THE EFFECT OF POTASSIUM ON THE QUALITY OF PLANT PRODUCTS

(Met opsomming in Afrikaans)

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Abstract

Quality of plant products are influenced by potassium. In this limited review, results from selected experiments with different crops are cited to illustrate and qualify the statement.

It is shown that the K content of the soil solution is a better parameter for availability than exchangeable K^+. The advantageous influence of K^+ on carbohydrate content is shown to coincide with the end of the vegetative period and the beginning of the reproductive period.

Crop quality must be evaluated in relation to crop yield, since increased yields may result in slightly decreased quality (eg sugar content), although the yield of the quality factor is substantially increased. There is proof of a beneficial KxN interaction which is ascribed to influence of K^+ on protein synthesis.

Many enzymes are selectively activated by K^+ and hence it plays a role in several biosynthetic processes, such as photophosphorylation and ATP synthesis. It enhances CO_2 assimilation and hence increases grain-filling rates.

K^+ favourably affects sugar synthesis and its translocation. Deficiency of K may contribute to the incidence of certain physiological diseases. The K/Ca balance is important in this regard. K^+ is required in the human diet to counteract negative Na^+ effects.

The effect of K^+ on the resistance of plants to certain fungus diseases, to drought and to frost is also discussed.

Introduction

It has been well known for many years that the quality of plant products can be influenced by fertilization. In this, potassium plays an important part. Alten & Coeze (1936) reported that the fibre of flax and hemp was improved by potassium. Adonsk & Jacob (1943), when evaluating a large number of field experiments, found a favourable effect of K^+ on the sugar content of sugar beets. Hoffman & von Schmeling (1955) suggested that abundant K supply increased the starch content of cereals. The content of vitamin C in fruits and vegetables, too, is affected by potassium nutrition (Scharrer & Werner, 1957). There are numerous references in literature according to which potassium exerts a beneficial effect on the quality of various crops. It goes beyond the scope of this paper to cite all these publications. The proceedings of the 8th Congress of the International Potash Institute held in Brussels in 1966 on Potassium and the Quality of Agricultural Products give an almost comprehensive survey of the effect of potassium on the quality of plant products.

The data reported in literature, slightly differ, and in some cases even rather conflicting results were obtained. In order to find an explanation for this incongruity and to bring the vast amount of observations and results to the essentials, the physiological processes and biochemical reactions should be considered which after all are responsible for those characteristics determining the quality of plant products. The object of this paper is to give some examples in this respect.

Discussion

Interaction between potassium and other factors

Fertilization is not identical with plant nutrition. The first term comprises only the addition of fertilizer to a soil. Nutrition, however, means that the plant nutrients move (diffusion) or are moved (mass flow) towards the plant roots by which they are taken up. Soil particles and especially clay minerals compete with the plant roots for the potassium given to a soil. It may happen that the major part of fertilizer added to a soil is strongly adsorbed or even fixed by clay minerals so that only a very small portion of the fertilizer potassium will be readily available to the plant. In such cases, an effect to potash application on plant quality cannot be expected. Effects on growth and quality presuppose an improvement of the potassium status of the plant.

This depends, above all, on the rate of potassium uptake by the roots and thus on the flux rate of potassium from the soil medium towards the plant roots (Mengel & von Braunschweig 1972). Soil moisture and K concentration of the soil solution are the most important factors controlling this flux rate. It is obvious that the flux rate decreases with increasing soil pF and that higher K concentrations in the soil solution result in higher K flux rates. For this reason it is the K concentration of the soil solution rather than the exchangeable K^+ of the soil that is the most important parameter of K^+ availability in the soil. This is clearly shown by the data of Figure 1, obtained from a pot experiment with *Lolium perenne* on four different soils (Grimme, Nemeth & von Braunschweig, 1971).

It appears that with increasing K^+ concentration in the soil solution the increase in yield follows a Mitscherlich curve. The content of exchangeable K^+ of these four soils amounted to 100, 100, 114 and 175 ppm K respectively as indicated in Figure 1. Although the content of exchange-

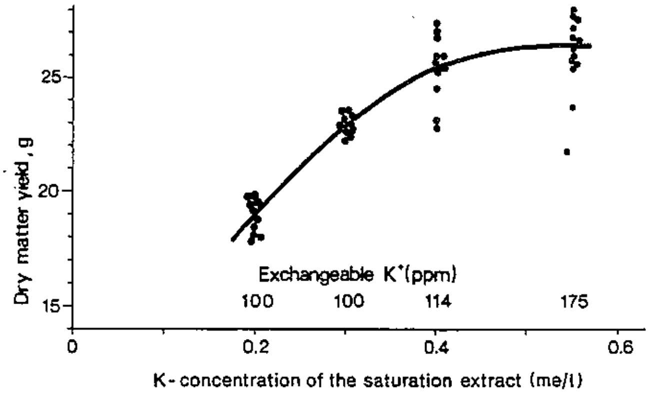

Fig. 1 Yield response of Lolium perènne *to K concentration of the soil solution and to exchangeable K^+ for four soils.*

able K^+ in the first three soils hardly differed, substantial differences in yield were observed. It is evident that the K concentration of the soil solution had a greater effect on yield than the content of exchangeable K^+. There exists a nearly linear relationship between the exchangeable K^+ of the soil and the K concentration in the soil solution. The slope of the curve is the steeper, the lower the clay content (Nemeth, Mengel & Grimme, 1970). This applies particularly to 2:1 clay minerals (vermiculite, chlorite, illite) which possess binding sites with a high selectivity for K^+. Kaolinite, the prevailing mineral in many South African soils, does not selectively bind K^+. The K^+ adsorbed to this clay mineral can easily be replaced by other cations, eg Ca^{++} or Mg^{++}. Soils with kaolinite as the predominant clay mineral are particularly subject to K leaching. These soils have a low K buffer capacity. Once the K^+ of the soil solution has been depleted due to uptake by the plants, replenishment of the soil solution with soil K^+ is restricted (Nemeth, 1974). As the behaviour of K^+ in the various soil types plays only an indirect part in the relationship between K^+ and plant quality, a detailed discussion of soil K^+ problems will go beyond the scope of this paper.

K application does not always result in an improvement of quality, eg increase in the starch content in sugarcane. There is no linear relationship between K^+ supply to the plant and improvement in quality; it rather follows a saturation curve. This means that an effect of K^+ on quality can only be expected, if the original K nutritional status of the experimental plants was unsatisfactory. A K effect on quality or the content of valuable organic constituents of plant matter depends furthermore on the physiological disposition of the specific crop. The data given in Table 1 may serve as an example (Hehl & Mengel, 1972). They show that an increase in K supply (K0, K2, K4) had no significant influence on the carbohydrate content of *Phleum pratense* at the start of vegetative growth.

At this stage of development the major part of the carbohydrates photosynthesized is used for the protein synthesis, ie for vegetative growth. At the end of the vegetative growth stage, however, the plants begin to accumulate carbohydrates needed for reproductive growth. At this stage, the physiological disposition of plant metabolism favours the synthesis and accumulation of carbohydrates, and it is during this period that K^+ exerted a remarkable influence on the starch and polyfructosan contents of *Phleum pratense* (see Table 1). A similar relationship was found in *Lolium perenne,* and it is assumed that this favourable effect of K^+ on the carbohydrate content at the end of vegetative growth is generally found in most grass species.

In practice, quality should not be considered separately. The yield level has also to be taken into account, because in most cases a certain yield level is needed to ensure some net profit to the farmer. Occasionally, quantity and quality of plant products are somewhat competitive. Table 2 shows the results of an experiment with sugar beet carried out under strictly controlled conditions (sand-solution culture).

TABLE 1 Effect of K on the carbohydrate content of Phleum pratense *at two different growth stages (Hehl & Mengel, 1972)*

	K0	K2	K4
Start of vegetative growth			
Starch, (%,on dry matter)	0,95	0,68	0,79
Polyfructosan, (%, on dry matter)	0,40	0,36	0,40
End of vegetative growth			
Starch, (%, on dry matter)	0,53	0,99	1,83
Polyfructosan, (%, on dry matter)	0,11	0,76	3,41

TABLE 2 Effect of the K concentration of the nutrient solution on yield and sugar content of sugar beets (Mengel & Forster, 1973)

Nutrient solution, me K/l	0,2	1,0	5,0
Roots, g/plant	392	602***)	647***)
Sugar, % (Pol.°)	16,3	16,0	16,5
Sugar yield, g/plant	49,1	68,9***)	71,9***)

***) highly significant with respect to 0,2 treatment

It is clear that the increase of K^+ in the nutrient solution from 0,2 me/litre to 1,0 me/litre resulted in a highly significant increase in yield of sugar beet roots, but the content of sucrose was slightly lowered. Higher root yield means that the physiological sink of the storage tissue is larger in volume. There were more cells in the storage tissue which had to be 'filled up' with sucrose. This explains the lower sugar content of the roots in the medium K treatment. With the highest K treatment (5,0 me/litre), however, this drawback was overcome. The root yield did not rise substantially, but the increase in the sucrose content to a satisfactory level of 16,5 per cent demonstrates that both quantity and quality were improved (Mengel & Forster, 1973).

Effects on quality are often due to the combined action of several plant nutrients. This is particularly true of nitrogen. Scharrer & Bürke (1953) reported that at low nitrogen supply the content of carotene in *Lolium perenne* was only slightly increased by K^+. With abundant N applications, however, the carotene content in dry matter rose from 214 ppm (K0 treatment) to 783 ppm (K3 treatment). This beneficial interaction between K^+ and N may be ascribed to the influence of K^+ on protein synthesis. Koch & Mengel (1972) showed that K^+ favours the uptake of nitrate, the reduction of nitrate in the plant and the incorporation of amino acids into protein. Table 3 gives the content of labeled N (^{15}N) in the protein fraction of shoots varied supplies of N and K^+ (Mengel & Koch, 1971).

The percentage of labelled N in the protein fraction is a reliable indicator of the rate of protein synthesis. It appears that with low N supply (N1) the higher K rate (K2) had no significant influence on the rate of protein synthesis, but at the highest N rate a marked effect of K^+ was observed. These data also show that with insufficient K supply, increasing N applications rather had a depressive effect on protein synthesis. The K x N interaction as illustrated in Table 3 may be of general and also practical importance. It is evident that higher nitrogen applications will only pay if adequate amounts of K^+ are given in addition.

An increase in the rate of protein synthesis does not necessarily mean an increase in the protein content of plant tis-

TABLE 3 Incorporation of labelled N into the protein fraction of young sunflower plants as influenced by N and K supplies (Mengel & Koch, 1971)

N treatment	% of labeled N in total protein N			
	Above-ground parts		Roots	
	K1	K2	K1	K2
N1	1,80	1,70	1,78	1,68
N2	1,50	1,65	1,29	2.95
N3	0,79	2,62	0,87	3,12

sue. The contents of all organic constituents in plant matter depend on the net rate of synthesis of such compounds and also on the growth rate of plant tissue. A relatively higher growth rate involves a dilution of the respective organic compound. This often occurs in young plants where K^+ favours the growth rate to a larger extent than the rate of protein synthesis. Table 4 illustrates such an example (Mengel & Koch, 1971).

Hsiao, Hageman & Tyner, (1970) made a similar observation. As is shown by the data of Table 4, the higher K supply resulted in an increased growth rate (fresh matter yield). K^+ likewise promoted the rate of protein synthesis as is evidenced by the heavier ^{15}N label of the protein fraction in the higher K treatment, but the protein content, referred to a fresh matter basis, was higher in the low K treatment than with increased K application. These results demonstrate that during the early growth period the growth rate is much more affected by insufficient K supply than protein synthesis.

Biosynthetic processes

According to Evans & Sorger (1966), today more than 40 different enzymes are known to be more or less selectively activated by K^+. The beneficial effect of K^+ on various

TABLE 4 Effect of the K concentration of the nutrient solution on yield, protein N content and incorporation of labeled N into the protein fraction of young sunflower plants (Mengel & Koch, 1971)

Nutrient solution me K/l	0,25	3,5
Yield, g fresh mass	6,8	10,8
Protein N, mg/100 g fresh mass	672	445
Labeled protein N, mg/100 g fresh mass	9,8	11,8

TABLE 5 Effect of the plant K status on photoreduction and photophosphorylation (Pflüger & Mengel, 1972)

	% K in dry matter	Photoreduction µeq e⁻/mg chlorophyll/h	Photophosphorylation µmole ATP/ mg chlorophyll/h
Vicia faba	3,70	512	216
	1,00	384	143
Spinacia oleracea	5,53	496	295
	1,14	424	185
Helianthus annuus	4,70	340	102
	1,60	326	68

processes of synthesis in the above mentioned plants are probably connected with these enzymatic reactions. It is supposed that K^+ plays a key role in phosphorylation processes, and especially in the synthesis of ATP. Table 5 shows the effect of foliar K^+ of various crops on the rate of electron transport in the photosynthetic electron chain and on the rate of photophosphorylation (ATP synthesis).

Both processes were accelerated by K^+ (Pflüger & Mengel, 1972); that means that in leaves with a high K status more energy (ATP) is available for synthetic work and a greater amount of reduced coenzymes is present for reducing reactions, such as the reduction of organic acids to sugars, the reduction of imino acids to amino acids, and the synthesis of fatty acids. This demonstrates the K^+ rather plays a more general than a specific role in various metabolic processes.

Carbon dioxide assimilation is a basic process in yield formation, Haeder (not yet published) found that K^+ enhanced the CO_2 assimilation rate in spring wheat resulting in higher grain filling rates. This beneficial effect became particularly evident during the milk stage, and it resulted in bigger grains and a higher 1000-grain mass which improves the seed quality of cereals. High 1000-grain masses of malting barley are regarded as a quality factor. The observation made by various authors that good K^+ nutrition increased the grain size can be ascribed to the fact that K^+ promotes the filling of the grain with organic constituents, especially with carbohydrates. Table 6 shows the grain fraction of barley grown in solution culture at two different K concentration (1,0 and 4,0 me K/litre).

Better K nutrition not only produced bigger grains, but also reduced the content of crude protein from 19,3 to 17,7 percent. This reduction is obviously due to a dilution effect brought about by the higher rate of grain filling with carbohydrates. It must be, however, admitted that a crude protein content of 17,7 percent in barley is still extremely high. It is caused by abundant nitrogen supply throughout the whole growing period (Mengel & Forster 1968).

The effect of K^+ on the crude protein content of cereals is not always clear, which means that a dilution effect does not occur in any case. In oats Mengel & Forster (1971) found an increase in the fat and protein contents of grains with increasing K supply, ie an improvement in feed quality.

In wheat, the baking quality is of particular interest. During the last decade it has been improved considerably in central Europe, not only due to the introduction of new varieties of better quality, but also by fertilizer application. No doubt, nitrogen plays a major role in this respect, but – as has been outlined above – full response to nitrogen is only obtained if sufficient K^+ is given in addition.

Table 7 shows that improved supply to spring wheat led to an increase in the crude protein content, raised the sedimentation values, increased the dough volume, and thus improved the baking quality substantially.

The results presented in Table 7 were obtained in a field experiment on a K-fixing site (Schäfer & Siebold, 1973). This explains the very high K rates (0, 250, 500, 750 kg

TABLE 6 Effect of K supply on grain size and crude protein content of barley (Mengel & Forster, 1968)

me K/l	1,0	4,0
Grain size	% crude protein	% crude protein
> 2,8 mm	14,9	38,4
2,5 – 2,8 mm	37,5	37,4
2,2 – 2,5 mm	25,3	16,4
< 2,2 mm	22,4	7,8
Crude protein (%)	19,3	17,7

TABLE 7 Effect of K application under K-fixing soil conditions on yield and quality of spring wheat (Schäfer & Siebold, 1973)

kg K/ha	(kg K_2O/ha)	Grain yield (kg/ha)	Grain protein (%)	Sedimentation rate	Rapid mix test (ml)
0	(0)	2240	13,8	47	690
250	(300)	2510	13,8	48	680
500	(600)	3840	14,4	53	720
750	(900)	4360	14,6	55	730

K/ha) applied. In this particular case the usual rate of about 83 kg K/ha possibly would not have led to any significant response of grain yield and quality. These high K rates have to be considered as a meliorative dressing applied once or twice in order to raise the fertility of the location to a satisfactory level. As emphasized by Schäfer & Siebold (1973), the heavy K supply not only improved yield and quality but also increased the profitability of wheat production.

Translocation processes

Not only processes of synthesis but also the translocation of photosynthates from the leaves to the storage organs and tissues may affect the quality of plant products. Hartt (1969, 1970) stated that the rate of basipetally-directed translocation of photosynthates in sugarcane well supplied with K^+ was higher than in plants with a poor K status. The favourable effect of K^+ on the sugar content as shown in Table 8 is probably due to both increased sugar synthesis and improved sugar transport.

Hartt's observation that K^+ favours the translocation of assimilates has been confirmed by various authors (Viro & Header, 1971; Header & Mengel 1972; Header, Mengel & Forster, 1973; Ashley & Goodson, 1972). It is, however, not yet clear which particular step in this source/sink relationship in crop production is influenced by K^+. Certainly also metabolic processes in the sink (fruits, storage tissue)

*TABLE 8 Effect of K on yield and sugar content of sugarcane; average values of 5 years (Rapport annual 1970 de l'IRAT) *)*

Annual rate kg K/ha	(kg K_2O/ha)	Cane t/ha	Sugar %	Extr. sugar t/ha
0	(0)	34	14,7	3,9
83	(100)	67	15,6	8,1
166	(200)	82	16,2	10,3
249	(300)	84	16,5	10,8

*) l'Agronomie Tropicale 27, 167–168 (1972)

affect the translocation rate in such a way that a high turnover rate in the sink accelerates the translocation to the sink. Header et al. (1973) found a higher rate of starch synthesis in potato tubers well supplied with K^+ than in low K tubers. The higher rate of starch synthesis could have been brought about only by an increased rate of translocation, but the reverse is also feasible, viz that the high rate of synthesis in the sink stimulated the translocation of assimilates to the sink.

Tomatoes insufficiently supplied with K^+ often show retarded maturation. In particular, the region of the fruit around the petiole does not ripen and remains green and hard. This so-called 'greenback' is an indication of poor quality. Table 9 shows the relationship between 'greenback' of tomatoes and K supply (Forster, 1974).

Very high K applications, especially at poor Ca supply, on the other hand favour the 'blossom-end rot' of tomato fruits. This disease is primarily caused by Ca^{++} deficiency, and it is intensified by high K dressings which restrict the uptake of Ca^{++} and its translocation to the fruits. The same applies to 'bitter pit' of apples. The supply of Ca^{++} to tomatoes and apples depends on the availability of Ca^{++} in the root medium, and especially on the Ca concentration in the soil solution and the transpiration conditions. Low transpiration rates result in poor acropetal translocation of Ca^{++} and hence insufficient supply of Ca^{++} to the fruits.

TABLE 9 Yield, total number of fruits, number of fruits with greenback and blossom end rot as influenced by the K concentration of the nutrient solution; average of six plants (Forster, 1974)

K concentration, me K/l	1	3	9
Yield, (kg)	8,60	9,10	11,6
Total number of fruits	187	209	242
Fruits with greenback	82	2	0
Fruits with blossom-end rot	9	15	21

TABLE 10 *Effect of the K concentration of the nutrient solution on the yield and cation content of tomato fruits (Viro 1973)*

K concentration (me K/l)	Yield (kg/plant)	K	Ca	Mg	Na
			(% on dry matter)		
2	3,27	1,6	0,09	0,07	0,10
10	5,22	2,5	0,08	0,08	0,07
20	4,16	2,7	0,07	0,09	0,06

'Black spot' of ware potatoes indicates poor quality. There is a close connection between the K content of the tubers and 'black spot'; the higher the K content, the lower is the occurence of 'black spot'. According to Vertregt (1968), the susceptibility of potatoes to 'black spot' is virtually reduced to nil, if the content of K in the tubers is higher than 2,5 percent in the dry matter. 'Black spot' is caused by a complex of iron and chlorogenic acid. Citric acid inhibits this complexation, probably by chelating Fe. The K of the tubers is positively correlated with the content of citric acid (Macklon & de Kock 1967). This is the reason why tubers high in K^+ are not susceptible to black spot.

Full insight into the physiological relation between the K and the content of citric acid has not been gained as yet. The content of citric acid and the quality of citrus fruits can also be improved by K dressings (Chow, 1966).

In conclusion, it should be stressed that in fruits and vegetables destined for human consumption K^+ alone is a quality factor. Modern human diet is often rich in Na^+, but low in K^+. High Na supply favours hypertension whereas K^+ acts as an antagonist counterbalancing the negative Na effect (Meneely, 1973). Abundant K supply results in K contents of fruits and other plant parts, because most plants take up the available K at high rates. Table 10 shows the effect of the K concentration in the nutrient solution on yield and cation content of tomato fruits (Viro, 1973).

TABLE 11 *Effect of K application on the infestation of winter wheat with* Septoria nudorum.

kg K/ha	(kg K_2O/ha)	% of ears infected
0	(0)	23,7
67	(80)	19,8
133	(160)	18,6
200	(240)	9,7

The highest K rate in this experiment amounted to 20 mmole K/litre in the nutrient solution, ie an extremely high concentration, which produced a substantial yield depression. With increasing K supply not only the K content but also the Mg content of the fruits went up. In this particular case, K^+ favoured the transport of Mg^{++} from the various plant parts towards the fruits, thus leading to a higher Mg content in the fruits.

Resistance and susceptibility to diseases

Disease resistance and susceptibility are not quality parameters *per se* but they often affect the quality of plant products in a more indirect way. The more intensive the cropping and especially the higher the supply of nitrogen, the greater is the susceptibility of crops to fungi infestation. Phosphorus and potassium, on the other hand, usually reduce the susceptibility of various crops to fungal diseases. Table 11 illustrates the relationship between K application and the infestation of spring wheat with *Septoria nudorum.*

The susceptibility of rice to 'brown leaf spot' (*Helminthosporium oryzae)* and of barley to 'brown rust' *(Puccinia hordei)* is also greater with insufficient K supply (Hak 1973). Bunescu, Tomoroga & Jancu (1972 found that the infection of wheat ears with *Fusarium graminearum* was considerably reduced in plots fertilized with K^+. Rot attack of maize culms (*Fusarium culmorum, F. nudorum)* is also diminished by K^+, particularly in case of excess N dressings (Trolldenier, 1969).

Drought resistance

There is also a connection between water consumption and drought resistance on the one hand and the potassium status of the plant on the other. Blanchet, Studer & Chaumont (1972) stated that the water consumption of alfalfa per kg dry matter produced was the lower the higher the K content of the plants. Similar observations were made by Linser & Herwig (1968) and by Mengel & Forster (1973). Resistance to drought and frost depends also on the amount of storage carbohydrates accumulated before the start of dormancy. As already pointed out, K^+ promotes synthesis and translocation of carbohydrates; thus in plants well supplied with K^+ usually larger carbohydrate reserves are avail-

TABLE 12 Effect of K^+ on the carbohydrate content of roots of alfalfa and the regrowth of plants in early spring (Hehl & Mengel, 1972)

	K0	K1	K2	K3	K4
Sucrose (% on dry matter)	12,2	13,7	14,3	13,4	13,7
Starch (% on dry matter)	5,8	7,7	11,3	10,2	11,8
Cellulose (% on dry matter)	27,8	25,2	25,0	25,5	24,4
Regrowth (g dry matter/ pot)	9,1	13,7	18,9	17,9	22,2

able during the rest period. Consequently, these plants have an increased chance to survive and they also show better regrowth. This becomes evident from the data of Table 12.

With the increased K supply particularly the starch content of alfalfa roots (lucerne) was raised and regrowth of these plants in spring considerably improved (Hehl & Mengel, 1972)

Opsomming

DIE INVLOED VAN KALIUM OP DIE GEHALTE VAN PLANTPRODUKTE

Die gehalte van plantprodukte word deur kalium beïnvloed. In hierdie beperkte oorsig word resultate van geselekteerde proewe met verskillende gewasse aangehaal om die stelling te illustreer en te kwalifiseer.

Dit word aangetoon dat die K-inhoud van die grondoplossing 'n beter parameter van beskikbaarheid is as uitruilbare K^+. Die gunstige invloed van K^+ op die koolhidraatinhoud val saam met die einde van die vegetatiewe periode en die begin van die reproduktiewe periode.

Oesgehalte moet in samehang met oesopbrengs ge-evalueer word aangesien verhoogde opbrengs effens verlaagde gehalte (bv suikerinhoud) tot gevolg mag hê, hoewel die opbrengs van die gehaltefaktor wesentlik verhoog is. Daar is bewyse van 'n gunstige KxN interaksie wat aan die invloed van K^+ op proteïensintese toegeskryf kan word.

Baie ensieme word selektief deur K^+ geaktiveer en daarom speel dit 'n rol in verskeie biosintesiese prosesse soos fotofosforilasie en ATP sintese. Dit bevorder CO_2 assimilasie en dus verhoogde graanvullingstempo.

K^+ beïnvloed suikersintese en suikertranslokasie gunstig. Gebrek aan K kan bydra tot die voorkoms van sekere fisiologiese siektes. In hierdie verband is die K/Ca balans van belang. K^+ word in die menslike dieet benodig om die negatiewe Na^+-effekte teen te werk.

Die invloed van K^+ op plante se weerstand teen sekere swamsiektes, teen droogte en teen ryp word ook bespreek.

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