being used in the production of fertilizers [1]. The K, abbreviation of word neo-latina *kalium* (derived from "alkali," latinized form of Arabic *al-qali* which means calcined ash), was isolated like an element by Humphry

Davy in 1807, but its compounds were already used in processes known from ancient times [2]. From the chemical point of view, K belongs to alkali metal family, being a univalent ion ray cation of 0.331 nm and hydration energy of 314 mols^{-1} [3].

The K is an essential macronutrient and one of the most important cations in higher plants, constituting about 2–10% of the mass of the dry matter [4]. The K is essential for enzyme activation, protein synthesis, and photosynthesis, as well as modulating osmotic regulation during cell expansion, stomatal movements and tropism [5], and transport of photoassimilates of fabrics sources for fabrics drains [3]. The cytoplasmic concentration of K in plant cells is estimated to be around 100 mM (40–200 mM). This concentration of K appears to be relatively stable, with an optimal concentration of K for enzymatic activity [6]. On the other hand, the concentration of K in the soil is low, being in micromolar range of 0.1–1 mM [7].

The absorption of K is performed by means of three groups of membrane proteins, the permeases (KT/HAK/KUP), transporters (Trk/HKT), and by proteins of cation-type antiporter (CPA) [8]. Electrophysiological studies have shown that under K millimolar concentrations, K absorption occurs passively through ion channels and actively through H^{+-}cotransporters when the K concentration is in the micromolar range [9, 10]. When K concentration in the soil solution is below 0.2 mM, high-affinity absorption mechanisms are activated; on the other hand, when K concentrations are above 0.3 mM, mechanisms of low-affinity absorption are activated [9, 11, 12].

In plants, K is characterized by great mobility, being easily transported to aerial part or even redistributed among various organs of plants. Due to considerable number of functions performed by K in plants, this macronutrient plays an important role in plant growth and development, as well as food quality.

Adequate potassium nutrition is associated with increased fruit production, fruit size, soluble solids increase and ascorbic acid concentration, fruit color improvement, fruit shelf life, and supermarket shelf life [13–16]. Additionally, K is involved in post-harvest quality of vegetables and fruits; it is considered a nutrient associated with quality of products of plant origin due to its important effects on post-harvest attributes such as color, size, acidity, resistance to transportation, handling, storage, nutritional value, and industrial qualities [17, 18].

One of strategies of high-quality food production is the adoption of hydroponic system of cultivation, in which the control of plant nutrition (i.e., concentration of nutrients, pH, and electrical conductivity of nutrient solution) and growing environment (i.e., temperature, luminosity, and humidity) are more effective in obtaining high-quality vegetables compared to field cultivation. Hydroponic vegetable production has increased significantly in recent years worldwide, allowing more efficient use of water and fertilizers, as well as better control of climatic and phytosanitary factors. In addition, hydroponic production increases the quality and productivity of vegetables, resulting in competitiveness and profitability [19].

In fact, there is a close relationship between plant nutrition and food safety, considering potassium nutrition interface of vegetables and human health, since one of the conditions for safe food is the production and availability of foods with nutritional quality [20]. Thus, good management of vegetable nutrition can contribute not only to gains in productivity and post-harvest quality but also to people's quality of life through the ingestion of healthy foods rich in mineral nutrients.

Coincidently, one of the most important mineral nutrients for human health is K; from physiological point of view it plays an important role in the conduction of electrical impulses by cells of nervous system, muscle contraction, and vascular functioning [21]. There are several food sources that can satisfy human needs of K, such as vegetables of its accessibility, low cost to consumer, and easy nutritional management. However, the production of vegetables in quantity and quality in hydroponic system is closely linked to nutritional management, especially of potassium nutrition, given the great importance of this nutrient in physiology and post-harvest quality of plants of food interest. The present chapter aimed to address the main aspects of potassium nutrition of vegetables and fruits, emphasizing the importance of interface plant nutrition and food safety in hydroponic farming system.

2. Source of potassium fertilizers

In hydroponic cultivation, the supply of K is carried out from fertilizers containing this element, which have considerable amounts of other nutrients as accompanying ions (**Table 1**). Thus, the choice of source depends on factors such as availability, commercial value, the requirement of culture by accompanying ion, and saline index. However, it is important that more than one source is available to facilitate the equilibrium of final concentration of K in culture solution, which depends on the requirement of each culture.

Fertilizer	Formula	Nutrient	Concentration (%)	Solubility (g L^{-1} at 20°C)
Potassium nitrate	KNO_3	K	38	316
		$N\text{-}NO_3^-$	13	
Monopotassium phosphate	KH_2PO_4	K	28	226
		P	23	
Potassium sulfate	K_2SO_4	K	45	111
		S	18	
Potassium chloride	KCl	K	60	330
		Cl	48	

Source: [19]

Table 1. Fertilizers containing potassium that is commonly used in the preparation of nutrient solutions.

3. Potassium nutrition in vegetables

The vegetables are very demanding in K and some species such as tomatoes require it in greater quantity than nitrogen (N) [22]. The factors that contribute to high requirement, in general, are a short cycle and short absorption period associated with high demand for nutrient. An important tool to assist technicians and producers with regard to nutrient quantity and application times is the study of gait of nutrient accumulation [23], which changes according to species. For example, while in tomato the demand for K increases over time, especially in fruiting phase [22], in lettuce plants, the rate of absorption of K decreases during the days of cultivation [24]. Another factor that must be taken into account when choosing the amount of nutrients to provide is where the recommendation information was obtained and should be representative of place where the recommendation will be used. In this context, the manual of recommendation for fertilization of vegetables, [25] clarifies the recommendations that should be followed in the absence of local information.

In relation to evaluation of nutritional status of crops, the main ways to do this is through visual analysis of deficiency or excess symptoms and nutrient content of plant tissue (leaf analysis). The visual analysis has the advantage of low cost, for dispensing laboratory analysis. However, when the plant expresses the symptoms of deficiency in the histological plane, much of productivity is compromised, which is an undesirable situation for producers. Leaf analysis has the advantage of detecting symptoms of deficiency or excess of nutrient that are not being demonstrated in the histological plane, by comparison with pre-established reference values.

The same care described about the use of recommendations should also be taken in relation to the use of reference values. For example, Trani et al. [26] indicate that for sugar beet, the critical K content ranges from 20 to 40 g kg^{-1} for field crops. However, if there is a change in cultivation system with an increase in green fertilization [27] and hydroponic cultivation [28], the critical levels of K increased to 70 and 84 g kg^{-1}, respectively.

A relevant nutritional aspect related to plant nutrition is a relationship between nutrients, because of its dependence on the chemical nature of nutrient. It also can affect absorption through root system, thus absorption rate of one ion can be affected by another, which are competing for the same membrane carrier [29]. This fact will depend on its concentration on nutrient solution, the permeability of nutrient to membrane, and its mechanism of absorption [30]. Thus, increasing the concentration of particular nutrient in nutrient solution may interfere with the plant's absorption of other nutrients. In this context, the important relationship between K, Ca, and Mg is framed and these three nutrients are found in expressive concentrations in plant tissues.

The K competes with Ca and Mg for the same membrane carrier and increase in K concentration in nutrient solution implies reduction in Mg uptake. Similarly, increasing K concentration may reduce Ca uptake, because K is preferentially transported in plant compared to Ca [31]. The Ca competes with Mg, which makes the absorption reduced and this is due to the high energy of hydration and the larger size of ionic ray of Mg^{2+} ion, when compared with the Ca^{2+} ion. Due to competition, it is possible to observe Mg deficiency in plants, which means high doses of potassium and calcium fertilizers [3]. According to Forster and Mengel [32], the reduced concentration of K in nutrient solution allowed a higher absorption of Ca and Mg; there is no competition between the nutrients for absorption site. Due to these factors, it is not a concern to describe the concentrations of K used in nutrient solutions as well as adequate levels of K in leaf tissues; the objective of this section on potassium nutrition is to demonstrate some examples of the role that K has on the plants, ranging from the seed to the final quality of the product.

It is possible to manage potassium nutrition in hydroponic systems considering the cultivation of plants with different objectives, since the maintenance of high K/Na ratio in the cytosol is of vital importance for the functioning of plant cells [33, 34], for example, the production of K-poor edible plants for groups of people with chronic kidney disease who have difficulty excreting K. In an experiment with strawberry plants grown under a hydroponic system and decreasing concentrations of KNO_3 in the phases comprised between anthesis and fruit formation, [35] obtained strawberry fruits with low K contents when the concentration of K in the nutrient solution corresponded to 1/32 of the control treatment. For this concentration of K, there was no reduction in yield and fruit quality. However, in a study with melon plants under hydroponic conditions [36] did not obtain similar results, since the melon plants absorbed and stored considerable amounts of K before the application of the restriction treatments of K in the nutrient solution. In this study, a significant redistribution of K of the vegetative structures was observed for the melon fruits.

In another study, there was the equivalent substitution of K for Na in sugar beet plants cultivated in a hydroponic system [37]. In this study, the equivalent substitution of K for Na did not promote growth reduction, but only significantly reduced the calcium contents in the shoot and root. Plants that support the substitution of K for Na without damage to the growth and ionic homeostasis are called natrophilic, being included in this classification sugar beet [37].

The management of K in hydroponic system can improve the growth of plants cultivated under conditions of saline stress. In a study with five tomato genotypes, [38] observed that 2 mM of K supplementation mitigated the effect of saline stress by promoting greater leaf, root, and fruit yield. However, it should be considered that the response to K addition was genotypic, since the Pearson cultivar presented the best response to the addition of K.

In order to evaluate induced changes in the proteomic level by the substitution of K for Na or even K deficiency in sugar beet plants, [39] observed that a wide range of physiological processes were impaired by K deficiency, such as light reactions of photosynthesis, CO_2 assimilation, glycolysis, and tricarboxylic acid cycle. Stimulation to the photosynthetic process was observed when there was K deficiency; however, due to the presence of Na, the cellular respiration process was affected. This study evidenced that Na is able to repair some damage due to K deficiency, but it did not replace K as an essential element to the growth of plants.

4. Potassium nutrition and quality of seeds and seedlings

The attention to adequate potassium nutrition must occur from the acquisition of seeds because nutritional status of mother plant affects not only the final yield of crop but also the quality of seeds produced. For example, Marrush et al. [40] found that K deficiency benefits a high incidence of premature germination, in other words, viviparity in bell pepper plants (*Capsicum annum* L. cv. "California wonder").

Consequently, the deficiency of K in mother plant, during the phenological stage of seed formation, may decrease the germination rate of harvested seeds [41]. However, the seeds of plants well-nourished with K may present the germination rate due to the accompanying ion of the source of K used, because of a negative correlation between germination percentage and concentration of Cl in sweet pepper seeds [42].

In relation to the production of *Brassica oleracea* seedlings, Zhang et al. [43] have demonstrated that although it depends on a relationship with other nutrients, the enrichment of substrate with K provides more vigorous seedlings. However, there is little research to verify if investment in seedling production is offset by the final productivity of plant in the field.

5. Potassium nutrition and its relationship with abiotic and biotic stresses

Among the factors that affect global food security are availability and quality of water resources [44]. Due to low availability of drinking water, the development of techniques that allow the lowest consumption of water or use of salt water in hydroponics is important to allow advancement in this mode of cultivation [45].

In this sense, an increase of K application in sweet potato plants irrigated with 50% of the field capacity was detrimental to the development of plants [46]. In relation to the use of salt water, one of negative consequences in hydroponics is a decrease in the accumulation of K [47]. However, it has been demonstrated in literature that, in tomato cultivars, the increase of K concentration in nutrient solution can be used to minimize salinity-induced oxidative stress, increasing the photosynthetic rate of plants and making them less sensitive to salinity [48]. Besides that, Ramadan and Shalaby 2016 [49] indicated that the foliar application of K resulted in an increased growth and yield of eggplants grown under conditions of salt stress.

A common situation in less-tech hydroponic crops is a lack of temperature control in production environment, because in these environments the temperature is not controlled, temperature variations are usually observed, which has harmful effects on plants. Thus, in an extensive compilation of data, Oosterhuis et al. [50] described that high K concentration in cells can improve cold stress tolerance by reducing the osmotic potential of cells and decreasing the freezing point of sap, preventing cell dehydration. On the other hand, considering that hydroponic crop plants experience high temperatures, but without water restriction, Römheld and Kirkby [51] indicate that an adequate nutrition results of K in an increase of plant's capacity to eliminate the reactive oxygen species. It is produced during the thermal stress and improving the efficiency of water use, these main factors are necessary to make plants less sensitive to heat.

In hydroponic crops, nitrogen is mainly supplied as nitrate (NO^{3-}). For leafy vegetables, the accumulation of NO^{3-} is a concern for humans, especially for children, it can be harmful to health, depending on the amount consumed in the diet [52]. Thus, the inclusion of ammoniacal N can promote a significant increase in productivity and contribute to growing demand for safer foods. However, several factors may alter the availability of ammonium (NH_4^+) to plants and increase their rate of absorption by plants, which may lead to phytotoxicity [53].

Potassium nutrition is efficient in minimizing the phytotoxic effects of excess NH_4^+, since K and NH_4^+ are very similar in relation to valence and ionic radius, in addition to being absorbed by the same carrier. Thus, increased K concentration may inhibit or even decrease NH_4^+ uptake and thereby mitigate the phytotoxic effects of excess NH_4^+ [54]. In addition, Hernandez-Gomez et al. [55] verified that the cultivation of peppers with high concentrations of NH_4^+ was possible to maintain plant productivity, increasing the K concentration of nutrient solution, which resulted in adequate K contents in the plant tissue. Also, in this study, the water relations, the photosynthetic rate, and the stomatal conductance were not affected, compared to plants cultivated with a high concentration of NH_4^+ and a low concentration of K.

K plays a very important role in the mitigation of biotic stresses to which plants are susceptible, since it participates in the synthesis of high-molecular-weight compounds such as proteins, starch, and cellulose, reducing the accumulation of soluble sugars, organic acids, and amides, of which pathogens are fed [3]. In this context, Perrenoud [56] gathered a series of studies where the incidence of pests and diseases was reduced as a function of nutrition with K and diverse cultures. However, there are important relationships of K with other nutrients, and an adequate K/N ratio in plant tissue may be responsible for increased productivity, lower incidence of diseases, and increased quality of product harvested.

For example, Adams and Massey [57], in order to maximize productivity, fruit quality, and greater resistance to diseases in tomato, suggest a K/N ratio of 1.2/1 in vegetative stage and 2.5/1 in reproductive stage. Another important factor to consider is the nutrient concentrations, which must be adjusted, depending on several factors. This way, Nam et al. [58] demonstrated a concentration of K in strawberry; this element was responsible for a higher productivity, but was not the same that bring results about lower incidence of diseases, which indicates that in conditions of high productivity, the quality of food can be affected.

6. Potassium and post-harvest nutrition of vegetables

Potassium is present in plant cells in cationic form K and plays an important role in the physiological activity of plants. In addition to metabolic functions of K in photosynthetic metabolism, enzyme activation, protein synthesis, osmotic regulation, and stomatal movement [59], K has a close relationship with post-harvest quality of vegetables, because post-harvest parameters such as fruit size, soluble solids, lycopene, and vitamin C concentration are influenced by this nutrient.

There is a set of experimental evidences that show a relationship between potassium nutrition and post-harvest quality of vegetables, since several studies report the effect of potassium nutrition on the post-harvest of fruits and leafy vegetables. In tomato fruits, the potassium nutrition provided under fertirrigation increased the concentration of lycopene in genotypes with contrasting production of lycopene [60]. This pigment or bioactive compound is associated with important antioxidant functions by acting on the detoxification of free radicals, reducing the appearance of cancers such as prostate [61, 62] and avoiding the onset of heart disease [63].

In another study about potassium fertilization in tomato plants, there is a linear increase in the concentration of lycopene with potassium fertilization [64]. This close relationship between potassium fertilization and concentration of lycopene in tomatoes seems to be related to enzymatic activation function exerted by K; more than one enzyme of metabolism of lycopene synthesis has the K activation cofactor, for example, phytoene desaturase or phytoene synthase, an enzyme that catalyzes the reaction of phytoene synthase from geranylgeranyl diphosphate, which is the first step in the route of carotenoid synthesis [65].

Another important antioxidant, vitamin C or acid ascorbic, is positively influenced by potassium nutrition, since several studies report a higher concentration of vitamin C as a function of potassium nutrition, as observed in pepper [66] and chili. K is responsible for the uniform ripening and the increase of acidity of fruit that is an important characteristic for quality and flavor of fruit [67].

With the advancement of ripening process, tomato fruits present changes in their characteristics as flavor and color. The taste of tomato is attributed to the content of soluble solids [68], acids, and volatile compounds [69]. The total soluble solids present greater accumulation in the final phase of maturation also is constituted of 65% of sugars (sucrose and fructose).

Soluble solids present in fruits such as watermelon, melon, tomato, and strawberry include important compounds responsible for taste and consequent acceptance by consumers, and the most important are sugars and organic acids. In general, there is a close relationship between potassium nutrition and soluble solids content as evidenced in several studies such as tomato fruit [60, 70]. It should be considered that the production of soluble solids is a genetic characteristic, but it is influenced by ambient temperature, irrigation, and fertilization [71].

7. Potassium and plant physiology

Potassium is present in plant cells in cationic form K and plays an important role in the physiological activity of plants. In general, K has a close functional relationship with photosynthetic metabolism, enzyme activation, protein synthesis, osmotic regulation, ionic homeostasis, and regulation of stomatal movement [59].

The modulation of photosynthetic activity by K occurs at several levels; however, its role in ionic equilibrium shows to be a major one. For example, K is a dominant ion that promotes the balance of positive charges due to the light-stimulated H^+ flux through the thylakoid membranes. In addition, it contributes to the generation of transmembrane pH gradient necessary for the synthesis of ATP by photophosphorylation. To maintain high pH (low H^+) in the stroma during light, additional K influx from the cytosol is required, in a process mediated by an H^+/K^+ anti-porter carrier [3]. However, the osmotic regulation of guard cells by K is a relevant factor in the control of gas exchange and water losses in plants, due to smaller or larger stomatal opening [72].

The K, as well as other univalent cations, activates enzymes by inducing conformational changes in their structures, making them biologically active and these changes are possible due to electrostatic bonding of K to enzyme [73]. Thus, K contributes to the occurrence of group of biochemical reactions of great physiological importance, such as the activation of carbohydrate metabolism enzyme in particular of pyruvate kinase (EC 2.7.1.40) and phosphofructokinase (EC 2.7.1.11), which catalyze the transference of phosphoric groups to pyruvate and D-fructose 6-phosphate, respectively [74].

Regarding protein synthesis, K is required at higher concentrations compared to its enzymatic activation function, which, for this function, the required K concentration is about 50 mM [3]. Due to osmotic properties, K plays an important role in the opening of stomata during the first hours of the day. This physiological phenomenon consists of influx of K in the guinea pigs, where the concentration of K increases from 100 to 400 mM or 800 mM, but decreasing throughout the day [72, 75].

K is also involved in the loading of sugars into phloem in a process coordinated by AKT3/3-like channels located on the brassicaea phloem *Arabidopsis thaliana* [76]. This process of loading sugars into phloem has great physiological importance because it allows the translocation of sugars from the source tissues to drainage tissues to supply the needs of growing organ such as roots system, fruits, and flowers [72].

Under conditions of adequate potassium availability, K uptake occurs through low-affinity transporters [77], with K translocation to plant tissues and redistribution to drain tissues. At the same time, photoassimilates are produced by the photosynthetic process and transport the same to drainage organs, with the consequent development and growth of plants (**Figure 1**). On the other hand, K deficiency triggers a set of changes in plants, which initially manifests in gene and molecular plane and then in physiological and morphological plane, culminating in the reduction of plant growth.

With low concentration of K in the plant growth substrate, carbohydrate metabolism disorders occur due to K being in low cell concentration to activate key enzymes of carbohydrate metabolism. With this, there is accumulation and inhibition of transport of photoassimilates from the source organs to draining organs, with the reduction of photosynthetic activity. In another way, K deficiency leads to changes in gas exchange, with reduction of stomatal conductance, reduction of CO_2 diffusion, and photosynthesis.

As a consequence, the consumption of NADPH-reducing power by Calvin cycle decreases, with the superduction of electron transport chain and the generation of free radicals, culminating in photooxidation, followed by chlorosis and foliar necrosis (**Figure 1**). In the attempt to reestablish ionic homeostasis, plants promote redistribution of accumulated K; however, due to classical relationship between K, Ca, and Mg, these latter two macronutrients are absorbed in greater intensity, compared to K, under conditions of K deficiency (**Figure 1**).

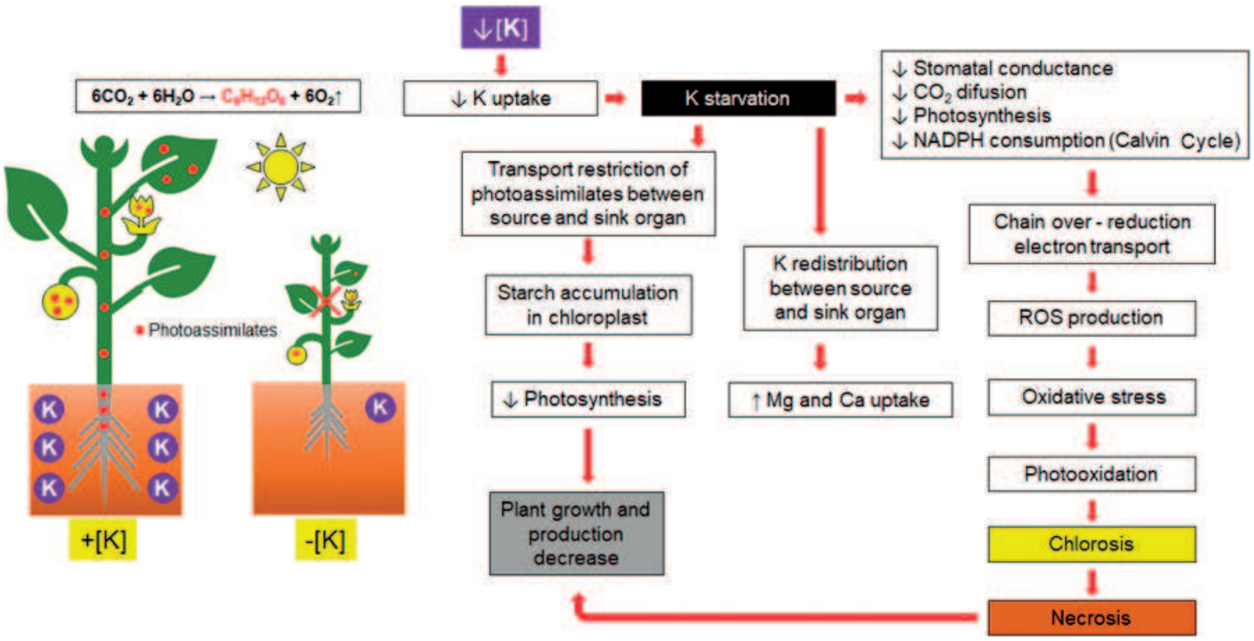

Figure 1. Physiological response of plants to normal and deficient potassium supply.

Due to importance of K in plant physiology and nutrition in relevant literature, several studies report negative effect of K omission on growth (i.e., plant height, leaf area, shoot dry mass accumulation, and root) and mineral metabolism of plants (i.e., nutritional balance of plants), like was observed in beet [78], cabbage [79], lettuce [80], and eggplant [81].

8. Potassium deficiency and toxicity symptoms in vegetables

As in other nutrients, K deficiency changes at different levels. The deleterious effects of deficiency begin in the dynamics of metabolism in biochemical plane, evolving at molecular, subcellular, and cellular levels, until reaching the tissues [23]. The visual perception of deficiency occurs when it reaches the level of tissue, that is to say that when verifying visual damages, a series of events deleterious to the development of plant have already occurred.

The first structures to experience potassium deficiency are the roots where there is a drastic reduction of nitrate levels, intermediates of glycolytic route (pyruvate), amino acids like malate and oxoglutarate, negatively charged amino acids such as glutamate and aspartate, increase in levels of soluble carbohydrates (sucrose, glucose, and fructose), and many amino acids with high C/N and/or positively charged amino acids such as glutamine, glycine, and arginine [81]. In addition, there is less transport of photoassimilates from the aerial part to roots, thus reducing root growth. In the strawberry, potassium deficiency increases the amount of root exudates favoring the infection and colonization of *Fusarium oxysporum* [82].

In the leaves, in the beginning of K deficiency, the content of this nutrient in the cytosol remains constant, although there is a decrease in the K content of vacuoles, probably because this reserve structure of K supplies the demand of cytosol. As deficiency persists and plant demand increases, cytosolic K reduction also occurs [83]. With this reduction, some enzymes such as pyruvate kinase are negatively affected, inhibiting glycolysis and causing a series of metabolic disorders following the tricarboxylic acid cycle [81].

There is an increase in the content of soluble carbohydrates in leaves due to reduction of their conversion to starch and reduction in the content of α-ketoglutarate derivatives [84–86]. Due to the decrease in the synthesis of compounds of higher-molecular weight, the leaves become more susceptible to attack by pests and diseases.

However, Carmona et al. [87] observed in cucumber plants the initial visual symptoms of K in the intermediate leaves (**Figure 2**). These authors suggest that the appearance of symptoms in intermediate leaves occurs as a function of time when the omission of K was applied (beginning of the fruiting), because the fruits in formation are strong drains of this nutrient, being the adjacent leaves to satisfy the demand of K of the fruits. In plants with undetermined growth, such as bean pod case (**Figure 3**) and in reproductive stages, potassium deficiency can also be observed in intermediate leaves, since leaves close to reproductive structures tend to supply K reproductive organs.

K is very mobile in plant being visible deficiency symptoms in the more mature leaves. It begins with a marginal chlorosis, which can also occur at leaf tips, followed by foliar limb necrosis and even necrotic part breakage (**Figure 4**) [88]. Carmona et al. [87] observed in cucumber plants the initial visual symptoms of K in the intermediate leaves (**Figure 2**). These authors suggest that the appearance of the symptoms in intermediate leaves occurs as a function of time when the omission of K was applied (beginning of the fruiting), because the fruits in formation are strong drains of this nutrient, being the adjacent leaves to satisfy a demand of K in fruits. In plants with undetermined growth, such as the bean pod case (**Figure 3**) and in reproductive stages, potassium deficiency can also be observed in intermediate leaves, since leaves close to reproductive structures tend to supply K reproductive organs.

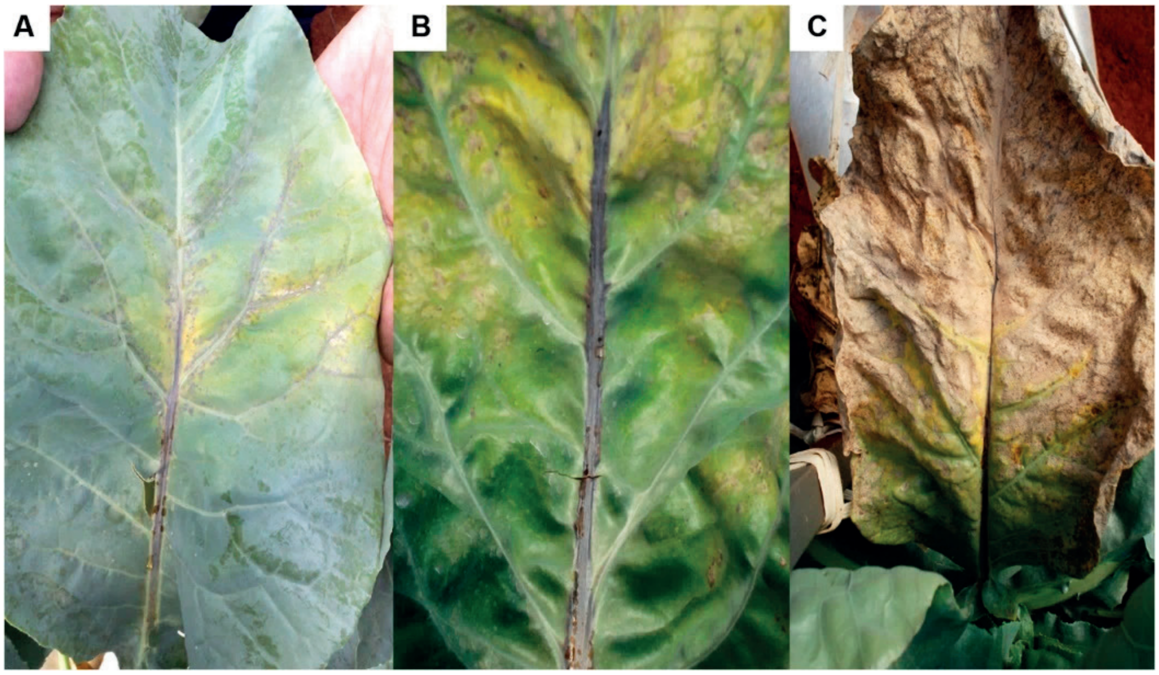

Figure 2. Initial chlorosis (A and B) and advance to marginal necrosis (C) in intermediary leaves of "Nikkey" cucumber as an effect of the omission of K in the nutrient solution. Source: [87].

The deficiency of K leads to lower protein synthesis and accumulation of soluble nitrogen compounds such as putrescine, toxic to plants [88]. The central area of leaves may be dark green in color, similar to phosphorus deficiency and a thickening of nervure in leaves (**Figure 4**) [88].

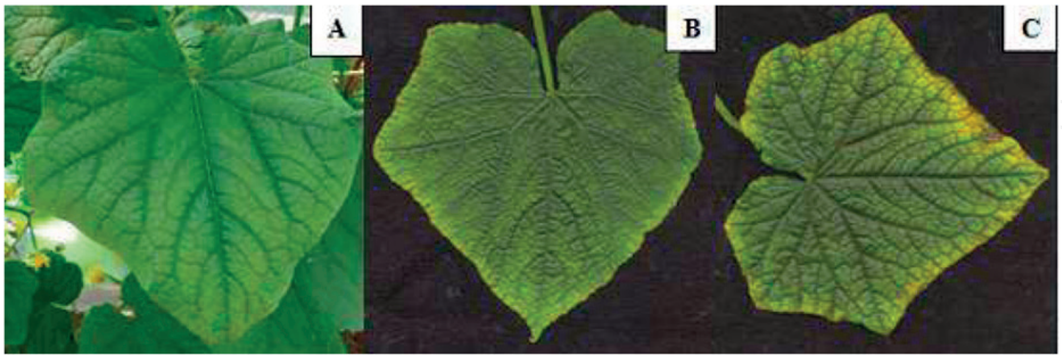

Figure 3. Potassium deficiency in bean pod plants (-K) compared to control (CS). Source: [89].

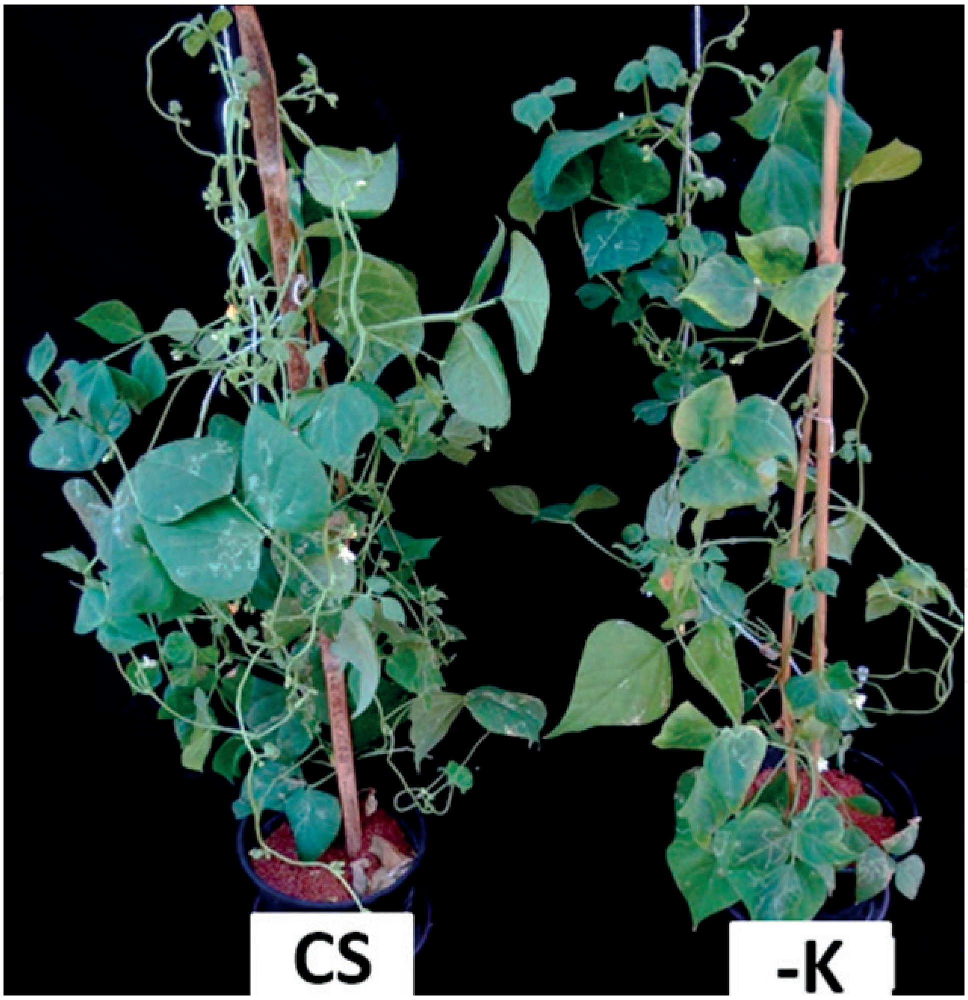

Figure 4. Progressive symptoms of K deficiency in the leaves of the cauliflower "Verona" after being supplied with a nutrient solution without K. Chlorosis and initial necrosis of the nervures (A), advanced stage of necrosis of the nervures (B), and advanced foliar necrosis (C). Source: [88].

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However, the molecular changes triggered by K deficiency are not restricted only to old leaves, because in new leaves there is an increase in the levels of oxaloacetate and phosphoenolpyruvate derivatives [86].

In fruits, the deficiency of this macronutrient decreases the glucose, fructose, and sucrose levels, and in plants of Rosaceae family, it decreases sorbitol levels [90], and in species with large amounts of lycopene such as tomato [91], there is less red color intensity due to reduction in the synthesis of this pigment [60, 64].

Several studies have demonstrated the important role of K in plant growth and development, with a considerable decrease in the production of dry mass of plants when K is omitted from culture medium [92]. In sugar beet, the omission of K promoted a considerable reduction of the dry mass of the aerial part and radicular, besides promoting symptoms of nutritional disorders characterized by the appearance of chlorosis markedly red of margins of leaves and evolving toward necrosis until reaching the leaf apex [78].

In other study with cabbage, the omission of K was limiting for the vegetative growth of cabbage, considerably reducing the height of plants, the number of leaves, leaf area, and dry matter of shoot, roots, and whole plant. The deficiency of K, besides promoting a decrease of nutrient content in the aerial part, caused imbalance between the other nutrients and, consequently, morphological alterations, translated as characteristic symptoms of K deficiency [79].

The absence of K in lettuce plants led to reduced growth, with a considerable decrease in height, leaf area, dry mass of shoot, root, and emergence of nutritional disorders [80]. In cultivation under omission of K and eggplants a reduction of dry mass of shoot and root, a decrease of leaf area, height and number of leaves were observed, in parallel to nutritional disorders resulting from the omission of K [93].

The great demand of plants for potassium and their capacity to accumulate this nutrient in the vacuoles makes the observation of symptoms of excess something very rare [23]. When K is excessed, it is also induced to plants; the use of sources such as potassium nitrate and potassium chloride (KNO_3 = 74; KCl = 116) [94] can generate physiological disorders and affect the development of plant. Therefore, experiments with excess of potassium should be recommended sources with lower salt content. In addition, attention should be paid to the effect of accompanying ions that may cause toxicity, and excess K in the nutrient solution may increase or decrease the absorption of other nutrients. The increase of potassium provides an increase in the absorption of nitrate and, on the other hand, can lead to lower absorption of Mg and Ca [23, 94].

9. Potassium in human health and food consumed

K is an essential mineral nutrient for humans because of its important physiological role in conducting electrical impulses in nerve tissue, electrolyte balance of body fluids, and blood pressure control. Ingestion of food of plant origin (i.e., vegetables, grains, cereals, etc.) and animal (i.e., meat, milk, eggs, etc.) are the main sources of K in human food. However, the process of cooking, the increased consumption of processed foods, and the decreased consumption of vegetables and fruits implied a reduction in K intake by the population [95].

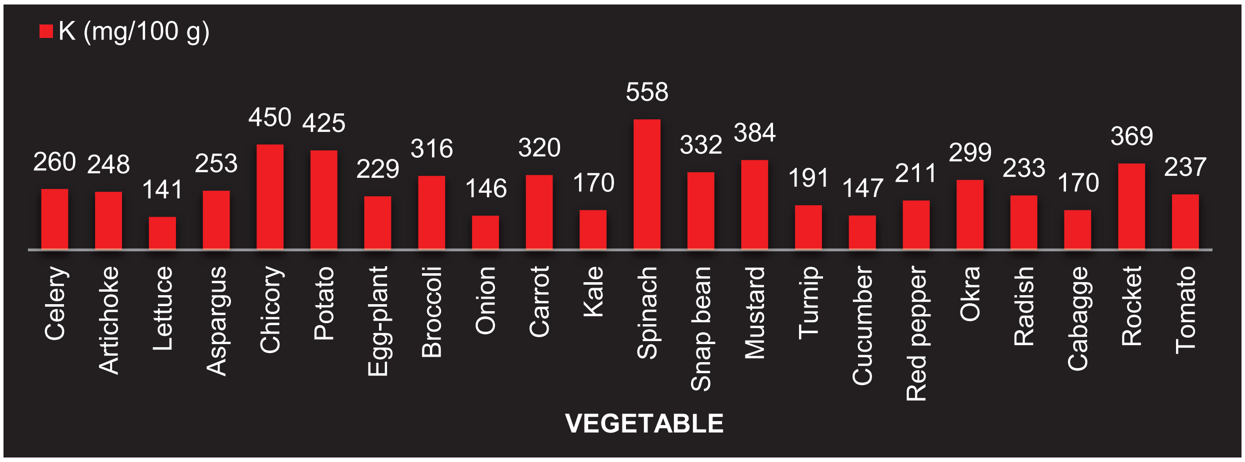

Figure 5. Average potassium content green stuff leafy. Source: [97].

Life stage	Age	Males (mg day^{-1})	Females (mg day^{-1})
Infants	0–6 months	400	400
Infants	7–12 months	700	700
Children	1–3 years	3000	3000
Children	4–8 years	3800	3800
Children	9–13 years	4500	4500
Adolescents	14–18 years	4700	4700
Adults	19 years and older	4700	4700
Pregnancy	14–50 years	–	4700
Breast feeding	14–50 years	–	5100
Source: [98]			

Table 2. Reference values for human potassium intake based on age and pregnancy.

A set of clinical and experimental evidence shows the reduction in K intake that is associated with the emergence of various chronic diseases such as hypertension or high blood pressure, an increased risk of cardiovascular disease, kidney disease, and demineralization of bones [95, 96] Thus, the consumption of foods of vegetable origin rich in K as a way to increase K intake and reduce the emergence of diseases associated with malnutrition relative to K intake is recommended. For this, there are several vegetables with varying levels of K in its edible parts (**Figure 5**), whose consumption associated with other food sources can supply the daily need for K intake based on age, sex, and gestation (**Table 2**).

10. Conclusions and future perspectives

This chapter approached the main aspects of potassium nutrition of vegetables and food safety, emphasizing potassium in the context of plant physiology, post-harvest physiology, and human health. In this sense, the cultivation of vegetables under environmental conditions adequate to the development of plants (i.e., phytosanitary management, optimal conditions of temperature, humidity, and luminosity) together with balanced nutrition in K are important factors that contribute to obtaining of foods with nutritional quality. The need for ingestion of foods rich in K and compounds with nutraceutical properties whose production by plant is directly or indirectly influenced by K such as lycopene and vitamin C in tomatoes is taken into account.

In addition, knowing the main biotic and abiotic stresses that can be mitigated by potassium nutrition constitutes an interesting strategy for cultivation and production of vegetables. Therefore, this chapter is proposed as additional information about the tool importance of potassium nutrition in the hydroponic and food safety context to be consulted by students, teachers, and researchers. Considering a modern world and the increase of food consumption processed, these foods still being poor in K foods have contributed to the emergence of diseases related to low intakes of this nutrient.

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