

Productivity and efficiency index of potassic fertilization in cabbage

Thaísa Fernanda Oliveira¹, Leonardo Angelo de Aquino², Priscila Maria de Aquino²,
Iandra Rocha Barbosa², Talita Gabriela Gentil², Junia Maria Clemente³

¹ Universidade de Lavras, Lavras, MG, Brazil. E-mail: thaisafernanda135@gmail.com

² Universidade Federal de Viçosa, Viçosa, MG, Brazil. E-mail: leonardo.aquino@ufv.br; aquino.agronomia@gmail.com; iandra.ufv@gmail.com; talitagabrielagentil@gmail.com

³ Instituto Federal do Sudeste de Minas Gerais, Manhuaçu, MG, Brazil. E-mail: junia.clemente@gmail.com

ABSTRACT: Cabbage presents high growth rate, which demands studies with potassium fertilization due to the high extraction and export of potassium (K). The objective of this study was to evaluate the productivity and efficiency index of K in the plant and soil in response to doses and sources of this nutrient applied to cabbage crop. Two field experiments were conducted in areas with different soil K availability. The experiment was designed as randomized blocks with four replicates. The treatments consisted of five doses of K₂O (0, 100, 200, 400 and 800 kg ha⁻¹) applied with Potassium Chloride (KCl) source, and an additional treatment with Potassium Sulphate (K₂SO₄) source at the dose of 200 kg ha⁻¹ of K₂O. Cabbage shows high use efficiency and recovery efficiency of K from soil under low K availability conditions. High yields may be achieved by applying low K doses. The crop accumulated high quantities of K in the shoot, but without having increases on productivity with rising K doses. Potassium export was most of the accumulated in the shoot in both growing seasons, which shows that cabbage is a high demanding crop. The differences between K₂SO₄ and KCl sources were minimal on productivity and efficiency index of potassium fertilization in cabbage.

Key words: agronomic efficiency; *Brassica oleracea*; potassium; recovery efficiency

Produtividade e índices de eficiência da adubação potássica em repolho

RESUMO: O repolho apresenta taxa de crescimento elevada, o que demanda estudos com adubação potássica devido à alta extração e exportação de potássio (K) por essa cultura. Diante disso, objetivou avaliar a produtividade e índices de eficiência de K na planta e no solo em função de doses e fontes desse nutriente aplicado na cultura do repolho. Foram conduzidos dois experimentos a campo em áreas com diferentes disponibilidades de K no solo. O delineamento experimental foi em blocos ao acaso com quatro repetições. Os tratamentos consistiram de cinco doses de K₂O (0, 100, 200, 400 e 800 kg ha⁻¹) com a fonte Cloreto de Potássio (KCl), e um tratamento adicional com a fonte Sulfato de Potássio (K₂SO₄) na dose de 200 kg ha⁻¹ de K₂O. O repolho apresenta alta eficiência de uso e de recuperação de K do solo quando em condições de menor disponibilidade de K, com a possibilidade de alcançar altas produtividades com aplicação de baixas doses de K. Com o incremento das doses de K a cultura acumula grandes quantidades do nutriente na parte aérea, porém sem incremento correspondente na produtividade. A exportação de K foi a maior parte do acumulado na parte aérea, o que evidencia ser o repolho uma planta esgotante do solo. São mínimas as diferenças entre as fontes K₂SO₄ e KCl sobre a produtividade e índices de eficiência da adubação potássica no repolho.

Palavras-chave: eficiência agrônômica; *Brassica oleracea*; potássio; eficiência de recuperação

Introduction

Cabbage is the main commercial crop from the Brassicaceae family and one of the main vegetables grown in Brazil (Anuário Brasileiro de Hortaliças, 2017). High nutritional value and hybrids adaptation to Brazilian climatic conditions explain its importance (Filgueira, 2012; Correa et al., 2013). It is a vegetable that have high nutrient demand, which must be considered for restitution of nutrients export and maintenance of soil fertility (Cecílio Filho et al., 2013; Correa et al., 2013).

Potassium (K) is among one of the most extracted macronutrients by cabbage (Cecílio Filho et al., 2016). It favors formation and translocation of carbohydrates and the water use efficient by plants; improves products quality and, consequently, the commercial value (Wang et al., 2013; Cecílio Filho et al., 2016).

The uptake of K by plants is higher than those needed to increase productivity, which is called “luxury consumption” (Correa et al., 2013; Cecílio Filho et al., 2016). In spite of this capacity, an excessive K fertilization may increase the saline concentration of the soil, reduction on the uptake of other cations, mainly calcium and magnesium, also promoting reduction of crop productivity, and losses by leaching (Trani & Raij, 1997).

When present in soil solution, K can move vertically, mainly by drainage water. Due to this movement, K can be lost by leaching, that is, it is transported to depths beyond those considered explored by roots (Souza et al., 2012). This movement depends mainly on the type of soil, texture, cation exchange capacity (CEC), water and dosage, and fertilizer solubility (Duarte et al., 2013; Sharma & Sharma, 2013; Fortin et al., 2015).

The increasing crops dependence of fertilizers, their high cost, and finite K reserves are factors that require constant improvement in the management of K fertilization in vegetable crops. The objective of this study was to evaluate the productivity and efficiency indexes of K in the plant and soil in response to doses and sources of this nutrient applied to the cabbage crop.

Material and Methods

Two fields experiments were performed at Federal University of Viçosa (UFV), Campus Rio Paranaíba (Latitude - 19°11'39" S, Longitude - 46°14'37" W). The altitude of the area is 1,073 m and the predominant climate is Cwa, according to

Köppen-Geiger classification, which is characterized by a dry season and a well defined rainy season that occurs between October and March.

The experiments were conducted in fields with different K availability in the soil during two growing seasons (summer and winter). Corn and millet were the previous crops of summer and winter fields, respectively. The dry matter of leaves and stems of corn and millet were removed in order to not provide K in the successive crops. The soils of both areas are classified as Red-Yellow Latosol with very clayey texture (Embrapa, 2013), whose chemical attributes are presented in Table 1.

The experiments of summer and winter growing seasons were installed on December 11, 2015 and May 13, 2016 and harvested on February 29, 2016 and August 15, 2016, respectively. The cabbage cultivar used was Astrus Plus, F1 hybrid, which shows good compactness (head firmness) and heads with medium to large size, slightly flattened shape and mass ranging from 1.4 to 2.2 kg. The seedlings were produced in styrofoam trays with 200 cells, under protected environment, using an agricultural substrate composed by coconut fiber and vermiculite. For both experiments, the treatments consisted of 0, 100, 200, 400 and 800 kg ha⁻¹ of K₂O applied as Potassium Chloride (KCl). An additional treatment consisted of Potassium Sulphate (K₂SO₄) at 200 kg ha⁻¹ of K₂O. These doses encompass and exceed recommended doses of K₂O for the crop according some authors: 100 to 150 kg ha⁻¹ (Filgueira, 2012); 180 to 240 kg ha⁻¹ and complement with fertilization as topdressing with 60 to 120 kg ha⁻¹ (Trani & Raij, 1997); and 240 kg ha⁻¹ (CFSEMG, 1999).

The dose of 200 kg ha⁻¹ applied as K₂SO₄ was tested in order to obtain a comparison between K sources. Except the control (dose 0 of K₂O), the other treatments received 100 kg ha⁻¹ of K₂O at seedlings transplant. Therefore, this treatment with 100 kg ha⁻¹ of K₂O was performed all at once in the transplant. Treatment with 200 kg ha⁻¹ of K₂O was split with 100 kg ha⁻¹ of K₂O at the transplant and 100 kg ha⁻¹ of K₂O at 10 days after transplant (DAT).

The treatment 400 kg ha⁻¹ of K₂O was split with 100 kg ha⁻¹ of K₂O at seedlings transplant, 100 kg ha⁻¹ of K₂O at 10 DAT, 100 kg ha⁻¹ of K₂O at 20 DAT and 100 kg ha⁻¹ of K₂O at 30 DAT. The treatment 800 kg ha⁻¹ of K₂O received 100 kg ha⁻¹ of K₂O at transplant, 100 kg ha⁻¹ of K₂O at 10 DAT, 250 kg ha⁻¹ of K₂O at 20 DAT and 350 kg ha⁻¹ of K₂O at 30 DAT.

The experiment was designed as randomized blocks with four replicates. The plots presented four rows with six meters length and the ones designed as useful were the two centrals, excluding

Table 1. Soil chemical analysis at 0-20 and 20-40 cm depth in the summer and winter growing seasons.

Period	Layer (cm)	pH ⁽¹⁾ H ₂ O	P-rem (mg L ⁻¹)	P ⁽²⁾	K ⁺⁽²⁾	S ⁽³⁾	Ca ²⁺⁽⁴⁾	Mg ²⁺⁽⁴⁾	Al ³⁺⁽⁴⁾	H+Al ⁽⁵⁾	O.M. (dag dm ⁻³)	V	m
				(mg dm ⁻³)			(cmol _c dm ⁻³)					(%)	
Summer	0-20	5.5	22.1	16.9	106.0	30.0	2.8	0.7	0.14	5.1	2.0	42.5	3.6
	20-40	5.3	17.8	8.5	76.0	35.0	2.8	0.6	0.27	4.9	1.8	42.3	7.0
Winter	0-20	5.7	22.4	12.8	65.0	24.0	4.4	1.0	0.00	3.6	3.1	60.7	0.0
	20-40	5.7	14.3	4.2	34.0	23.0	3.6	0.9	0.00	3.5	2.5	56.7	0.0

⁽¹⁾ Ratio 1:2.5; ⁽²⁾ Mehlich 1 extractor; ⁽³⁾ monocalcium phosphate extractor in acetic acid; ⁽⁴⁾ KCl 1 mol.L⁻¹ extractor; ⁽⁵⁾ calcium acetate extractor 0.5 mol.L⁻¹/pH 7.0.

60 cm from edges. The plants were spaced at 38 cm between rows and plants for both experiments. The densified spacing was adopted to attain commercially accepted heads with a mean mass of about 1.5 kg, as suggested by Aquino et al. (2005).

The soil preparation consisted of a plowing and two harrowings. Excepting for K, the soil correction acidity and fertilizations were carried out according to soil chemical analysis and crop recommendations. In both experiments, on planting fertilization were applied 100 kg ha⁻¹ of N, 740 kg ha⁻¹ of P₂O₅, 2 kg ha⁻¹ of B, 1 kg ha⁻¹ of Cu and 5 kg ha⁻¹ of Zn, which were incorporated into the bed before of the transplant of the seedlings. Coats were performed at 10, 20 and 35 days after transplantation with 50 kg ha⁻¹ of N in each application according to the optimum dose suggested by Aquino et al. (2005). Crop treatments, pest control, and conventional sprinkler irrigation were performed according to crop needs. The seedlings were transplanted at 35 days after sowing.

The harvest was performed when heads compactness reached commercial acceptance. Ten uniform plants were harvested from useful plot and separated in heads (commercial part) and external leaves (vegetal remains), that originate the data of productivity and mean fresh mass of heads and external leaves.

After weighing, the heads and external leaves were then washed, grinded and placed in a forced air oven at 65° C until reaching constant weigh, in order to determine the dry matter (DM). The K content was determined according to Malavolta et al. (1997).

The K accumulations in each part of plants (head and external leaves) were calculated by the product between DM and K content for each organ. The total accumulated in the heads and external leaves are nutrients accumulation in the shoot, and the total accumulated only in the heads was the nutrients export.

The K available in soil (mg dm⁻³) after harvest was determined at 0-20 and 20-40 cm depths in order to analyze the soil contribution to the K uptake by plants at both depths. In each plot, 10 simple soil samples were collected and K content was determined using Mehlich-1 extractor (Tedesco et al., 1995).

The agronomic efficiency (AE) was calculated by the ratio between productivity gain and the applied dose of K₂O, calculated by the following Equation 1 (Fageria, 1998):

$$AE = \frac{P_{CAd} - P_{SAd}}{Q_{Ap}} \quad (1)$$

In which:

- AE - Agronomic Efficiency (kg kg⁻¹);
- P_{CAd} - Productivity in the plot with fertilization (kg ha⁻¹);
- P_{SAd} - Productivity in the plot without fertilization (kg ha⁻¹);
- Q_{Ap} - Amount of nutrient applied to the soil (kg ha⁻¹).

The recovery efficiency (RE) measures the percentage of K recovered by the plant from the K applied via fertilizer, and was calculated using the following Equation 2 (Fageria, 1998):

$$RE = \frac{(Q_{Ad} - Q_{NAd})}{Q_{Ap}} \times 100 \quad (2)$$

In which:

RE - Recovery efficiency by plant of the K applied via fertilizer (%)

Q_{Ad} - Amount of nutrient uptake by plant in the fertilized plot (kg ha⁻¹);

Q_{NAd} - Amount of nutrient uptake by plant in the non-fertilized plot (kg ha⁻¹);

Q_{Ap} - Amount of nutrient applied in the soil (kg ha⁻¹).

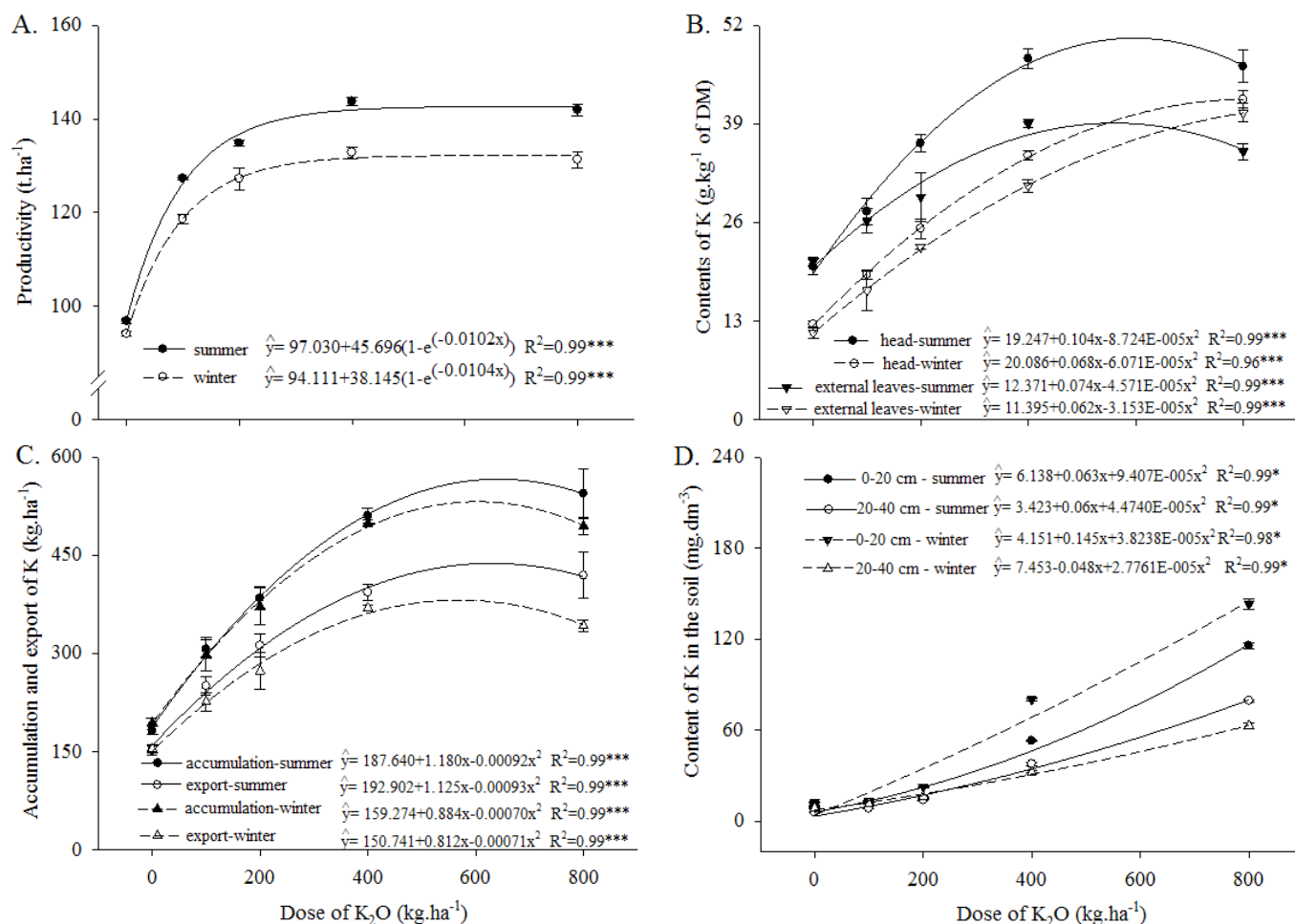
The best doses were defined as those that provided 95% of the maximum productivity estimated by fitted models. 5% was considered as field losses caused by failures at seedlings transplant, suppressed plants, wheels track of machines and implements, among others. Data were submitted to analysis of variance (F test for doses, p < 0.05), regression analyzes were performed and equations were fitted according to coefficients of determination. The sources were compared by t test (p < 0.05).

Results and Discussion

Figure 1A displays the nonlinear model fitted to cabbage productivity in response to K doses. Although the soils showed average K availability, between 1.6 and 3.0 mmol_c dm⁻³ (Trani & Raji, 1997), the plants responded to K fertilization (Table 1). The dose to obtain 95% of the maximum estimated productivity in summer season was 182 kg ha⁻¹ of K₂O and in winter season was 168 kg ha⁻¹ of K₂O, with productivities of 135.59 and 125.64 t ha⁻¹, respectively. These productivities overcome those observed by Moreira et al. (2011) of 56.5 t ha⁻¹, Correa et al. (2013) of 44.5 and 30.0 t ha⁻¹, and Cecílio Filho et al. (2011) of 72.7 t ha⁻¹. This difference may be related to the use of different plant populations. The cultivation of cabbage with denser spacings, with populations between 56 and 83 thousand plants per hectare, optimize the production by guaranteeing the mean mass of the heads around 1.5 kg which is considered ideal for the consumer market (Aquino et al., 2005).

Adapted to temperate climates (Filgueira, 2012), the new cabbage cultivars have shown good adaptation to tropical climates, which is reinforced by higher productivities of summer growing season than winter (Figure 1A). Summer season provides longer days with greater availability of solar radiation and water to plants, which are factors that affect their photosynthetic activity, mainly for improving the opening and closure of stomata, thereby, resulting in greater production, translocation and accumulation of photoassimilates (Xue et al., 2016; Guoying et al., 2017).

The leaf contents of K to obtain 95% of the maximum estimated productivities were 35.29 and 29.80 g kg⁻¹ of DM in the heads, and 24.32 and 20.92 g kg⁻¹ of DM in the external leaves, for summer and winter plants, respectively (Figure 1B). They are within adequate range (25 to 50 g kg⁻¹ of DM)



DM: dry matter. * and *** significant at 5% and 0.1%, respectively, by F test.

Figure 1. Productivity of cabbage (A), contents of K in cabbage from the heads and external leaves (B), accumulation of K in the shoot (heads and external leaves), export of K (C) and content of K in the soil after cabbage cultivation (D), submitted to doses of K in summer and winter growing seasons.

according to Trani & Raji (1997). The accumulation in the shoot and K export did not show great divergence regarding summer and winter growing seasons at the dose to reach 95% of the maximum estimated productivity (Figure 1C). In the summer growing season, shoot accumulation was 374.93 kg ha⁻¹, whereas in winter was 355.66 kg ha⁻¹.

Increasing doses of K to cabbage accumulated large amounts of this nutrient in the shoot, without corresponding increases on productivity (Figure 1A). Uptake of K beyond the crop demand is observed when K is in a soil with high K availability, assigning to the cabbage a "luxury consumption" state (Correa et al., 2013; Cecílio filho et al., 2016).

Correa et al. (2013) did not observe increases on productivity with an increasing K dose and reported a higher concentration of K in cabbage the higher KCl dose applied. Increased accumulation of K can also be considered as a "safety strategy" to enable the plant to better survive a sudden environmental stress condition (Kafkafi, 1990), such as soil water deficit. Thus, in this condition the plant can maintain high K⁺ content in the cytoplasm, mainly to ensure enzymatic activity and osmotic potential (Marques et al., 2014; Pottosin & Dobrovinskaya, 2014).

Most of the K was accumulated in the shoot (Figure 1C) for both growing seasons, being 80% in summer and 75% in winter, which shows that cabbage is a soil exhausting crop regarding K and the importance of replacement during cultivations. K accumulation in the cabbage shoot in the two growing seasons (Figure 1C) was close to the total availability of K in the soil considering the differences in the contents available at 0-20 and 20-40 cm depths before (Table 1) and after cultivations (Figure 1D).

Potassium that would be accumulated in the whole plant considering also stem and root is not possible to be evaluated, as only external leaves and heads were collected in this study. For the dose of higher productivity (277.8 kg ha⁻¹ of K₂O), root and stem contributed with 14.7 and 7.1%, respectively, in the DM partition of the plant according to Moreira et al. (2011). Therefore, in these 22% of DM, it is possible that K accumulation by plants is equivalent or higher than the total available at 0-40 cm depth of soil.

Potassium availability to plants depends on the contents and forms of K in the soils (non-exchangeable K, exchangeable K and soluble K), which vary with degree of pedogenetic development (Chaves et al., 2015). Researches on Brazilian

soils has shown that quantities of K extracted by plants were higher than those estimated by routine extractors regarding the availability of K in the soil, which suggests good nutrition in K to plants from non-exchangeable forms of K in short, medium and long term (Chaves et al., 2015; Manning et al., 2017).

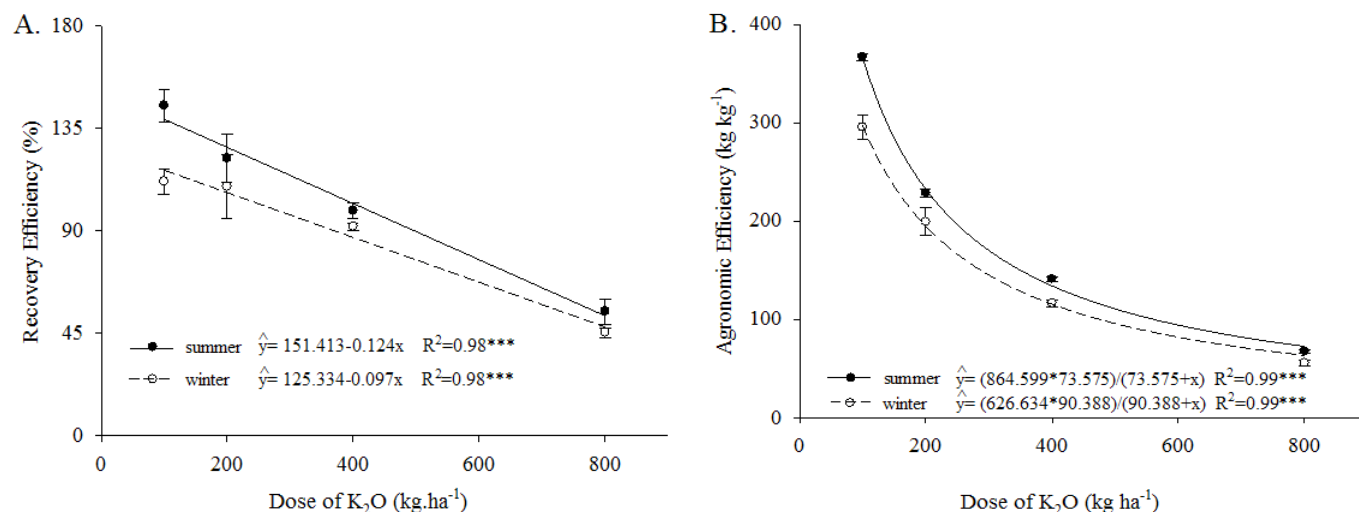
In addition to the fact that plants can access K forms that most of the usual extractors do not quantify (Wang et al., 2011; Chaves et al., 2015), K from deeper layers may contribute (Souza et al., 2012), and, in this case, layers beyond 40 cm are analyzed. Deeper soils, such as Latosols and intensive agriculture regions with application of high doses of fertilizers, and deeper layers are considered nutrient reserves for plants because K is more susceptible to leaching (Liao et al., 2013; Sharma & Sharma, 2013; Fortin et al., 2015)

The recovery efficiency (RE) reflects the percentage of the applied nutrient that plants uptake (Figure 2A) and presented a linear decrease with increasing K_2O doses for both growing seasons, that is, the efficiency of nutrient uptake reduces when nutrient availability is higher than crop demand. To obtain 95% of the maximum estimated productivity the RE was 128% and 109% in summer and winter growing seasons, respectively (Figure 2A).

High values of RE show that cabbage plants are very efficient to recover K from soil when K availability is low and, there was contribution of non-exchangeable K or exchangeable K below 40 cm from soil surface, regarding the absorbed by cabbage. As with other plants (Chaves et al., 2015; Manning et al., 2017), cabbage is able to access K forms that are not quantified by usual extractors in soil chemical analysis.

Nonlinear models fitted to agronomic efficiency (AE) decreasing in response to K doses for both growing seasons (Figure 2B). To obtain 95% of the maximum estimated productivity, the AE was 248.90 $kg\ kg^{-1}$ in the summer season and 219.20 $kg\ kg^{-1}$ in the winter season. By defining the productivity per kg of nutrient applied, the AE shows that cabbage is a plant with high use efficiency of K, possibly achieving high cabbage yields by applying low K doses.

Regarding the K sources, they did not influence most of the characteristics evaluated (Table 2). In the summer, K_2SO_4 provided higher leaf content of K in the plant remains and higher content of K available in the soil after cultivation at 20-40 cm depth. In the winter experiment there was difference only for the content of available K at 20-40 cm depth; higher values were observed for K_2SO_4 . There was no difference between KCl and K_2SO_4 sources for fresh and dry matter of



*** significant at 0.1% by F test.

Figure 2. Recovery efficiency (A) and Agronomic efficiency (B) of cabbage, cultivar Astrus Plus, submitted to doses of K in summer and winter growing seasons.

Table 2. Productivity, contents and efficiency index of K fertilization in cabbage, cultivar Astrus Plus, submitted to the sources of KCl and K_2SO_4 at 200 $kg\ ha^{-1}$ of K_2O , in summer and winter growing seasons.

	Summer		Winter	
	KCl	K_2SO_4	KCl	K_2SO_4
Productivity ($t\ ha^{-1}$)	134.3 a	134.9 a	127.5 a	128.6 a
Content of K in external leaves ($g\ kg^{-1}$ of DM)	25.2 b	30.9 a	22.7 a	24.5 a
Content of K in heads ($g\ kg^{-1}$ of DM)	36.5 a	34.1. a	29.4 a	29.4 a
Extraction ($kg\ ha^{-1}$)	384.1 a	389.0 a	371.0 a	371.7 a
Export ($kg\ ha^{-1}$)	312.1 a	295.0 a	272.9 a	273.1 a
Recovery efficiency (%)	121.7 a	125.1 a	106.3 a	106.4 a
Agronomic efficiency ($kg\ kg^{-1}$)	229.0 a	226.0 a	200.0 a	210.9 a
Content of K at 0-20 cm ($mg\ dm^{-3}$)*	14.7 a	14.8 a	22.3 a	22.7 a
Content of K at 20-40 cm ($mg\ dm^{-3}$)*	13.8 b	15.0 a	16.5 b	19.5 a

Means followed by the same letter, in the row, do not differ statistically by t test at 5% probability. * Available K in soil after cabbage cultivation.

head and external leaves outside the head; number of leaves (internal and external); diameter and head height according to Correa et al. (2013).

There was no effect of K_2SO_4 source on the KCl source in the study to determine the effect of these sources on growth and yield of kale, celery and lettuce cultivated in hydroponics (Inthichack et al., 2012). Applying KCl resulted in relatively higher yield of celery, but there was no difference for kale and lettuce, regardless K dose. In addition, K supply with K_2SO_4 source resulted in higher tips burn compared to KCl, especially at high K concentrations.

Regarding K available in the soil after cultivation, it was verified, for both soils, that K_2SO_4 presented greater availability of K at 20-40 cm depth (Table 2). It indicates higher K leaching with KCl for layers beyond 40 cm of soil. Sharma et al. (2013), evaluating the leaching of K comparing the accompanying anions Cl^- , SO_4^{2-} , NO_3^- and $H_2PO_4^-$, determined that leaching of KCl is greater than K_2SO_4 , following the order $SO_4^{2-} \leq H_2PO_4^- < NO_3^- = Cl^-$.

Conclusions

Cabbage presents high use and recovery efficiencies of K from the soil when under low K availability, possibility reaching high yields by applying low K doses.

Cabbage accumulates large amounts of K in the shoot, but without having a corresponding increase on yield with high K doses.

Most of the K is accumulated in the shoot in both growing seasons, which shows that cabbage is a soil-exhausting plant.

The differences between K_2SO_4 and KCl sources are minimal on productivity and efficiency index of potassic fertilization for cabbage.

Acknowledgments

The authors would like to thank CNPq, CAPES and FAPEMIG for their financial support for research, and to CAPES for the master's scholarship granted to the first author and CNPq for the research productivity scholarship of the second author.

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