

Agronomic efficiency of potassium fertilization in lettuce fertilized with alternative nutrient sources¹

Eficiência agrônômica da adubação potássica na alface adubada com fontes alternativas de nutrientes

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ABSTRACT - The aim of this study was to evaluate the effect of alternative sources of nutrients on the nutrition, yield and efficiency of potassium fertilization in lettuce. The experiment was carried out in a greenhouse, using 3.7 kg pots filled with a dystrophic red-yellow Latosol of medium texture. The experimental design was randomized, with treatments divided into a 4 x 6 factorial: four doses of potassium (0; 200; 400; 600 kg ha⁻¹ K₂O) and six alternative sources of nutrients (breccia, ultramafic, biotite schist, phlogopite, and mining and Chapada by-products), with four replications. Content and accumulation were determined for potassium (K), copper (Cu), zinc (Zn) and nickel (Ni) in the lettuce shoots, and from these data two indices were calculated for the efficiency of potassium as a fertilizer. The application of increasing values of alternative sources of nutrients promoted improvements in nutrition and increases in lettuce yield. The efficiency of potassium fertilization decreased with the increase in values of potassium taken from alternative nutrient sources, with the mining by-products and the ultramafic being superior to the other sources. Crushed silicate rocks and mining by-products can therefore both be used as fertilizer in organic and conventional production systems.

Key words: *Lactuca sativa* L. Silicate rocks. Mining by-products.

RESUMO - O objetivo desse estudo foi avaliar o efeito da aplicação de fontes alternativas de nutrientes na nutrição, produção e eficiência da adubação potássica na alface. O experimento foi conduzido em casa de vegetação, em vasos com 3,7 kg preenchidos com um Latossolo Vermelho Amarelo distrófico de textura média. O delineamento experimental foi inteiramente casualizado e os tratamentos foram distribuídos em arranjo fatorial 4 x 6, sendo quatro doses de potássio (0; 200; 400; 600 kg ha⁻¹ de K₂O) e seis fontes alternativas de nutrientes (brecha, ultramáfica, biotita xisto, flogopitito, subproduto de mineração e subproduto de chapada), com quatro repetições. Foram determinados o teor e o acúmulo de potássio (K), cobre (Cu), zinco (Zn) e níquel (Ni) na parte aérea da alface e com esses dados foram calculados dois índices de eficiência da adubação potássica. As aplicações de doses crescentes das fontes alternativas de nutrientes promoveram melhorias na nutrição e aumentos na produção da alface. A eficiência da adubação potássica diminuiu com o aumento nas doses de potássio aplicadas pelas fontes alternativas de nutrientes, sendo que o subproduto de mineração e a ultramáfica foram superiores às demais fontes. Diante disso, pode-se afirmar que as rochas silicáticas moídas e os subprodutos de mineração constituem uma opção para adubação em sistemas de produção orgânica e convencional.

Palavras-chave: *Lactuca sativa* L. Rochas silicáticas. Subproduto de mineração.

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INTRODUCTION

Potassium makes up 2.6% of the Earth's crust, being the third mineral element most used as a nutrient by plants after iron and calcium. Mineral potassium in rocks is found mainly in silicates which release this nutrient into the soil through the process of continuous weathering (WILPERT; LUKES, 2003).

Reserves of potassium salts used for the production of fertilizers in Brazil are mostly composed of minerals with low solubility in water due to the resistance of the structure of the minerals to be broken down under natural soil conditions (OLIVEIRA; SOUZA, 2001). Allied to this, low efficiency in the use of nutrients in Brazilian agriculture contributes to an even greater dependence on imports.

The source which is most used in the country is potassium chloride (KCl) with a consumption of 4.8 million tons of potash product KCl (OGASAWARA, 2010), with 91% of this being imported. However, in certain systems of cultivation such as organic agriculture, the use of such mineral fertilizers as KCl is not permitted. In this case, the feasibility of its being used not only depends on the cultivation system, but on the distance between the places of application and production. Crushed rocks are still not considered to be soil conditioners, or used to correct acidity, or as fertilizers under Brazilian law, but these products are becoming an alternative method of fertilisation in the various systems of agricultural production (FYFE *et al.*, 2006; GUARÇONI; FANTON, 2011; SILVEROL; MACHADO-FILHO, 2007; STOCCO *et al.*, 2010; VAN STRATEEN, 2006).

In most regions of the country there are materials that are by-products of mining activities. Currently these by-products in the major part of these regions, are considered an environmental liability if left unused. On the other hand, because they contain nutrients they may be used for fertilisation thus turning them into important materials. The feasibility of their use will depend mainly on the distance from the place of transportation to the farm, in a similar way to what happens with limestone.

Brazil has an area of 35,000 hectares of lettuce planted by small farmers, and directly generates employment of around five people per hectare (COSTA; SALA, 2005). The states of São Paulo and Minas Gerais are the largest producers of this vegetable (PIMENTEL *et al.*, 2009). In the mid-west region of Brazil most of the production is in the area composed of the towns of Goiânia, Anápolis and around Brasília (IEA, 2010).

All these regions are close to areas where alternative sources of nutrients are available, such as silicate rocks that can be crushed and used for correcting

soil acidity, and also as a source of nutrients such as potassium. Among these are breccia (Rio Verde, Goiás), chapada mining by-products (Chapada, Goiás), biotite schist (Nova Era, Minas Gerais), mining by-products (Sete Lagoas, Minas Gerais), *Verdete* (Cedro de Abaeté, Minas Gerais), ultramaphic rocks (Lages, Santa Catarina) and phlogopite (Campo Formoso, Bahia).

The use of crushed potassic rocks to correct soil acidity, and as an alternative source of nutrients (NOGUEIRA *et al.*, 2012; PRATES, *et al.*, 2012), combined with a greater efficiency in fertilisation and minimal environmental impact on agricultural areas (ANDRADE *et al.*, 2008; SANTOS *et al.*, 2002), if made viable, will help silicate rocks become an alternative source of nutrients for Brazilian farmers in various agricultural production systems.

Accordingly, the present study was undertaken to evaluate the effect of crushed silicate rocks and mining by-products that were selected from among several promising materials in terms of nutrition, of providing potassium, and of the efficiency of potassium fertilisation, in the lettuce.

MATERIAL AND METHODS

The experiment was carried out in a greenhouse of the Department of Soil Science at the Federal University of Lavras, in Lavras, Minas Gerais, from December 2010 to February 2011. To that end, samples of a sandy clay loam dystrophic red-yellow Latosol were collected at Itutinga, Minas Gerais, in an area of natural vegetation, at a depth of from 0 to 20 cm. Subsequently, the collected soil was air dried, had all clumps removed, passed through a two-millimetre sieve, homogenised and placed in pots with 3.7 kg per pot. Samples were collected and analysed for a chemical and physical characterisation of the soil from each pot (Table 1).

The pH was determined in water, with a soil: solution ratio of 1:2.5; (H + Al) was determined with 0.5 mol L⁻¹ Ca (OAc)₂, pH 7.0; exchangeable Ca²⁺, Mg²⁺ and Al³⁺ were extracted with 1 mol L⁻¹ KCl and determined by titration; P, K⁺ and Na⁺ were extracted by Mehlich 1 and analysed by colorimetry (P) and flame photometry (K⁺ and Na⁺); organic carbon was determined by oxidation with potassium dichromate; Zn, Mn, Cu and Ni were extracted by Mehlich 1 and determined by atomic absorption spectrophotometry. The values of CEC (t); CEC at pH 7.0 (T), sum of bases (SB) and base saturation (V%) and aluminium (m) saturation were obtained indirectly, using the values of potential acidity, exchangeable bases, and exchangeable aluminium (CFSEMG, 1999).

Table 1 - Chemical⁽¹⁾ and physical⁽²⁾ attributes of the soil used in the study

Chemical attributes ⁽¹⁾														
pH _{water}	P	K ⁺	Zn	Cu	Mn	Fe	Ca ²⁺	Mg ²⁺	Al ³⁺	H+Al	T	m	V	M.O
	mg dm ⁻³						cmol _c dm ⁻³				-%		g kg ⁻¹	
5.4	0.9	22	0.5	0.7	0.4	27.4	0.1	0.1	0.1	1.7	2.0	25	15	0.8
Physical attributes ⁽²⁾														
Sand					Silt					Clay				
-%														
60					17					23				

A completely randomized experimental design was used, and treatments were distributed in a 4 x 6 factorial: four treatments of potassium (0; 200; 400; 600 kg ha⁻¹ K₂O) and six alternative sources of nutrients (breccia, ultramaphics, biotite schist, phlogopite, mining by-products and chapada by-products), with four replications. The crushed silicate rocks and mining by-products used in this study originate in different processes and regions of the country, and are presented below:

- 1) Alkaline volcanic breccia (a rock outcrop in Santo Antônio da Barra, Goiás): a rock formed in volcanic conduits, composed of feldspathoids, zeolites and volcanic glass. Among the rocks used, this is the only one that does not come from a mining process;
- 2) Alkaline ultramaphic (a quarry in Lages, Santa Catarina): a rock formed by an igneous intrusion, composed of ferromagnesian minerals (olivine, pyroxene and phlogopite), plagioclases and carbonates. Collected from an old quarry used for the production of building materials;
- 3) A by-product of chapada-mining: (biotite schist, Novo Horizonte, Goiás): a rock formed by hydrothermal alteration processes from granitic rocks that generated copper ore and gold, composed of biotite and muscovite, with quartz and carbonates as accessories. This material originates in the process of grinding and flotation, in which no chemical transformation of the rock was involved;
- 4) Biotite schist (Nova Era and Itabira, Minas Gerais): a rock formed by hydrothermal processes from the passage of fluids of granitic composition over ultramaphic rocks, producing emeralds, and composed of biotite and quartz. This material accumulates in the waste from emerald mining;
- 5) Phlogopite (Campo Formoso, Bahia): a rock formed by hydrothermal processes from the passage of fluids from ultramaphic rocks of granitic composition,

producing the emerald, consisting of phlogopite and serpentinite. This material accumulates in the waste from emerald mining;

6) A by-product of manganese mining (Sete Lagoas, Minas Gerais): Residue of the metallurgical processing of manganese. In processing, the potassium is separated from the ore and concentrates in the residue.

The quantities of the alternative nutrients sources used in each treatment were defined based on the concentration of potassium oxide (Table 2).

The total quantities of alternative sources of nutrients in tonnes per hectare, corresponding to treatments of 200; 400; 600 kg ha⁻¹ of K₂O were respectively: breccia (13.64; 27.28; 40.92 t ha⁻¹ rock), ultramaphic (9.59; 19.18; 28.77 t ha⁻¹ rock), a chapada-mining by-products (8.77; 17.54; 26.31 t ha⁻¹ rock), mining by-products (2.52; 5.04; 7.56 t ha⁻¹ rock), biotite schist (14.36; 28.72; 43.08 t ha⁻¹ rock) and phlogopite (3.86; 7; 72; 11.58 t ha⁻¹ rock). The rocks were milled and passed through 0.3 mm sieves. Besides K, the rocks used in this study also supply other micronutrients, such as Ni, Cu and Zn, the nutrients being added to the soil in varying amounts in accordance with the amount of K₂O applied in the different treatments (Table 3).

After addition of the rocks, 10 lettuce seeds cv. Vera were planted per pot on 01/12/2010. After germination, when the plants presented true leaves, the crop was thinned to three plants per pot.

Soil moisture was maintained through daily weighing of the pots, one pot from each treatment being randomly sampled, defining the amount of water on a weight basis to be replenished by watering, which was carried out on the surface of the pots. This control of moisture was carried out based on maintaining the water at 60% of total pore volume (TPV).

Maintenance fertilisation was performed with reagents (PA) in all treatments, with 300 mg kg⁻¹ of P at

Table 2 - Total K₂O, Na₂O, P₂O₅, CaO, MgO, Cu, Zn e Ni content in the alternative nutrient sources¹

Rocks	K ₂ O ⁽²⁾	Na ₂ O ⁽²⁾	P ₂ O ₅ ⁽²⁾	CaO ⁽²⁾	MgO ⁽²⁾	Cu ⁽³⁾	Zn ⁽³⁾	Ni ⁽³⁾
	-----%-----					-----mg kg ⁻¹ -----		
Breccia	2.18	0.31	0.94	9.03	7.09	59.9	128.7	73.9
Ultramaphic	3.10	1.71	1.22	13	18.50	87.4	113.1	651.9
SBC ⁽⁴⁾	3.39	1.62	0.19	3.19	3.88	437.5	123.0	2.8
SBM ⁽⁵⁾	11.80	0.72	0.42	3.58	0.70	816.8	28,184.2	380.3
Biotite schist	2.07	0.86	0.06	5.27	13.8	9.9	290.5	146.4
Phlogopite	7.71	0.16	0.2	0.98	22.89	9.1	902.7	1425.2

¹Rocks milled to 0.3 mm for analysis. ²Method 4A e 4B of Acemelabs Laboratory (Canada) which has as its principle the fusion of the sample in lithium metaborate/tetraborate (Acemelabs, 2010). ³Method USEPA-3052 of the Environmental Protection Agency (USEPA, 1996). ⁽⁴⁾ By-product of chapada-mining. ⁽⁵⁾ mining by-product

Table 3 - Total quantity of alternative sources and micronutrients (mg pot⁻¹) added to treatments

Rocks	Treatment 200 kg ha ⁻¹ de K ₂ O				Treatment 400 kg ha ⁻¹ de K ₂ O				Treatment 600 kg ha ⁻¹ de K ₂ O			
	Total rocks applied	Ni	Cu	Zn	Total rocks applied	Ni	Cu	Zn	Total rocks applied	Ni	Cu	Zn
	mg pot ⁻¹											
Breccia	20.45	1.51	1.22	2.63	40.91	3.02	2.44	5.26	61.36	4.53	3.66	7.89
Ultramaphic	14.38	9.37	1.26	1.63	28.77	18.74	2.52	3.26	43.15	28.11	3.78	4.89
SPC ⁽¹⁾	13.15	0.04	5.75	1.61	26.31	0.08	11.5	3.22	39.46	0.12	17.25	4.83
SBM ⁽²⁾	3.78	1.44	3.09	106.53	7.56	2.88	6.18	213.06	11.34	4.32	9.27	319.59
Biotite	24.54	3.59	0.24	7.13	43.08	7.18	0.48	14.26	64.62	10.77	0.72	21.39
Phlogopite	5.78	8.24	0.005	5.22	11.56	16.48	0.01	10.44	17.34	24.72	0.015	15.66

⁽¹⁾Sub-product of chapada mining. ⁽²⁾Mining sub-product

planting, 150 mg kg⁻¹ N in three layers and 50 mg kg⁻¹ of S when fertilising with a layer of nitrogen.

The experiment was harvested 71 days after planting, when the plants were cut at ground level. From the material collected, the leaves were separated and the root systems removed from the pots with the aid of a water jet directed onto the soil. All the plant material was packed into paper bags and dried at 75 °C in a forced-air circulation hothouse until reaching a constant weight. After drying, the dry weight of the roots and shoots was determined. Subsequently, the dry mass of shoots was ground in a Willey-type mill, and samples equivalent to two grams were removed. In the samples from the lettuce leaves, the total K, Ni, Cu and Zn content was determined from extracts obtained by nitro-perchloric digestion (TEDESCO *et al.*, 1995). The analytical determinations were done by ICP-OES.

Quality control of the analyses was performed using the NIST standard reference (National Institute

of Standards and Technology) BCR ® 414 - Plankton, which has known amounts of Ni (18.8 mg kg⁻¹) Cu (29.5 mg kg⁻¹) and Zn (111.6 mg kg⁻¹), these quantities being the closest to those expected for lettuce among the reference standards available. The recovery rate was 82, 92 and 91% for Ni, Cu and Zn respectively.

Accumulation values for K, Ni, Cu and Zn in the lettuce shoots were determined by the product of the dry mass and nutrient content. After obtaining these data, the following indices of the efficiency of potassium fertilisation were calculated:

a) Recovery of applied potassium (RAA) = K accumulation in the shoot (mg) with potassium fertilisation - accumulation of K in the shoot (mg) without fertilisation / K₂O treatment applied (mg) x 100, in % (FAGERIA, 2010).

b) Agronomic Efficiency of the applied K (AEK) = dry weight of shoots with potassium fertilisation (mg) - dry weight of shoots without potassium fertilisation (mg) / K₂O

treatment (mg); in mg shoot dry-weight/mg applied K₂O (FAGERIA, 2010).

The data were subjected to variance analysis, and where differences were detected the Scott-Knott test at 5% probability was applied using the SISVAR ® 4.3 software (FERREIRA, 2008); for comparisons between averages, and for the effects of treatments and alternative nutrient sources and their interaction, regression analyses were carried out, and mathematical models chosen according to those equations which best fit.

RESULTS AND DISCUSSION

Significance was observed (p<0.05) between treatments and sources, as well as the interaction between these factors, for the dry mass of shoots and roots, content and accumulation of K, Ni, Cu and Zn in the lettuce shoots. The applied crushed rocks caused increases in the production of the shoot and root dry mass of the lettuce with the increases in potassium treatments (Figures 1a and 1b).

Both the ultramaphic rock and the mining by-products were those that stood out among the alternative sources in relation to the dry mass of shoot and root, as they promoted a greater release of nutrients for the growth of the lettuce. The other sources promoted similar production

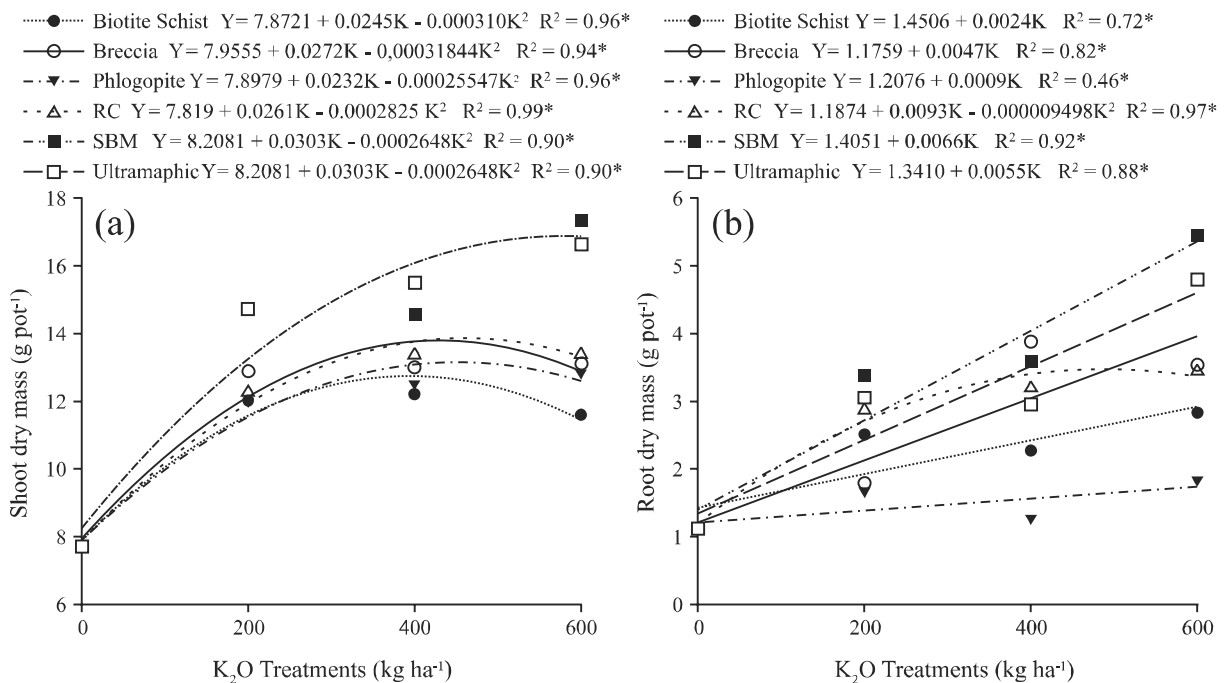
of shoot dry matter. The greatest production of shoot dry matter for all rocks was obtained with the treatment of 600 kg ha⁻¹ of K₂O, the exception being in the application of the biotite schist which gave maximum production with the treatment of 400 kg ha⁻¹ K₂O.

The greatest production of root dry matter in the lettuce was caused by better utilisation of nutrients in the soil fertilized with the ultramaphic rock and mining by-products, this is due to increased contact of the roots with ions in solution, resulting in increased growth of the shoots in the plants fertilized with those crushed rocks.

Similar results were obtained with a soybean crop, in which greater root development was seen with the application of ultramaphic rock, besides an increase in the availability of K and in seed production (RESENDE *et al.*, 2006).

This response in root production, and consequently shoot production, in lettuce fertilized with ultramaphic rock, can be explained by its greater ability to correct soil acidity (RIBEIRO *et al.*, 2010) and its composition, containing as it does various nutrients (Table 2) related to minerals such as feldspars. These minerals may release other nutrients besides K (BAKEN, 2000; WILPERT; LUKES, 2003), making the ultramaphic rock an option for the fertilisation of lettuce in organic farming systems.

Figure 1 - Effect of alternative nutrient sources in different treatments of K₂O in shoot (a) and root (b) dry mass in the lettuce



*5% Level of significance (P<0,05), by the Scott-Knott test for the effect of alternative nutrient sources

Feldspar belongs to the group of tectosilicates that are found in igneous and metamorphic rocks. Its hydrolysis reaction may be total or partial, where in the former it produces phyllosilicates, silica and soluble K^+ and in the latter it produces silica, 2:1 clay minerals, montmorillonite and soluble K (POSS, 1997). In feldspar hydrolysis reactions oxidrils (OH^-) are generated which also contribute to the neutralisation of soil acidity.

The response of lettuce plants to the application of alternative nutrient sources is not only a function of mineralogical composition, but also of factors which determine the capacity and intensity of the solubilisation of minerals, allied with the physical and chemical properties of soils (RIBEIRO *et al.*, 2010).

A lesser response in root growth was observed when using phlogopite and biotite schist respectively. This fact is associated with a lower presence of calcium and phosphorus in the composition of these rocks (Table 2). These nutrients have important roles in plant root growth, so that their lower availability reflects in lower yields of lettuce.

The levels of K in the shoots increased with the increasing amounts of K_2O applied in the form of crushed rock (Figure 2a). The highest K content in the lettuce shoots was 30.2 g kg^{-1} in soil fertilised with the mining by-products, in the treatment of 600 kg ha^{-1} of K_2O (Figure 2a).

Kano *et al.*, 2010, compared similar treatments to those evaluated in this study, but supplied as potassium chloride. The results presented by the authors showed that the K in the lettuce shoots was between 14 and 27 g kg^{-1} without the application of potassium, and for a treatment of $2.5 \text{ g plant}^{-1} K_2O$ respectively. However, optimal values of K in lettuce shoots should be in the range of from 45 to 80 g kg^{-1} (WEIR; CRESSWELL, 1993). Therefore, the different treatments of alternative nutrient sources evaluated in this study, led to absorption of the element below the sufficiency level.

The nickel content in the shoots of lettuce fertilized with milled rocks ranged from 0.85 mg kg^{-1} to 2.61 mg kg^{-1} (Figure 2b). Plants growing in soil uncontaminated by Ni present dry-mass levels in the range of from 0.1 to 5.0 mg kg^{-1} , whereas those values considered as phytotoxic are in the range of from 24 - 308 mg kg^{-1} (MALAVOLTA, 2006) and 10 to 100 mg kg^{-1} (KABATA; PENDIAS, 2001). In an experiment with lettuce grown in soil treated with different amounts of sewage sludge, at 9.4 mg kg^{-1} Ni, the levels in the lettuce shoots were 0.5 mg kg^{-1} (LOPES *et al.*, 2005). Therefore, the different crushed rocks used in this study did not release Ni at dangerous levels.

For the Cu and Zn content, the exceptions were the breccia and mining by-products respectively. In the case of Cu, all rocks produced similar levels in the lettuce shoots, except for the breccia which was significantly lower when compared to the other alternative nutrient sources (Figure 1c). For Zn, the mining by-products were different from the other rocks, giving levels of 228 mg kg^{-1} Zn in the lettuce shoots (Figure 2d).

Production of the lettuce plants was better when the Zn content in the leaf was 22.0 mg kg^{-1} , reaching levels of toxicity at 200 mg kg^{-1} (FURLANI; ABREU, 2000). In this context, it should be noted that mining by-products, in addition to being a source of potassium, are an important source of Zn for crops, maybe even exceeding the upper limit depending on the amount applied.

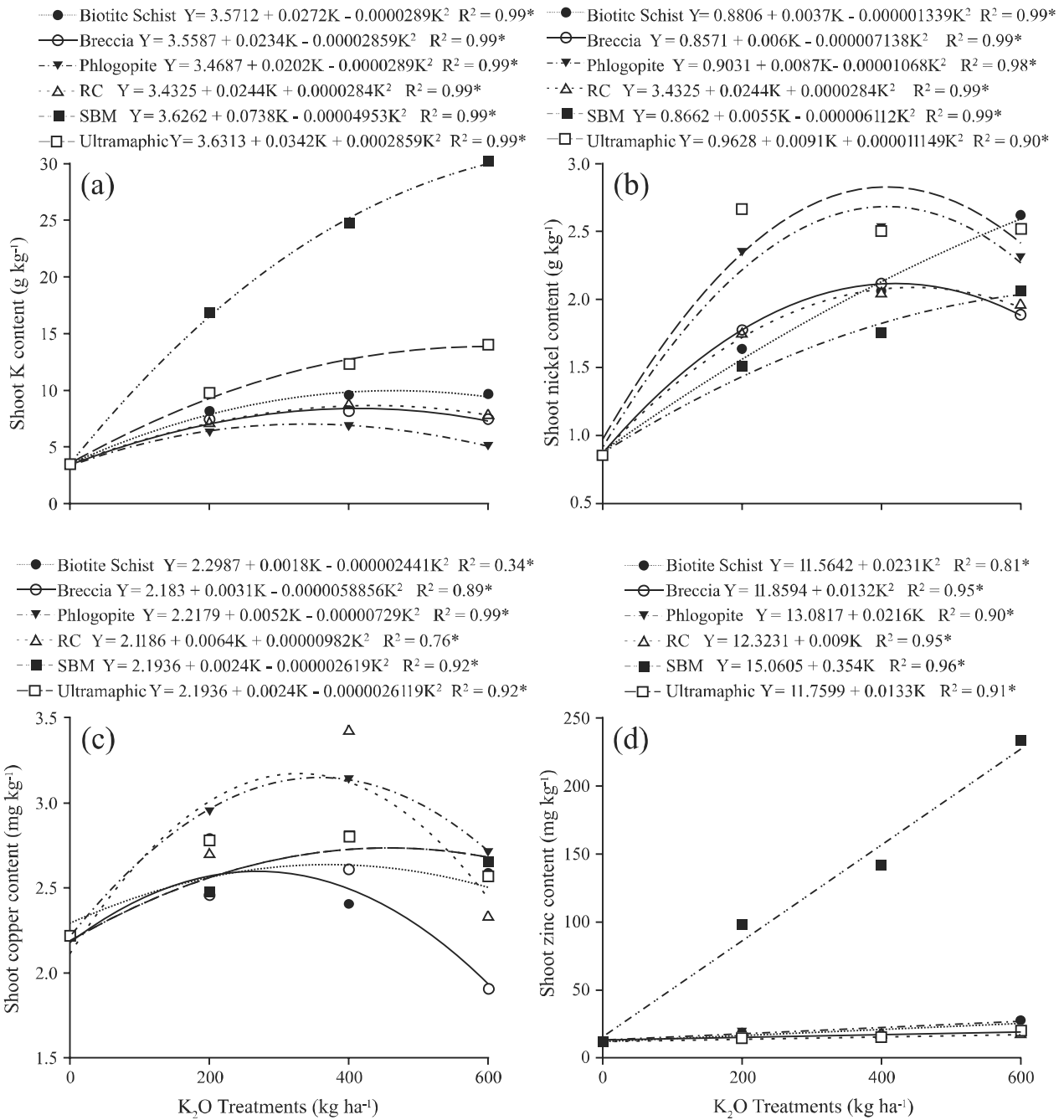
The mining by-products caused an accumulation of K in the lettuce shoots which was superior to that from the other alternative nutrient sources, being followed by the ultramaphic. The descending sequence of K accumulation for the treatments was as follows: mining by-products > ultramaphic > biotite schist = chapada by-products = breccia > phlogopite (Figure 3a).

With the exception of the mining by-products, the rock that released the most K^+ was the ultramaphic, as it contains feldspars in its mineralogy which results in increased availability of K in the soil. When compared, the values for the accumulation of K in the lettuce reflect the difference between the sources.

In the case of phlogopite, which was the rock which resulted in the lowest accumulation of K in the lettuce shoots, the main minerals which supply the element are from the group of micas such as phlogopite (dark micas). The micas have a structure of tetrahedral and octahedral sheets (2:1), in which the K^+ occupies the space between the layers, being strongly bonded to the oxygen molecules of the tetrahedron. This binding prevents the expansion of the layers and causes a lesser release of mineral K^+ into the soil. The release of the K^+ from phlogopite having trioctahedral sheets can be explained by the composition of the octahedral sheets of these minerals (CURI, 2005; WILSON, 2004).

In trioctahedral micas the bond length K-O is greater (0.3 nm) than in the dioctahedral (0.285 nm), causing trioctahedral micas to have weaker K-O bonds. Furthermore, in the dioctahedral micas there is a repulsive force caused by octahedral Al^{3+} ions against the H^+ ion from the oxydril which diverts the H towards the vacant octahedron, further distancing the potassium (AZZONE; RUBERTI, 2010; MANNING, 2010). Thus, the proximity between H^+ and K^+ ions in trioctahedral micas causes repulsion and weaker K binding compared to the dioctahedral micas (BIGHAM *et al.*, 2000).

Figure 2 - Effect of alternative nutrient sources for different treatments on the K₂O content of potassium (a), nickel (b), copper (c) and zinc (d) in lettuce shoots

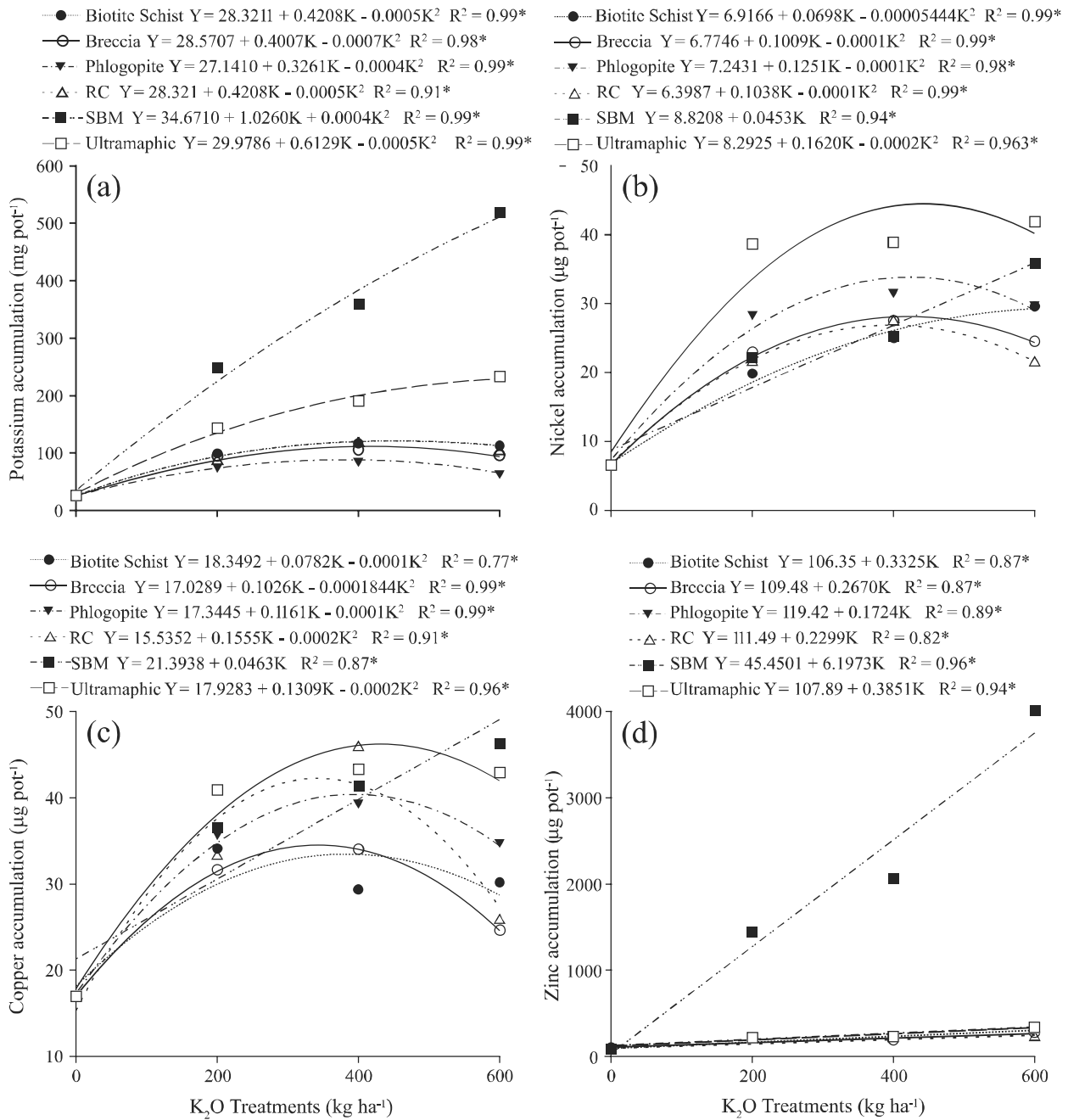


*5% Level of significance ($P < 0,05$), by the Scott-Knott test for the effect of alternative nutrient sources

The mineralogical composition and structure of the K in the phlogopite therefore, contributed to this rock's producing less content and less accumulation of potassium in the lettuce shoots, as well as lower yield responses. This effect was the opposite of that observed for the mining by-products and the ultramaphic rock.

Besides the potassium in equivalent treatments, crushed rocks also provided other nutrients in varying amounts (Tables 2 and 3). Among these nutrients the micronutrients Ni, Cu and Zn stand out for being in higher concentrations in the rocks, making them not only sources of K, but also potential suppliers of micronutrients.

Figure 3 - Effect of alternative nutrient sources for different treatments of K_2O in the accumulation of potassium (a), nickel (b), copper (c) and zinc (d) in the lettuce



*5% Level of significance ($P < 0.05$), by the Scott-Knott test for the effect of alternative nutrient sources

The rock which provided the largest addition of Ni to the soil, and the greatest accumulation in the lettuce was the ultramaphic (Figure 3b). Ni concentrations are found in ultramaphic rocks in the range of from 270-3,600 mg kg^{-1} with a mean value of 2,000 mg kg^{-1} (MALAVOLTA, 2006). For each ton of crushed ultramaphic rock applied per hectare and used in this experiment are added 651.9 g of Ni (651.9 mg kg^{-1} Ni).

A treatment of 600 kg of K_2O , applied through ultramaphic rock, provided 19.14 mg Ni per pot and gave an accumulation rate in the lettuce shoots of 0.04184 mg Ni per pot. These values demonstrate that only part of the total nutrient present in the rock is solubilized and delivered to the plant in the short term.

The mining by-products and ultramaphic rock were the alternative nutrient sources that promoted the

greatest accumulation of Cu in the lettuce shoots. Among the alternative nutrient sources, the mining by-products have the greatest concentration of Cu; a large part of that total Cu content is in a form that can be quickly released into the soil, resulting in a higher availability of this micronutrient for the roots to absorb and consequently in a higher accumulation in the shoots.

The highest rates of Cu application (the amount of each material applied was calculated based on K₂O levels) occurred in soils fertilized with chapada and mining by-products respectively (Table 3). However, in the case of the chapada by-products, the highest amount of Cu applied by this material did not promote higher accumulation values in the shoots of the plant. This can be explained by the fact that only part of this Cu was released from the minerals present in the chapada by-products into the soil solution, which resulted in a lower accumulation of Cu in the plants compared to those alternative nutrient sources that have lower total levels of the element in their composition. Additionally, these materials possess different values of relative energy for total neutralisation (RETN), differentially altering the pH of the soil, a chemical property which directly influences the availability of micronutrients.

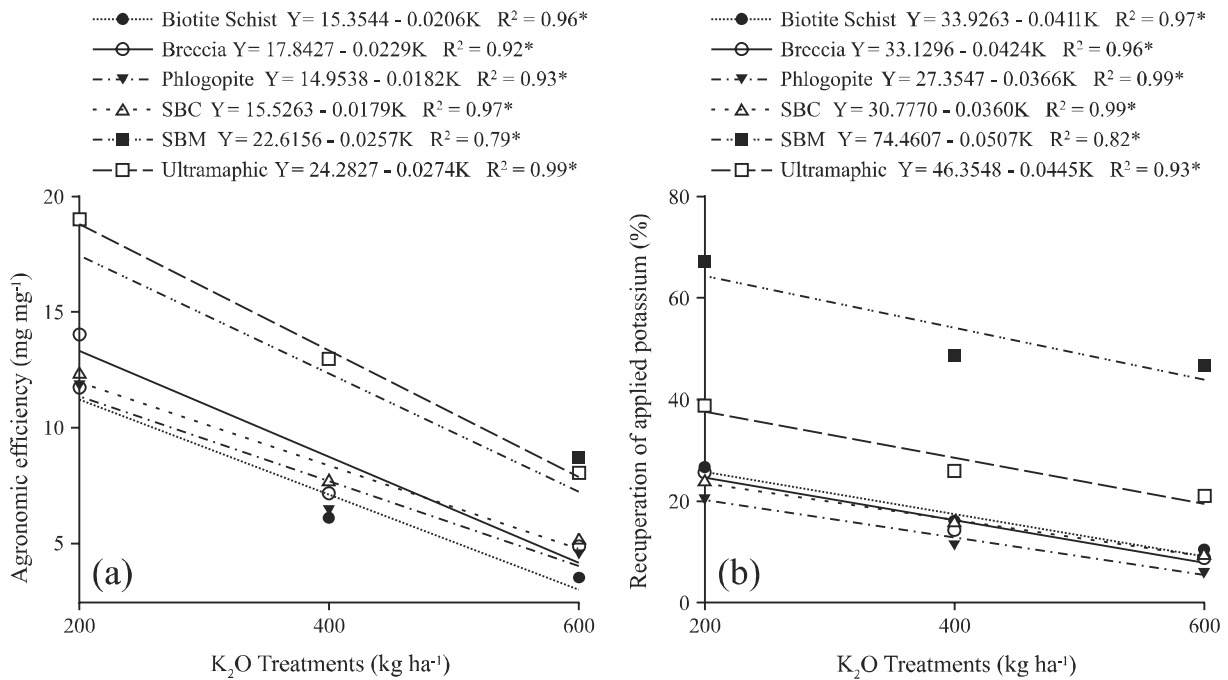
The highest accumulation of Zn was obtained in lettuce fertilised with the mining by-products (Figure

3d). This was due to the large amount of available Zn (28,184.2 mg kg⁻¹) in the by-product, resulting in higher availability in the soil and greater accumulation in the lettuce shoots.

The efficiency indices of potassium fertilisation showed significant differences (p<0.05) for the isolated effect of treatments and crushed rocks. All the efficiency indices of potassium fertilisation decreased with the increasing potassium treatments applied in the form of crushed rocks (Figure 4).

There is little information on the effectiveness of potassium fertilisation in the lettuce. However, it has been reported that the average ratio of potassium absorbed by crops is 40% of that applied (BALIGAR *et al.*, 2001). It's important to point out that in most cases these indices are obtained using soluble sources, the main one being potassium chloride. In the case of the alternative sources used in this study, the solubility of the K present in the minerals is variable, and depends primarily on the granulometry, mineralogical composition, formation, and solubilisation environment of the minerals present in the crushed rocks. However rarely do these materials provide agronomic efficiency similar to a soluble source of K, although besides the release of potassium, crushed silicate rocks and mining by-products do release other nutrients, and some of

Figure 4 - Effect of alternative nutrient sources for different K₂O treatments in agronomic efficiency (a) and recovery of applied potassium (b) in the lettuce



*5% Level of significance (P<0,05), by the Scott-Knott test for the effect of alternative nutrient sources

these materials have the energy to correct soil acidity, resulting in improvements in soil fertility (RIBEIRO *et al.*, 2010). Because of this, these materials may be alternatives, depending on the area of availability, system of cultivation and the chemical, physical and mineralogical properties of each material.

The highest agronomic efficiency of potassium fertilisation occurred in lettuce fertilized with the ultramaphic rock and the mining by-products.

The descending sequence of agronomic efficiency of the rocks was as follows: ultramaphic = mining by-products > breccia = chapada by-products = phlogopite = biotite schist. The main factor affecting agronomic efficiency is the solubilisation of the K from the rock into the soil solution. Materials in which it is supposed that the nutrients are linked to minerals which may be solubilized more rapidly, made potassium available for absorption by the roots, providing increased production per kg of K applied as crushed rock. The plant factor is also important, since the greater the volume of land used by the root system, the greater will be the absorption of nutrients. This was observed in cultivated soils for the ultramaphic rock and the mining by-products, which had a higher production of root dry matter (Figure 1b), providing higher content and accumulation of K in the lettuce shoots (Figures 2a, 3a) also having an effect on production (Figure 1a) and the agronomic efficiency of potassium fertilisation (Figure 4a).

Just as seen for agronomic efficiency, the recovery of the applied potassium also decreased with increasing treatments of K₂O when applied in the form of crushed rock, and was greater in applications of the mining by-products (Figure 4b).

CONCLUSIONS

1. Crushed rocks can be used as nutrient sources as they promote an appreciable release of potassium, nickel, copper and zinc, increasing the levels and accumulation of these nutrients in the shoots, with zinc toxicity seen only in the treatment of 600 kg ha⁻¹ of K₂O applied from the mining by-products;
2. Agronomic efficiency and the recovery of the applied potassium decrease with the increase in the amount of crushed rock applied;
3. The ultramaphic rock and mining by-products stood out among the other crushed rocks with regard to nutrition, production and the efficiency of potassium fertilisation in the lettuce.

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