Chapter 4

Potassium Fertilization in the Production of Vegetables and Fruits

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Additional information is available at the end of the chapter

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Abstract

Consumption of vegetables worldwide has increased, not only by population growth but also by the trend of changes in consumers' eating habits, making it inevitable to increase production. The consumer of vegetables has become more demanding, having to produce them in quantity and quality, as well as maintaining their supply throughout the year. Hydroponics is an alternative technique of cultivation in a protected environment, in which the nutritious solution is replaced by the nutrient solution. Among the essential mineral nutrients for plants, K stands out for its influence on quality attributes that affect the concentration of phytonutrients critical for human health. It acts as the determinants in the commercialization of vegetables, and can be found in various foods such as vegetables, and fruits. Adequate levels of this nutrient will benefit the consumer's health and also prevent disease. Among the essential plant nutrients, K stands out for its influence on quality attributes that affect the concentration of phytonutrients critical to human health. The horticulturist should prioritize the use of potassic fertilizers with lower salt content, if possible free of chlorine and containing magnesium and sulfur. However, it is essential to remember that the high potassium content in plants can induce deficiency of calcium and magnesium.

Keywords: hydroponics, fertilizers, nutrient management, stress, production

1. Introduction

Plasticulture is a term adopted internationally to designate the use of plastic cover in agriculture, aiming the creation of improved and controlled environments, more propitious to the development of the plants. Vegetables come from the most diverse regions of the world, from arid and desert regions up to the most humid tropical forests, from the icy north to the calico equator, from the sea level to the top of the mountain ranges, and from America to Asia.

The protected cultivation consists of a technique that allows certain control of climatic variables like temperature, humidity of the air, solar radiation, and wind. This control translates into a gain in productive efficiency, reduces the effect of seasonality, favoring a more balanced supply over the months; in addition, the use of this technology allows the effect of seasonality to decrease. This benefit is most evident in regions with a cold climate, as the heat accumulated inside the greenhouses makes it possible to produce certain crops out of season and shorten the production cycle.

The production of vegetables in this type of environment in Brazil is not so recent. In the 1980s, when the production of vegetables began, it was found that, after 3 years of cultivation, many producers could no longer obtain the productivity nor the quality obtained at the beginning of cultivation. At the time, the producers suffered from damages caused by inadequate practices resulting from lack of information and adequate technical assistance. This and other occurrences reinforced the myth that protected cultivation was not feasible. The advance of research, however, showed that the problem was not the system in use but the management adopted.

In countries where protected cultivation is in an advanced stage, the nutritious solution is being replaced by different substrates, with the main objective of circumventing adverse phytosanitary and nutritional factors, allowing strict control of the root environment, especially in relation to water and nutrient management. One of the ways to work around problems of nutritious solution contamination is the use of hydroponic farming systems, in which nutrients are supplied by means of an aqueous solution containing all essential chemical elements to the vegetables.

The main feature of the fertilizers used in hydroponics is that they are soluble in water. One should keep in mind the importance of chemical compatibility between different fertilizers. Macro- and micronutrients are used that are diluted in water to compose up the nutrient solution.

In Brazilian agriculture, potassium (K) is the second nutrient most extracted by vegetables, after phosphorus, which is the nutrient most consumed as fertilizer. The permeability of the plasma membrane makes K to be easily absorbed and transported at long distance by xylem and phloem. Much of the total K of the plant is in the soluble form; therefore, its redistribution is facilitated in the phloem. Thus, under conditions of low K supply through the medium, the element is redistributed from the older leaves to the younger leaves and then transferred to the growing regions. The main biochemical function of K in the plant is enzymatic activation; more than 50 enzymes are dependent on K for their normal activity, such as synthetases, oxidoreductases, dehydrogenases, transferases, and kinases. For leaf and fruit vegetables, several authors have already demonstrated the importance of this nutrient, in addition to increasing production, favoring the improvement of the commercial quality of these products.

2. Objectives

This chapter aims to present the cultivation of vegetables and fruits, their nutrient management in hydroponics and salinity condition, and the role of potassium fertilization on the physiological, biochemicals, and antioxidative quality of vegetables and fruits.

3. Hydroponic cultivation of vegetables and fruits

Hydroponics is an agrotechnology for plant cultivation outside the nutritious solution and in nutrient solution, becoming a promising alternative for the diversification of agribusiness. This system of production provides greater yield per area, lesser incidence of pests and diseases, greater ease of execution of cultivation practices, better programming of production, and shorter cycles, due to better environmental control [1].

Among the different hydroponic systems that do not use substrates, the Nutrient Film Technique (NFT) system is the most widespread in Brazil and worldwide [2]. This technique favors the continuous or intermittent circulation of the nutrient solution in cultivation channels, which may have varying dimension sizes and made by different materials, poly(vinyl)chloride (PVC), polyethylene, polypropylene, asbestos, and masonry being the most widely used [3]. Currently, hydroponic cultivation has great importance in several countries, such as Holland, the United States, France, Spain, Japan, and Israel among others. However, one must consider the cost of implementation and the high level of technology required in this system.

The most planted vegetables in this system are lettuce, arugula, and tomato. Other vegetables are restricted to smaller areas, such as cress, parsley, peppers, strawberries, and melons. In general, hydroponic crops require permanent monitoring, mainly as regards the uninterrupted supply of electricity and the control of the chemical and physical characteristics of the nutrient solution [4].

All essential nutrients must be supplied at levels compatible with the requirements of each species, according to the development stage [5]. In order to minimize experimental errors in the analysis of symptoms induced by excess or deficiency nutrient in nutrient solution, it is recommended to use minimum concentrations [6]. The definition of these minimum concentrations should be studied in view of the genotypic, environmental, and demand differences associated with the different phases of development. In general, there is a tendency to reduce the ionic concentration of the nutrient solution in commercial hydroponic crops, especially in environments whose temperature, luminosity, and relative humidity are high in the hottest seasons of the year [7].

It is worth mentioning that the rational use of fertilizers, in addition to reducing costs and guaranteeing production quality, minimizes contamination of the environment and its consequences. These are the eutrophication of surface and groundwater and the accumulation of high levels of nitrate in the groundwater and plants [8]. In the handling of the nutrient solution, factors such as temperature (optimum levels around 24°C), pH (suitable values between 5.5 and 6.5), and electrical conductivity (EC) of the nutrient solution (optimum range between 1.5 and 4.0 dS m^{-1}) should be monitored and controlled periodically [9].

4. Nutrient solution management

One of the basic principles for plant production is the provision of all the nutrients the plant requires [9]. In this environment, when nutrient imbalance occurs, production will be limited. For the adequate development of the cultures, macro-and micronutrients that are essences for the growth and production of the plants are necessary, which are presented in **Figure 1**.

That division, between macro- and micronutrients, takes into account the amount that the plant requires of each nutrient for its cycle, all being equally important in nutritional terms. In this way, it is important to observe that the total amounts absorption are of secondary importance since, in hydroponic cultivation, the concentration of nutrients in the growth medium is maintained constant, which does not occur when cultivated in the nutritious solution.

The optimum pH values for the nutrient solution are between 5.5 and 6.5, being important to keep these values in the solution to favor the availability of nutrients to the plants. If the pH is above 6.5, elements such as phosphorus, manganese, and iron begin to precipitate, remaining

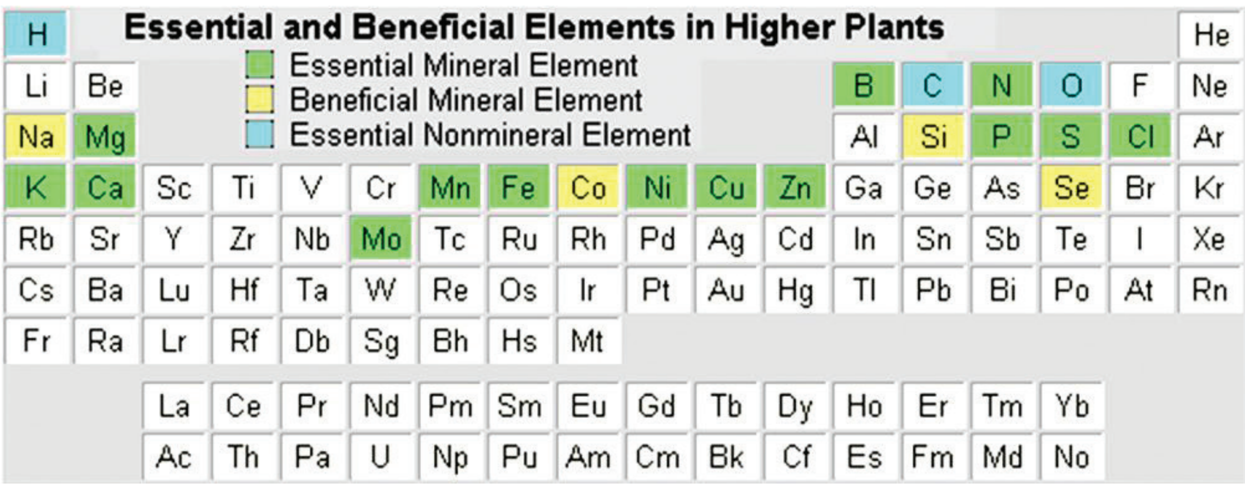

Figure 1. Chemical elements used in plant production [3].

in forms unavailable to plants. If the pH is lower than 5.5, magnesium, calcium, and molybdenum, in particular, have reduced availability, as shown in **Figure 2**.

Using a conductivity meter, we established the ability of the nutrient solution to conduct the electric current. As this capacity changes according to the content of the mineral salts, the value of the electric conductivity allows estimating the total concentration of the nutrients in the solution. The higher the EC, the higher the content of mineral salts in the nutrient solution. Normally, when the electrical conductivity is reduced to a certain level of the initial solution (about 30–50%), it is advisable to replace it. The level at which EC value should be maintained varies according to climate and culture.

The pH and EC characteristics of the water used and then of the nutrient solution (water and nutrients diluted in it) should be those indicated for each type of crop. In theory, pH may range from 0 to 14, but in practice, extreme values are incompatible with plant life. Second to the pH values, the quality indexes for the water used in hydroponics can be classified (**Table 1**).

In preparing the solutions, fertilizers contain macronutrients that must be weighed in the correct amount, indicated by the chosen formulation, then diluted one by one in the tank with water to approximately two-thirds of its capacity. Posteriorly, added the micronutrients are in the form as concentrated solution, in finally, the solution is added with chelated iron. The main fertilizers used for the preparation of nutrient solutions are found in **Tables 2** and **3**.

Table 4 presents the adapted solutions [3] for use in the preparation of the nutrient solution in the NFT system, for leafy vegetables and fruits.

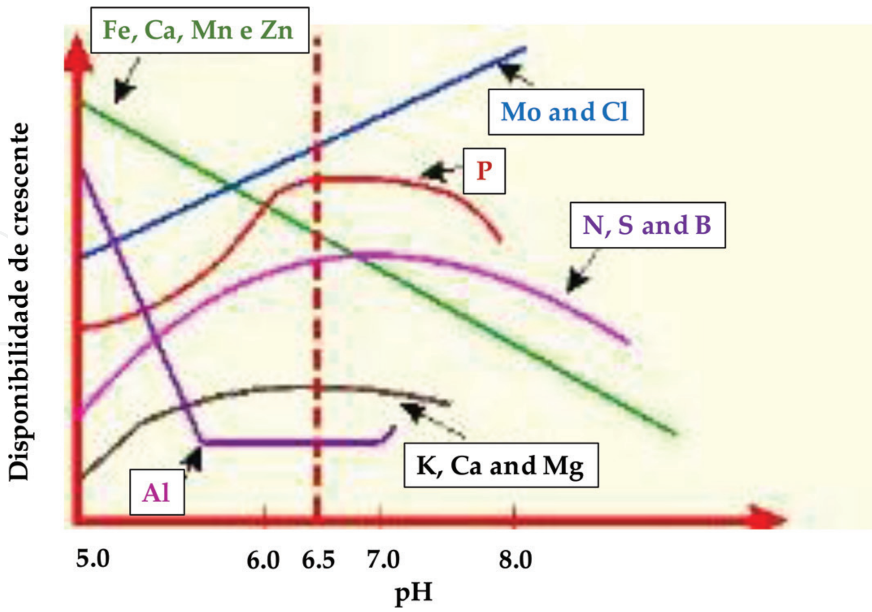

Figure 2. Relationship between pH and element availability.

Units	Good	Acceptable	Maximum limit
EC mS cm	<0.75	<0.75–1.50	2.0
pH	6.50	6.80	7.5
HCO^-_3 mmol L^{-1}	1.60	3.30	7.5
Na^+ mmol L^{-1}	0.87	1.30	2.61
Cl^- mmol L^{-1}	1.14	1.71	2.86
SO^2_4 mmol L^{-1}	0.83	1.26	2.08
Ca^{+2} mmol L^{-1}	6.50	10.00	14.00
Fe µmol L^{-1}	—	—	0.08
Mn µmol L^{-1}	—	—	0.04
Zn µmol L^{-1}	—	—	0.02
B µmol L^{-1}	—	—	0.03

Table 1. Quality indices for water used in hydroponics [3].

Fertilizers	Nutrient %					
	N	P	K	Ca	Mg	S
KCl	—	—	49.8	—	—	—
$NH_4H_2PO_4$	10.0	21.8	—	—	—	—
$NH_4H_2PO_4$	11.0	21.8	—	—	—	—
$Ca(H_2PO_4)_2H_2O$	—	24.6	—	15.9		
KH_2PO_4	—	22.8	28.7	—	—	—
NH_4NO_3	34.0	—	—	—	—	—
$Ca(NO_3)_24H_2O$	15.0	—	—	20.0	—	—
$Mg(NO_3)_26H_2O$	7.0	—	—	—	6.0	—
KNO_3	13.0	—	36.5	—	—	—
$NaNO_3$	16.0	—	—	—	—	—
$(NH_4)_2SO_4$	20.0	—	—	—	—	24.0
$CaSO_4{\cdot}2H_2O$	—	—	—	21.4	—	17.0
K_2SO_4	—	—	41.5	—	—	17.0
$MgSO_4{\cdot}7H_2O$	—	—	—	—	9.7	13.0
$K_2SO_4{\cdot}2MgSO_4$	—	—	18.2	10.8	—	22.0

Table 2. Main sources of macronutrients used for the preparation of nutrient solutions.

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Fertilizers	Nutrient %					
	B	Cu	Fe	Mn	Mo	Zn
H_3BO_3	17.0	—	—	—	—	—
$Na_2BO_2 \cdot 10H_2O$	11.0	—	—	—	—	—
$CuCl_2 \cdot 2H_2O$	—	37.0	—	—	—	—
$MnSO_4 \cdot H_2O$	—	—	—	43.0	—	—
$ZnCl_2$	—	—	—	—	—	48.0
$FeCl_3 \cdot 6H_2O$	—	—	21.0	—	—	—
$(NH_4)_6Mo_7O_{24} \cdot 4H_2O$	—	—	—	—	54.0	—
$NaMoO_4 \cdot 2H_2O$	—	—	—	—	34.0	—
$CuSO_4 \cdot 5H_2O$	—	25.0	—	—	—	—
$MnSO_4 \cdot 7H_2O$	—	—	—	32.0	—	—
$ZnSO_4 \cdot 7H_2O$	—	—	—	—	—	20.0
$Na_2B_4O_7 \cdot 5H_2O$	14.0	—	—	—	—	—
MoO_3	—	—	—	—	66.0	—

Table 3. Main sources of micronutrients used for the preparation of nutrient solutions.

Culture	$N\text{–}NO_3^-$	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Mo	Zn
	mg L^{-1}											
Lettuce	238	62	426	161	24	32	0.3	0.05	5.0	0.4	0.05	0.3
Tomato	169	62	311	153	43	50	0.2	0.03	4.3	1.1	0.05	0.3
Pepper	152	39	245	110	29	32	0.3	0.03	3.7	0.4	0.05	0.3
Eggplant	179	46	303	127	39	48	0.3	0.05	3.2	0.6	0.05	0.3
Cucumber	174	56	258	153	41	54	0.2	0.03	4.3	1.1	0.05	0.3
Melon	170	39	225	153	24	32	0.2	0.03	2.2	0.6	0.05	0.3
Strawberry	125	46	176	119	24	32	0.2	0.03	2.5	0.4	0.05	0.3

Table 4. Values of mineral nutrients in nutrient solutions used for the NFT system.

5. Potassium salinity in nutrient solution and its effects on metabolism

Potassium is an essential nutrient for all living beings, playing a key role in photosynthesis, which is the transformation of light energy into chemical energy (ATP and NADPH). As all vital plant functions depend directly or indirectly on ATP and NADPH, the influence of K on plant metabolism becomes evident. It also plays an important role in the activation of more than 60 enzymes, which act on several metabolic processes such as photosynthesis, protein synthesis, and carbohydrates, also affecting water balance and the growth of meristematic tissues [10].

K absorbed by the root is led to the aerial part by the xylem and phloem, its internal redistribution is quite easy. The element is directed from the older leaves to the younger leaves, to the growing regions and to the fruits. This is due, in part, to the fact that about 75% of plant potassium is soluble in tissues.

Cultures differ in their K requirements because of differences in the physiological functions in which K is involved. Cultures where the harvested part consists of young plant tissue, as is the case of leafy vegetables and fruits, have high requirements of K per unit of dry weight produced. When the same crop is harvested at the complete maturation stage, the requirement for potassium per dry weight unit is substantially lower. Cultures that produce fleshy fruits or storage organs have high K requirement when compared to cereals [11].

Among the various functions of potassium in plants, water use efficiency is better cited, as a consequence of the control of the opening and closing of the stomata, greater translocation of carbohydrates from the leaves to the other organs of the plant, and improved enzymatic efficiency and commercial quality of crops [12].

Relative quantitative evaluations for a particular mineral element can be achieved through the profile scanning of stomata. This type of comparisons between elements can only be made by applying calibration factors. In this way, K contents of guard cells of the opened and closed stomata can be measured. In opened stomata, there is more K, and there is more Cl than the closed one but the differences are not so great. On the other hand, P contents are almost the same.

Comparison of the traces and stomata indicates, as might be expected, that the P peaks coincide with the nuclei [13] (**Figure 3**).

Potassium also increases the natural resistance of the aerial part of plants, the fungal diseases, pests, damping-off and counter balances the effect of excess nitrogen absorption. However, excess potassium imbalances the nutrition of vegetables, making it difficult to absorb calcium and magnesium [13].

K is required for protein synthesis; when plants are deficient in K, there is less protein synthesis and accumulation of soluble nitrogen compounds, such as amino acids, amides, and nitrates. Thus, the proper use of nitrogen fertilizers depends, also, on an efficient supply of potassium to the plants. The supply of potassium fertilizers to the crops, besides affecting the production, also has an effect on the quality of the harvested fruit. Specifically for tomato, these qualitative characteristics are important both for use in industry and for consumption “in natura.” In tomato, the fruit’s flavor is determined by the amount of solids, mainly sugars and organic acids, and volatile compounds. Considering that, in the ripe fruit, 95% of its constitution is water, only a small amount of solid matter will determine its quality [14]. The decrease in the sugar contents correlates with high doses of nitrogen, which leads to the hypothesis that the apical pruning, associated to the various doses of N and K, can influence, in a certain moment, the level of substances in the fruits [14].

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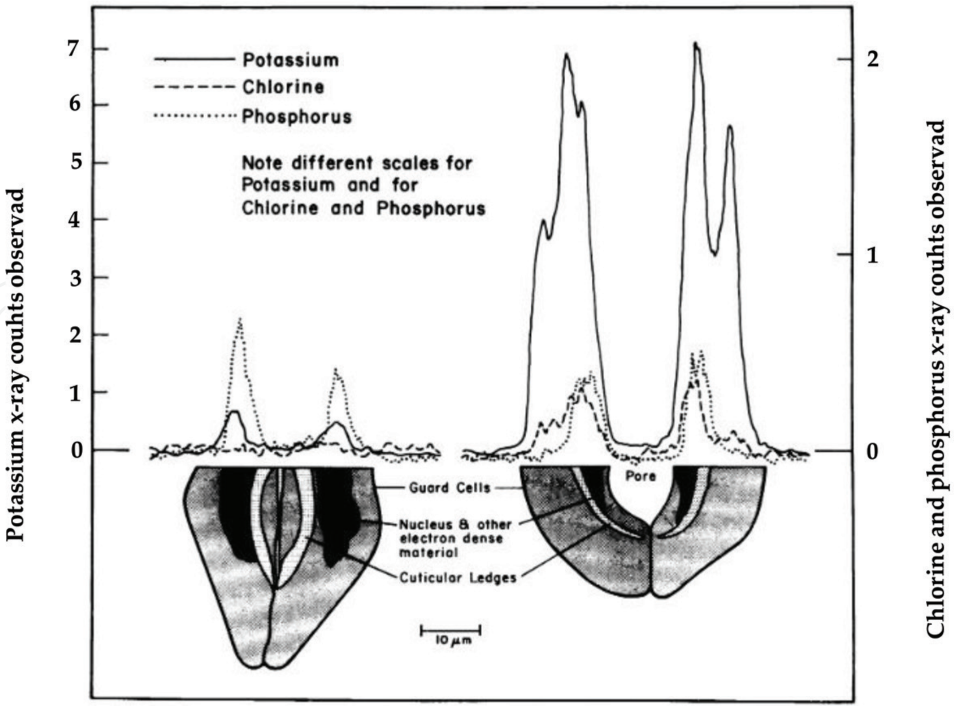

Figure 3. Profiles of relative amounts of K, Cl, and P across an open and a closed stoma. The traces are the result of scanning a 0.5–1 μm diameter beam across the stomata shown diagrammatically below the traces. In order to indicate the profile scanned, the images of the stomata have been cut off in this diagram where the beam crossed the guard [13].

The salinity of the nutrient solution is quantified by the electrical conductivity, which at varies function to the culture and nutrient balance in the solution. Once salts are diluted in the solution, the producer cannot identify which element is causing increasing osmosis power. The salinity in vegetables grown in the hydroponic system causes lower growth in plants, which is also due to the reduction in the absorption of some of the main nutrients, mainly Ca and K [15].

Plants are very sensitive to salinity where they absorb water having high contents of salts, which causes toxicity. This excess absorption promotes imbalances in the cytoplasm, causing damages to appear mainly at the edges and at the apex of the leaves, regions where the accumulation of absorbed salts occurs [16].

Imbalances may be the result of the salinity effect of nutrients above the required, or may be caused by physiological inactivation of an essential nutrient when it increases its internal requirement in the plant [17].

In a yield response curve, there is a point at which maximum production is reached and maintained at that level until an ionic concentration is reached in the solution, where production begins to decrease. This interval, between nutritional deficiency conditions and toxicity, depends particularly on the nutrient and nutritious solution salinity conditions [18].

Lower absorption of K by vegetables has been attributed to the higher competition between Na and K by the absorption sites or a higher flow of K from the roots. The reduction in K concentration, under saline stress, is an additional complicator for plant growth, since in some situations this element is the main nutrient contributing to the decrease of osmotic potential [19].

In relation to calcium, it has been demonstrated that increased salinity may induce its deficiency [20]. The reduction in Ca^{2+} absorption may lead to loss of plasma membrane integrity, with consequent loss of the absorption capacity of some ions, especially K^+ [21]. Salinity-tolerant varieties tend to have higher K^+ transfer rates and only slight reduction in Ca^{2+} transfer to aerial part, in order to maintain a positive relationship between those nutrients and Na^+ and Cl^- ions [22].

The high salinity of some fertilizers, mainly of KCl, compromises the growth and distribution of the roots, as well as the absorption of water and nutrients [23]. Potassium chloride is the main source of K for agriculture, followed by potassium sulfate used on a smaller scale. Potassium sulfate has a lower salinity effect than potassium chloride, which makes it more suitable for the preparation of nutrient solutions [24].

Plants undergo changes in their metabolism when maintained under adverse environmental conditions. Plant tissues are endowed with different response systems to control the production of free radicals. Due to their specific compartmentalization in the cells, the enzymes and organic compounds formed in situations of environmental stress can be determined. In saline conditions, there is a reduction in the availability of water to the plants; as water tends to move from point larger to the smaller the osmotic potential (of the salinized nutritious solution toward the plant), there will be greater energy expenditure for its absorption. The greater or lesser effort to overcome the osmotic potential difference varies according to vegetable species for adaptation to different salinity conditions [25]. In addition, this factor may influence the photosynthetic process, since the content of chlorophyll in the plants will be affected [26].

The high saline concentration in the solution can cause nutritional imbalance, toxicity of some ions, and interference in the hormonal balance, which are able to decrease the plasticity of the cell, causing reduction in the permeability of the cytoplasmic membrane.

The role of calcium in vegetable adaptation to saline stress is complex and not well defined. Saline stresses were observed in the positive effects of this nutrient. The effects of K and Mg are little studied because they have a beneficial effect on the plant to increase the tolerance of vegetables to salinity in the nutrient solution [27].

Applications of high and continuous doses of KCl may also raise the chloride ion content in the plant, leading to a chlorosis and necrosis of the leaves, as well as a drop in production. Chlorine does not enter into the constitution of organic compounds, being necessary for the photolysis of water, during photosynthesis and electron transport [28].

When applied externally, Ca^{+2} decreases saline stress by means of an unknown function that preserves K^+/Na^+ selectivity and inhibits K^+ absorption sites, which can reduce the Na^+ influx mediated by the K^+ absorption low-affinity component. Calcium is usually maintained in the cytoplasm at 100–200 mol m^{-3} by active transport, and NaCl promotes a rapid increase in its concentration in the cytoplasm, probably acting as a signal of general stress. Although there is no confirmation that this increase is a salinity tolerance effect, the higher concentrations of Ca^{+2} in the cytoplasm may be transient. Results suggest that this increase, as a function of exposure to NaCl, may be reduced by the increase in Ca-ATPase activity [29]. The eggplant presents resistance to salinity induced by potassium sources, being considered a plant that can be used in conditions of high osmotic potential [24].

6. Potassium affecting plant growth and yield

Salinization is a problem that invariably occurs in protected environments, due to the accumulation of salts present in fertilizers. This problem tends to aggravate over time with greater or lesser speed, according to the practices adopted. The effects of salinity on fruit and leaf vegetables are intense, causing flowers to fall, alteration of the fruits color, flowers abortion, and burn on leaf margins [30] (**Figure 4**).

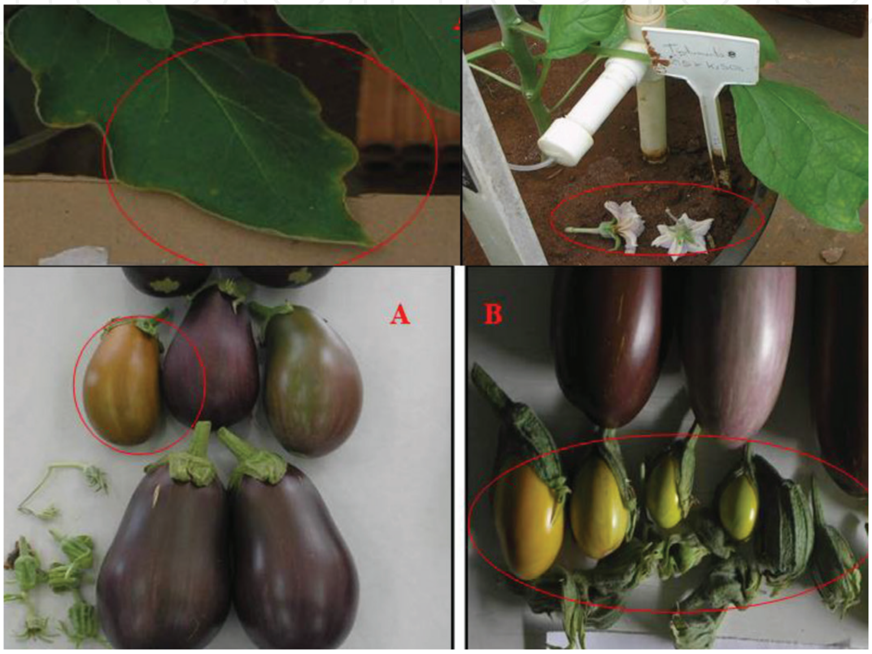

Figure 4. Images of the effects of salinity on eggplant.

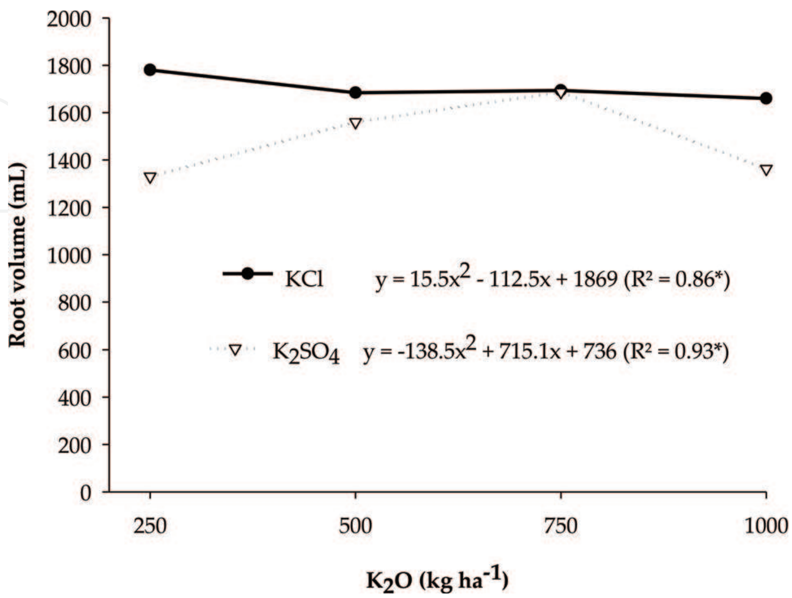

Figure 5. Root volume of eggplant (*Solanum melongena* L.), cultivar Embu, as a function of potassium doses and sources.

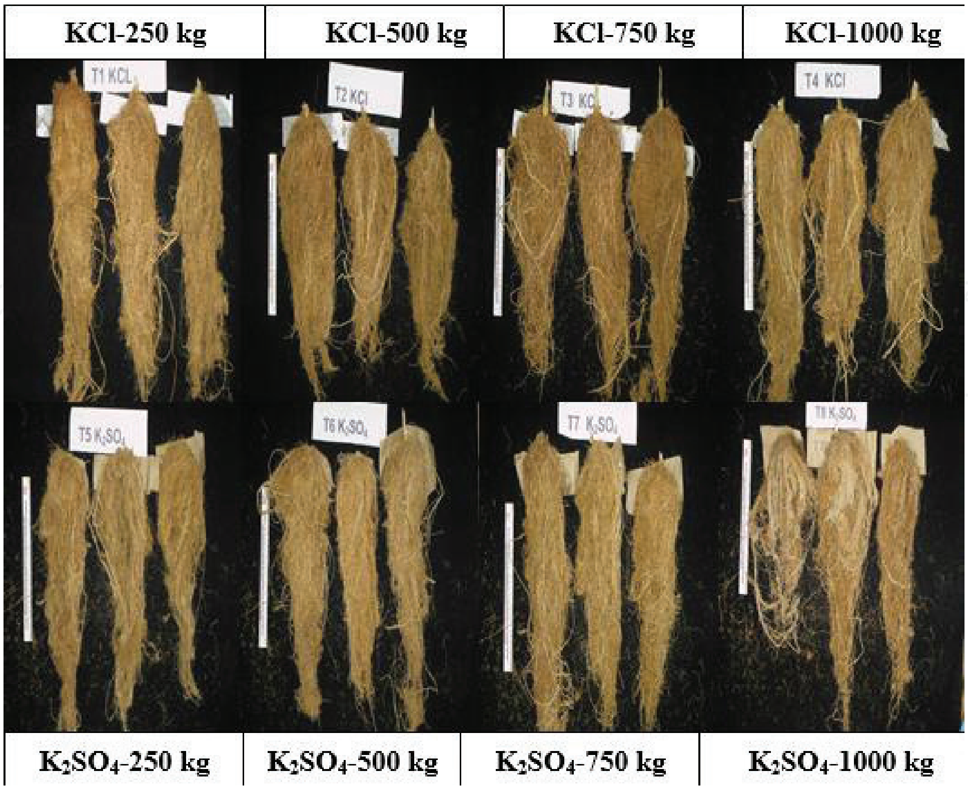

Figure 6. Roots of plants of eggplant (*Solanum melongena* L.), grow crops "Embu," according to doses and potassium sources.

Comparatively higher root volume was found when potassium chloride was used as the source of potassium fertilization than potassium sulfate (**Figures 5** and **6**). Considering the use of K_2SO_4, it is observed that the root volume increases with increasing doses, up to an estimated maximum value of 645 kg ha^{-1} K_2O; from here, there is a decrease, indicating a stressing effect on the plant. On the other hand, with KCl as source there is no definite trend of increase or decrease in the root volume, values found being stable and higher than those found with the K_2SO_4 source [30].

7. Cation dynamics in leaves and fruits of vegetables

Many problems have been observed related to excessive fertilization, leading the nutritious solution to an accumulation of salts. Although the water used in irrigation in the protected crop is of good quality, using the fertigation technique increases the risk of salinization [31].

In the process of nutrient absorption, the cationic interactions at the adsorption sites and the concentration of nutrient ions in the solution are important aspects in plant nutrition and crop production. The rate of absorption of a nutrient by the plant depends on the cations dissolved in the solution in dynamic equilibrium with the cations of the nutritious solution exchange complex [32]. The absorption of a nutrient is also affected by the nature of the complementary cations, that is to say, there is influence of an ion adsorbed in the release of another ion to the solution, besides the relations that involve the cations [33].

The elevation of K content in the solution can induce nutritional imbalance for the plants, due to antagonism, competitive inhibition, and noncompetitive inhibition among nutrients, in addition to synergism, which can cause a differentiated dynamics between cations in the leaves and roots of plants. However, little is known about the interactions between cations caused by excess doses of K_2O induced by different sources. When the K_2O doses are increased, regardless of the source used, the electrical conductivity increases linearly (**Figure 7**). However, it is observed that the values of electrical conductivity are significantly higher with the use of KCl, indicating an increase in nutritious solution salinity [34].

The electrical conductivity ranges between 3.82 and 1.33, with a mean of 2.49 dS m^{-1} when a dose of K_2O 250 kg ha^{-1} for KCl fertilizer was applied, whereas values were between 4.24 and 0.86 dS m^{-1} and averaged 2.55 dS m^{-1} for K_2SO_4 (**Figure 8A**). A decreasing trend of electrical conductivity was evidenced during the experimental period, and this reduction was more pronounced during 60 days after transplantation because of the onset of flowering and fruiting. In case of K_2O 500-kg ha^{-1} KCl dose, the electrical conductivity ranges between 3.46 and 0.89 dS m^{-1} and the average of 2.16 dS m^{-1}, while the range was between 3.30 and 0.28 dS m^{-1} with a mean of 1.79 dS m^{-1} for K_2SO_4 as potassium source (**Figure 8B**). A greater fluctuation of electrical conductivity was observed after K_2O 750 kg ha^{-1} especially for KCl, and the range was as high as 6.27 and as low as 1.30 having an average of 3.78 dS m^{-1} (**Figure 8C**). When K_2SO_4 was applied, electrical conductivity values obtained were between 4.27 and 1.03 dS m^{-1} with a mean of 2.65 dS m^{-1}. Subsequently, at a dose of K_2O 1000-kg ha^{-1} electrical conductivity in KCl and K_2SO_4 treatments remained within the ranges from 7.12 to 1.82 and from 3.36 to 1.25 dS m^{-1} (**Figure 8D**), with a mean of 4.47 and 2.11 dS m^{-1}, respectively [35].

The use of K_2SO_4 as a source of potassium fertilization generates a direct form of competition with Mg^{2+} in the roots of eggplants, high doses of K_2O affect production, and excess K induces

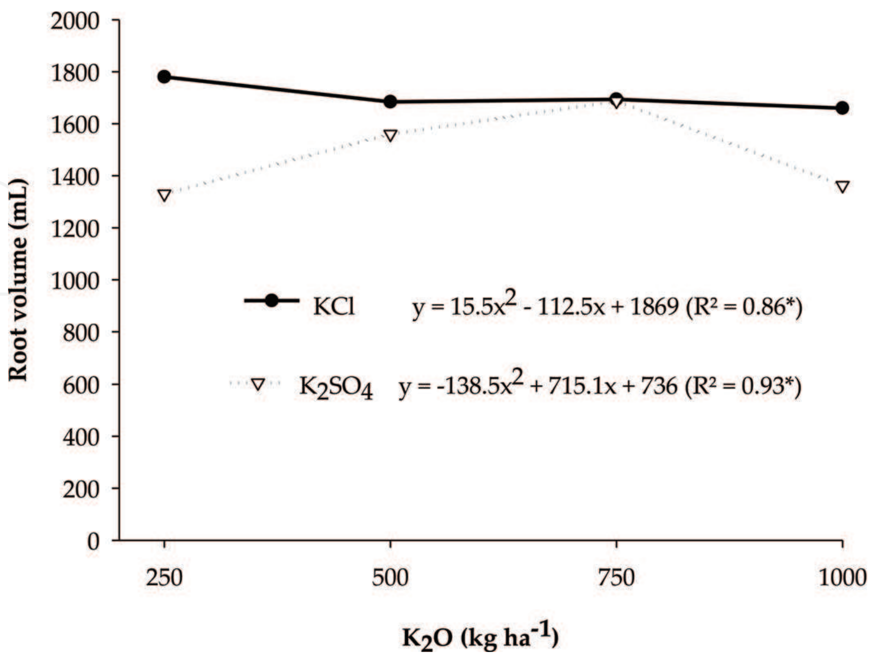

Figure 7. Electrical conductivity (EC) in function to sources and potassium doses.

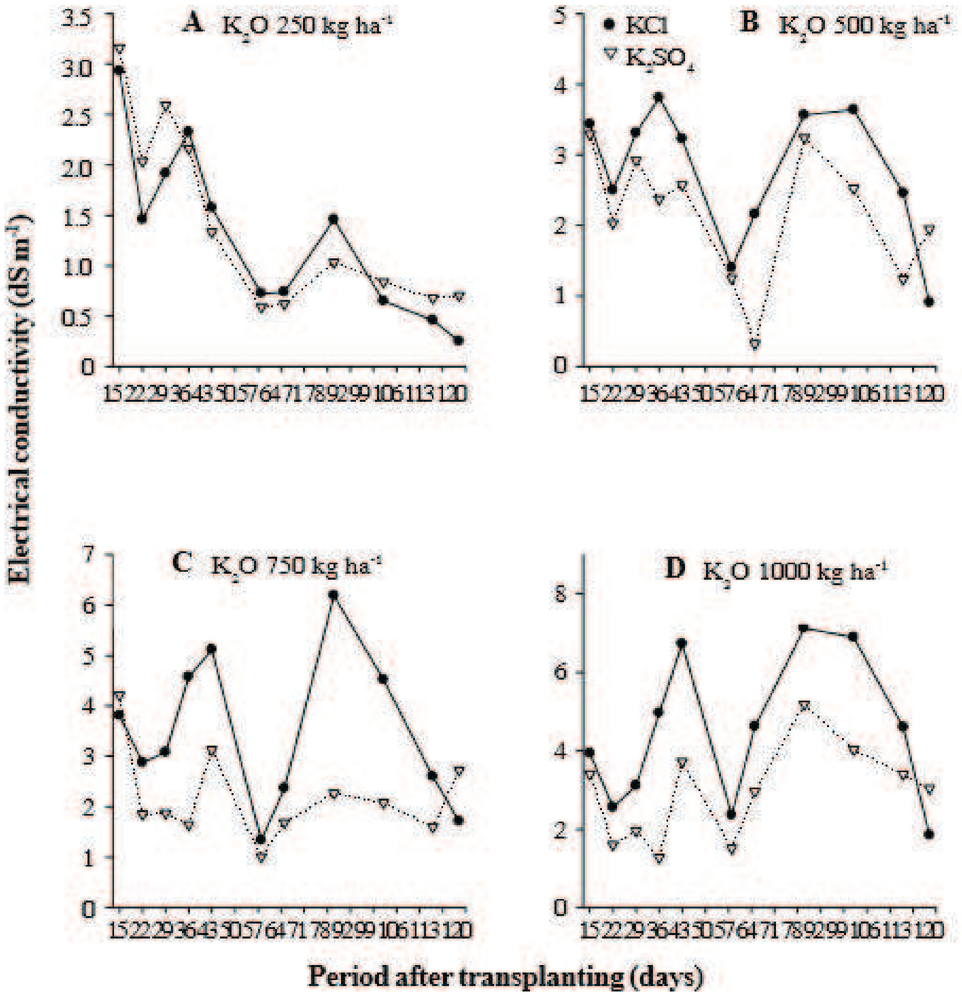

Figure 8. Electrical conductivity (EC) corrected for function and the sources and doses 250 (A), 500 (B), 750 (C) and 1000 (D) kg K_2O (KCl and K_2SO_4) in relation to the days after transplantation (DAT).

competitive inhibition between cations; however, the use of K_2SO_4 is less harmful, when used in excess, than that of KCl [34].

The elements are absorbed by the plants at different speeds, generally following the decreasing order as follows:

1. Anions—$NO_3^- > Cl^- > SO_4^{2-} > H_2PO_4$
2. Cations—$NH_4^+ > K^+ > Na^+ > Mg^{2+} > Ca^{2+}$

The accompanying ion, as a consequence of this, also influences at the absorption of its pair, so, for example, the maximum absorption of NH_4^+ will occur when it is accompanied by NO_3^-, the speed will be minimal if accompanied by $H_2PO_4^-$. **Table 5** presents examples of interionic effects.

The inhibition consists in the reduction of the mineral absorption due to the presence of another one, being considered competitive inhibition when the element and the inhibitor

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Ion present	Second ion	Effect of the second on the first
Mg^{2+}, Ca^{2+}	K^+	Competitive inhibition
$H_2PO_4^-$	Al_3^+	Not competitive inhibition
K^+, Ca^{2+}	Al_3^+	Competitive inhibition
$H_2BO_3^-$	NO_3^-, NH_4	Not competitive inhibition
K^+	Ca^{2+} (high concentration)	Competitive inhibition
SO_4^{2-}	SeO_4^{2-}	Competitive inhibition
SO_4^{2-}	Cl^-	Competitive inhibition
MoO_4^{2-}	SO_4^{2-}	Competitive inhibition
Zn^{2+}	Mg^{2+}	Competitive inhibition
Zn^{2+}	Ca^{2+}	Competitive inhibition
Zn^{2+}	$H_2BO_3^-$	Not competitive inhibition
Fe^{2+}	Mn_2^+	Competitive inhibition
Zn^{2+}	$H_2PO_4^-$	Competitive inhibition
K^+	Ca^{2+} (low concentration)	Synergism
MoO_4^-	$H_2PO_4^{2-}$	Synergism
Cu^{2+}	MoO_4^{2-}	Not competitive inhibition

Table 5. Examples of interionic effects [36].

are disputed at the same site of the carrier in the membrane. No competitive inhibition happens when binding occurs at different sites of the carrier. In the first case, the effect of the inhibitor can be annulled by increasing the concentration of the inhibited element, which does not occur at the second case. An example of competitive inhibition is observed between Ca, Mg, and K [36].

Synergism occurs when the presence of one element enhances the absorption of another, for example, Ca^{2+} in low concentrations increases the absorption of cations and anions (Viets effect), due to its role in maintaining the functional integrity of membranes, which has a consequence in the practice of fertilization; another example is Mg^{2+} which increases the absorption of phosphorus [36].

The black bottom or rot apical of the tomato (**Figure 9**) is a very common anomaly in fruits. It can cause high losses, above 50% of the fruits produced, especially in the lower parts. It is characterized by black spots, hard and dry in the apical extremity, and well visible from the formation of the fruits. The main cause is the lack of calcium in the tissue, caused by the competitive inhibition between K, Ca, and Mg, which causes Ca deficiency. This anomaly occurs very frequently in tomato culture in hydroponic system, because of the accelerated growth of plant, due to the environment conditions and the fact that calcium is still in the plant's phloem. This problem is aggravated when water deficiency occurs.

Figure 9. Physiological anomaly called black bottom or apical rot.

8. Changes in leaf proline protein induced by potassium

The proline concentration was significantly modified independently of potassium source, and higher level in this parameter occurred under potassium rate of K_2O 1000 kg ha^{-1} [35], as shown in **Figure 10A**. As for the protein content, with the increase in K_2O concentration there was a reduction in the content (**Figure 10B**).

Under normal conditions, proline is produced using glutamate and arginine while glutamate is the main pathway in stress conditions [37]. When plant experiences stress such as inadequate situations of mineral, salt, and water, proline protects the cell against denaturation processes, because this organic compound is highly soluble in water. It is accumulated in the cytoplasm of cells present in leaves, stems, and roots. Abiotic stresses like salt stress to *Oryza sativa* plants showed several biochemical consequences at different proline levels [38]. Significant changes in *Glycine max* plants under water deficit as an abiotic stress [39] were also found.

Some authors affirm that proline has functions linked to processes of adaptation to water deficit; however, others point to proline as an indicator of stress. Although there is no clear evidence of proline accumulation in tolerant species, its accumulation in species sensitive to water deficit has been observed, and this mechanism seems to be part of the protection against this type of stress [40].

The synthesis of proline has special importance in plants, because it is closely related to the water potential of the tissues. Plants in conditions of water stress or saline have high levels of proline compared to plants under normal conditions. This phenomenon seems to be related to the mechanism of protection against lack of water, because proline helps reduce the water potential of tissues and thus retain water. It is not by chance that the solubility of proline is much superior (162 g in 100 mL) than that of the other protein amino acids (in the range of <1–25 g in 100 mL). Although the two proline synthesis pathways are equally important under normal conditions, the evidence is more favorable to direct glutamate pathway (without acetylation) in water stress conditions [39].

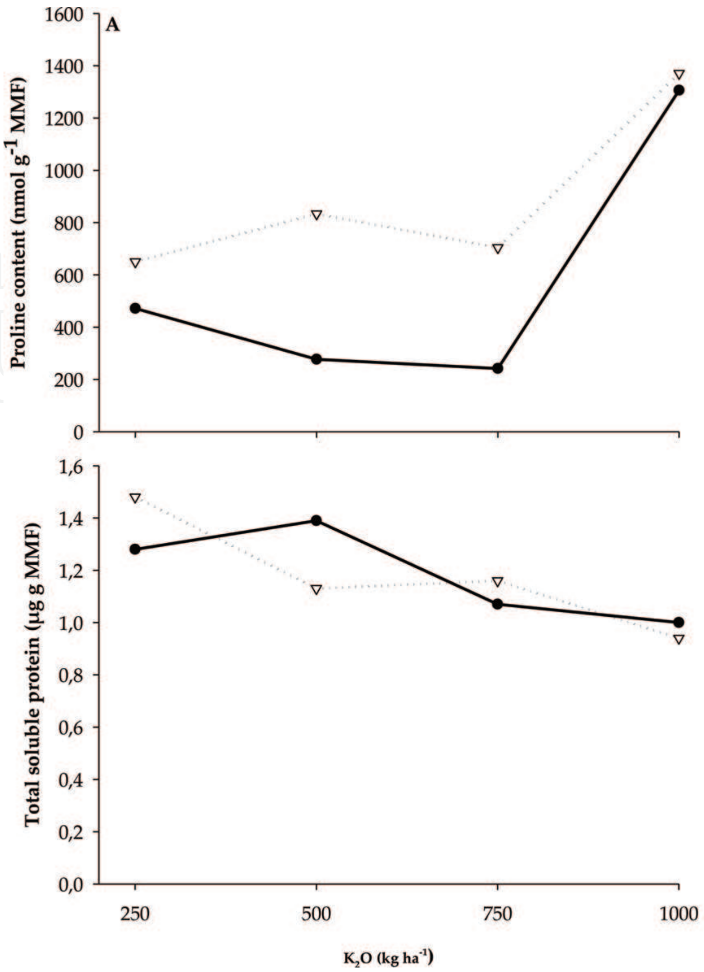

Figure 10. Concentration of proline (A) and soluble protein (B) in the gram of fresh matter mass (MMF) in function to the sources and doses of potassium.

In tomato culture, the accumulation of proline was detected within the first 24 h of the beginning of the treatment with excess fertilizers, observing its osmoregulatory activity. Halophytic or glycophytic plants adapt to high saline concentrations by lowering the osmotic potential of their tissues, with increased solutes absorption (Na and Cl ions). However, in less tolerant species, the growth is inhibited in function to the toxic effect of the accumulation of solutes [41].

9. Effect of potassium sources on the antioxidant activity

Plants have a high requirement for K for mainly maintaining a high K content in the cytoplasm, mainly to ensure enzyme activity [42]. A high concentration of K in cytosol and chloroplast stroma is also required to maintain anion neutralization and an appropriate pH level for cell functioning [21]. It can also participate in the control of stomatal opening and closing which is essential for photosynthesis. Despite the great importance of K, excess of it can reduce the osmotic potential of the solution, making the nutritious solution saline, resulting in a modified nutritious solution in which the growth of most species is prejudiced by the presence of high concentrations of soluble salts, exchangeable Na, or both in the rhizosphere [43]. Among the potassium fertilizers available on the Brazilian market, KCl is the most popular. Besides, K_2SO_4, $K_2SO_4 \cdot 2MgSO_4$, and other K sources are widely used in different agricultural segments in Brazil [44]. The above K source fertilizers produce different levels of salinity in nutritious solution, as, for example, KCl has a higher salt content than K_2SO_4. In the case of potato and eggplant, KCl application has resulted in lower yields compared to K_2SO_4 [41].

The enzymatic activity of catalase (CAT) is an enzyme that increases the rate of dismutation of the superoxide radical in hydrogen peroxide and is considered as an antioxidant enzyme (reactive oxygen species—ROS). CAT activity increases with increasing K_2O concentrations (**Figure 11**). High rates of KCl and K_2SO_4 increased the proline concentration at higher doses and reduced the protein concentration (**Figure 10**). The proline content of the leaf and the development of the eggplants are larger for the K_2SO_4 source [41].

Salinity can restrict the absorption of water and nutrients, reduce photosynthetic processes, and increase respiration, inducing a reduction in plant growth [45]. In the case of water deficit, the activity of the enzyme system and the production of compounds related to the antioxidant system of plants are altered [46]. This plant response occurs due to excessive accumulation of ROS in plant cells, in particular of superoxide, hydroxyl radical, and hydrogen peroxide [47]. Salinity can promote an intense ROS production that can lead to the degradation of proteins and membranes, reducing photosynthesis and plant growth [48]. Among the enzymatic mechanisms involved in detoxification of ROS, there are the isoforms of the enzyme such as superoxide dismutase (SOD), CAT, ascorbate peroxidase (APX), and peroxidase phenols (POX). SOD acts by converting O_2 into H_2O_2 and is localized mainly in the mitochondria and chloroplasts. These organelles generate most of the ROS in plant cells [49]. Peroxidases and catalases convert

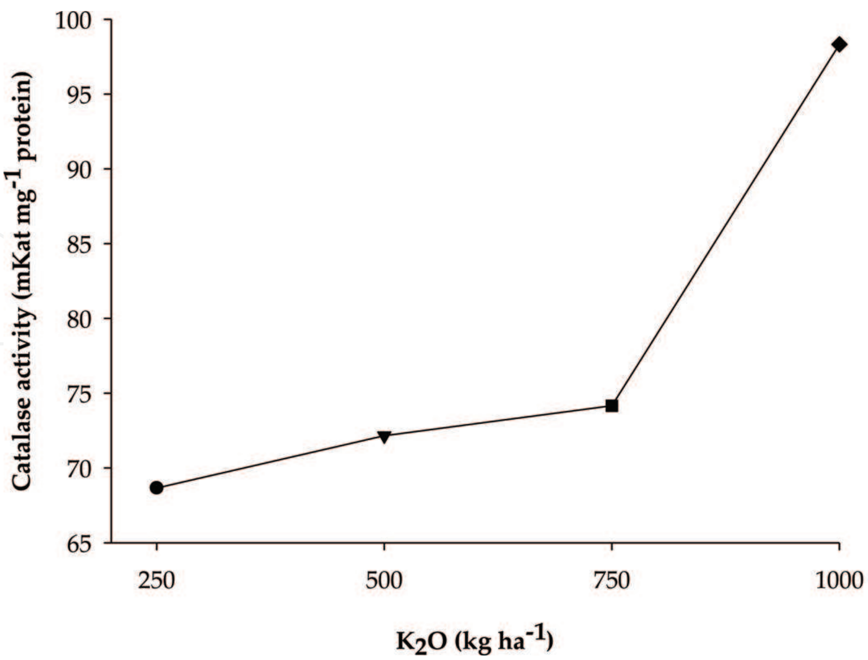

Figure 11. Catalase activity (mKat mg^{-1} of protein) as a function of potassium sources and doses.

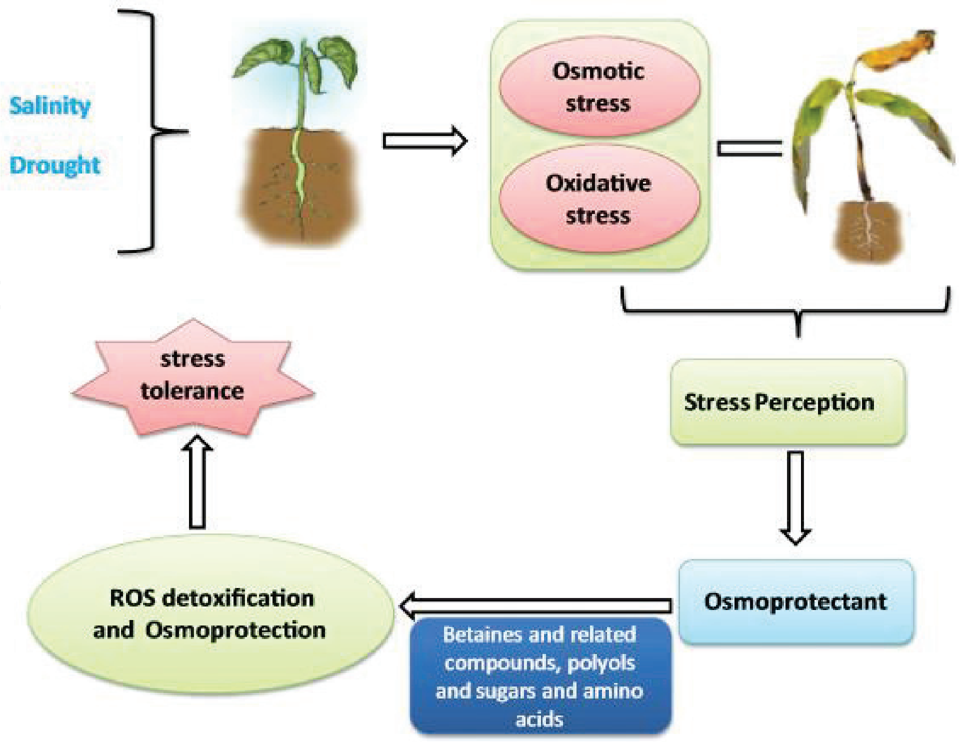

Figure 12. A general scheme of salt and drought stress tolerance in plants.

H_2O_2 into water and molecular oxygen, which are harmless to plants. Although the salinization leads to the production of ROS, at certain concentrations, K has an effect of reducing the harmful effects of salinization and ROS, mitigating stress effects [50]. This effect has been widely investigated in view of the need to understand its relationship with salinity and stress tolerance better. **Figure 12** [51] shows the general scheme of salt and drought stress tolerance in plants. Some osmolytes are involved in salt and drought stress tolerance through osmoprotection and ROS detoxification. They protect the plant from osmotic and ionic stresses [51].

10. Potassium increases crops quality

K is usually the most abundant cation in the cultures, being found in the tissues in greater proportion in the ionic form (K^+). K stimulates vegetation and tillering (grasses); increases the content of carbohydrates, oils, fats, and proteins; stimulates the filling of the grains, reducing the chopping; promotes storage of sugar and starch; helps symbiotic N fixation; increases the use of water; and increases resistance to droughts, frosts, pests, and diseases. As K improves the quality of agricultural products, it is described as the "quality nutrient." It is interesting to note the high correlation of K and proteins in the seeds of several cultivated plants, since cultures with high protein contents require (and export) large amounts of K through the grains.

Among the essential mineral nutrients for plants, K stands out for its influence in quality attributes that affect the concentration of phytonutrients critical for human health. However, many plants, nutritious solutions, and environmental factors often limit the absorption of K from the nutritious solution in sufficient quantity to optimize the quality attributes mentioned earlier [52].

K is a nutrient particularly required by carbohydrate-producing plants, as it participates in the photosynthetic process, transports carbohydrates from the leaves to the tuber or stalk, and activates the starch synthetase enzyme. In sugarcane, research results have shown a close relationship between the K content in the stems and with the sugar production. In the soybean culture, increased potassium fertilization promotes an increase in the grain protein content and a reduction in the oil content. This one fact can be understood by the participation of K in the process of protein synthesis in the plants. For citrus cultivation, it was observed that the increase of the K content in the leaves increases the size, the production, and the number of fruits. It also increases the vitamin C content and the percentage of acid in the juice, and decreases the concentration of soluble solids and the percentage of juice and solids/acid in the fruit.

The acidity in the tomato and the solids and starch content in the potato are positively correlated with the potassium fertilization, which also affects the composition and quality of strawberry, grape, grapefruit, pistachio, watermelon, and tomato. Generally, K appears to affect acidity, the pH, and carotenoid content. In tomato, the increase of K in the nutritive solution improves the color of the pulp and increases the content of lycopene, which is the carotenoid responsible for the red color of tomato and watermelon [53].

Lycopene is not essential for humans and animals, but research shows that it is then beneficial because it has antioxidant properties, which neutralizes free radicals that can cause cell damage. Lycopene is the most sensitive pigment to K deficiency, since K being an essential cofactor for protein synthesis, its deficiency could lead to reduced rates of enzymatic reactions involved in the synthesis of carotenoids and their precursors [54].

11. Final considerations

Potassium presents many important functions in leaf and fruit vegetables, including enzymatic activation, regulation of the osmotic potential of cells, cell expansion, and opening and closing of the stomata, being the nutrient that most affects the quality of leaf and fruit vegetables. Due to potassium performance in several physiological processes, especially in the enzymatic activity, its adequate nutrition is fundamental for the development and quality of the vegetables. The horticulturist should prioritize the use of potassic fertilizers with lower salt content, if possible free of chlorine and containing magnesium and sulfur. However, it is essential to remember that the high potassium content in plants can induce deficiency of calcium and magnesium.

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