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Application of andesite rock as a clean source of fertilizer for eucalyptus crop: Evidence of sustainability

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A B S T R A C T

Global demineralization of agricultural soils due to unsustainable use of highly soluble fertilizers and intensive exploitation is an issue of increasing concern. Methods of remineralization include the application of volcanic rock by-product, such as vesicular andesite on mineral-deficient fields. The present work analyzed the petrography, mineralogy, and chemistry of volcanic rock by-product (vesicular andesite rock), as well as on-field experiment with eucalyptus. The petrographic description was performed on a polished thin section by optical microscopy. The mineralogical phases were identified with X-ray diffraction. The by-product chemical composition was determined by X-ray fluorescence and inductively coupled plasma mass spectrometry for potentially toxic elements. Additional chemical compositions were analyzed using a scanning electron microscope equipped with a dispersive X-ray detector. A nine-month field experiment was carried out to evaluate the agronomic performance of *Eucalyptus saligna* Smith cultivated in an Ultisol. Four different doses (treatment T1 = control, treatment T2 = nitrogen, phosphorous, and potassium fertilizer 100%, treatment T3 = by-product 100%, and treatment T4 = by-product 50% and nitrogen, phosphorous and potassium fertilizer 50%), were applied on soil. Responses to treatments were evaluated from height and diameter at breast height at three, six, and nine months after eucalyptus planting. The total phosphorous and potassium content in soil was measured at three and six months after eucalyptus planting. The results showed that the by-product is composed of plagioclase, potassium feldspar, zeolite, smectite, and opaque minerals with apatite as an accessory mineral. The primary oxides found in by-product via X-ray fluorescence were silicon, aluminum, iron, calcium, sodium and with lower concentration, the potassium and phosphorus. In all evaluated parameters, it was verified that T2 and T4 treatments significantly enhanced the available soil phosphorous, and the eucalyptus height, with maximum gains (79% and 62% of phosphorous, and 20% and 23% of height) at nine months after eucalyptus plantation. The maximum gains of eucalyptus diameter at breast height were similar (23% and 24%) at six months after plantation. Soil available potassium was significantly enhanced in T3, T4 and T2 treatments at nine months after planting, with maximum gains of 71%, 55% and 53%. The work indicated an improvement in the phosphorus and potassium levels in soils, and in eucalyptus crop growth by adding by-product, being a partial nitrogen, phosphorous, and potassium fertilizer substitution strategy. The use of these geological materials is presented as an alternative to increase agricultural productivity and reduce the environmental impacts caused by excessive use of highly soluble fertilizers.

1. Introduction

Eucalyptus is one of the most common and economically important forest species that have been established in many areas of the world due to their fast growth and profitability (Goded et al.,

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2019). Most of these areas are tropical and have a low fertility soil, often poor and acidic, with very low phosphorus (P) and potassium (K) contents (Rabel et al., 2018). These nutrients are needed by eucalyptus to obtain high productivity (Gonçalves et al., 2008). For this reason, the highly soluble fertilizers have been applied to guarantee an adequate nutrient supply for crops (Korchagin et al., 2019).

The commonly used fertilizers for eucalyptus are ammonium sulphate ($(NH_4)_2SO_4$), potassium chloride (KCl), and single superphosphate (SSP). Nitrogen (N), P, and K from sources such as $(NH_4)_2SO_4$, SSP, and KCl are highly soluble and can be rapidly lost through leaching (Manning, 2010). Most N fertilizers cause the soil to acidify, significantly affecting soil biota and plant nutrient availability (Huang et al., 2017). The main threat of soluble fertilizers is the pollution of surface water during the first months after its application and planting (Gonçalves et al., 2013).

It is evident that measures need to be taken to decrease soil demineralization and highly soluble fertilizers consumption (Korchagin et al., 2019). One of the measures taken was to add crushed rocks to maintain soil fertility and to support crop production (Manning and Theodoro, 2018).

Several studies demonstrated positive results from the use of rock dust as soil remineralizers, such as: a single application can be effective for up to four or five years (Machado et al., 2016); the P, K, calcium (Ca), and magnesium (Mg) levels have been increasing over time and the productivity is similar to or higher than soluble fertilization (Theodoro et al., 2013); and low availability of potentially toxic elements (PTEs) and aluminum (Al) (Ramos et al., 2017); lower risk of contamination or eutrophication of water sources because the crushed rock has a gradual solubility, contrary to highly soluble fertilizers. This is a relevant issue where continuous application of fertilizers, especially single superphosphate, has resulted in cadmium (Cd) toxicity in soils throughout the world (Greger et al., 2016).

Other advantages are a widespread availability of volcanic rocks in the Earth's surface (Gill, 2010); and the volcanic rock mining by-product use as a soil remineralizer do not need chemical processing, that is, can be used as it is mined (*in natura*) (Silva et al., 2013). There is a notorious production of by-products from the volcanic rock mining in southern Brazil (Dalmora et al., 2016). These by-products are accumulated alongside different quarries, ultimately needing an environmentally appropriate final disposal (Korchagin et al., 2019).

By-products application in agriculture should be considered as an alternate to remineralize nutrient-depleted soils, and for reducing the environmental risk of this material that requires mineralogical and chemical characterization and an evaluation of their agronomic performance (Korchagin et al., 2019). This approach contributes both to solving environmental issues associated with rock mining and to create a cleaner alternative for soil fertilization.

Basalt by-products from quarries in South Brazil are well known as soil remineralizers (Nunes et al., 2014), but not yet the vesicular andesite by-product. It is of great relevance to conduct research on the agronomic performance of these rocks.

In Brazil, soil remineralizers have been developed, and Brazilian federal law nº 12890 (Brazil, 2013) allows these to be used for crop nutrition, with specifications clearly defined by appropriate regulation (Brazil, 2016). Soil remineralizers are all mineral materials that have only size reduction and size classification by mechanical processes and that change the soil fertility indices by addition of macro- and micronutrients for crops and improve the physical or physicochemical properties or the biological activity of soils (Brazil, 2013). This approach provides a model for all countries to explore local geological sources and reduce the use on of high solubility fertilizers (Manning and Theodoro, 2018).

In this study, the relationship between petrographic, mineralogic, and geochemical characteristics of one by-product (andesite vesicular) from a quarry in Estância Velha city and the effects of four agronomic treatments in the availability of P and K to soil and in the growth of the *Eucalyptus saligna* Smith clonal in Triunfo city, Southern Brazil were discussed.

This work seeks to bring awareness on the impact of mining activity, the unsustainable consumption of highly soluble fertilizer (NPK) and provide information on eucalyptus fertilization practices in subtropical regions with the use of volcanic rock mining by-products.

2. Material and methods

2.1. Soil, by-product, and seedlings samples

Soil samples were collected at depths of 0–20 cm from several points of the experimental site, before remineralization treatments application. The samples were composited from 45 sub-samplings.

Ten t of vesicular andesite rock powder (by-product) with particle sizes below 2.8 mm (for chemical characterization and soil application) and ten kg of bedrock (for petrographic description and chemical composition by scanning electron microscope) were supplied by the Incopel Indústria e Comércio de Pedras Ltda of the Estância Velha district.

The clonal *Eucalyptus saligna* Smith (ESS) seedlings were purchased from Metalúrgica e Viveiro DACKO, located in the municipality of Herval Grande, Rio Grande do Sul, Brazil. The seedlings had an average size of 30 cm. This species was chosen because it is resistant to frost, its rapid growth, and high homogeneity in the field (Delgado-Matas and Pukkala, 2011).

2.2. Analytical methods

2.2.1. Petrography

Petrographic thin section observations were made to identify the andesite vesicular mineral phases. The sample was analyzed on optical microscope (Model Eclipse 50i POL, Nikon, Japan) under natural (NL) and polarized reflected light (PL).

2.2.2. Mineralogy

X-ray diffraction (XRD) technique was employed to characterize the mineralogical composition of the by-product using a Philips X-ray diffractometer (Model X'PertMPD, Philips, Amsterdam), equipped with a curved graphite monochromator and fixed copper anode, operating at 40 kV and 40 mA. The angle range analyzed was from 5 to 75°. The step size used was 5°/1 s. Cu Kα radiation (1.54184 Å), Kα1 (1.54056 Å), Kα2 (1.54439 Å), and Kβ (1.39222 Å). The mineral identification from XRD data was done using the X'pert High Score Software, version 2.0a (2.0.1).

2.3. Chemical composition analysis

2.3.1. By-product

Chemical analyses of the by-product were performed in triplicate, after manual milling using a porcelain mortar and pestle to obtain particles less than 0.074 mm. Chemical composition in percentage weight of oxides was determined by X-ray fluorescence (XRF) (Model MagiX (DY1583), Panalytical, Amsterdam) after digestion of 2 g of the sample by total fusion with lithium tetraborate in an automatic machine (Silva et al., 2011).

The by-product sample was digested with four acids (hydrochloric, nitric, hydrofluoric, and perchloric) in a microwave for 1 h (Querol et al., 1997) to determine a PTEs composition. The analysis was performed at the Institute of Environmental Assessment and Water Research (Spain) by inductively coupled plasma-mass spectroscopy (ICP-MS).

The mineral compositions of the by-product were investigated on a polished thin section using a scanning electron microscope (SEM) (Model EVO MA10, Zeiss, Germany), equipped with an energy-dispersive X-ray spectrometer (EDS). The mineral identifications were made based on morphology and grain composition using back-scattered electron mode.

2.3.2. Soil

Soil samples were subjected to chemical extraction by Mehlich (1984). The P and K content were determined by inductively coupled plasma-optical emission spectrometer (ICP-OES). These analyses were performed before treatments applications to determine the amount of inputs to be applied in agronomic treatments, and after three and six months of eucalyptus plantation to verify the agronomic efficiency of the treatments. The experimental soil was classified as Ultisol (USoil) according to the United States Department of Agriculture soil classification (USDA, 1999), with 44.5% of clay in A horizon. Briefly, the USoil presented concentrations of 3.1 mg l^{-1} of P and 37 mg l^{-1} of K. This indicated a poor soil and practically without reserve of these nutrients, according to the SBCS (2004).

2.4. Experimental site and preparation

This work started in September 2015 in an experimental site of 0.41 ha at Triunfo (485.959 S; 6,722,047 W, South American Datum 1969) (Fig. 1) in the state of Rio Grande do Sul, Brazil. The Triunfo site was characterized by a gentle slope.

Based on fertilization practices used in the region, treatments were defined to increase P (from 3.1 to 12 mg l^{-1}) and K (from 37 to 60 mg l^{-1}) according to the Brazilian Society of Soil Science (SBCS, 2004). The agronomic treatments were added on the soil surface, 30 d before planting of eucalyptus seedlings (Table 1).

2.5. Experimental design

The experiment was conducted side by side with four agronomic treatments replicated three times (Fig. 2). Plots were composed of three rows of 3 m wide with 14 plants per row; space between rows was of 2 m and 3 m between plants in the row. Six plants of the central rows were measured for height (H) and diameter at breast height (DBH). A visual inspection was conducted each week for one month in order to detect and replace dead seedlings. Treatments response was evaluated by H and DBH at three, six, and nine months after eucalyptus planting. Soil samples were taken at depths of 0–20 cm on the central rows of every treatment (each sample composed by ten sub-samplings). Treatments response was evaluated by total P and K in soil after three and nine months after eucalyptus planting.

All data were submitted to analyses variance by the Least Significant Difference (LSD) test at a significance level of 5% ($p < 0.05$) using the statistical software SAS Enterprise Guide 6.1.

Table 1
Doses of limestone (DL), SSP and by-product applied in field experiment.

Treatments	DL	By-product	KNO_3	SSP
	kg ha^{-1}			
T1 – Control	0	0	0	0
T2 – NPK fertilizer	6000	0	230	660
T3 – By-product	0	6600	0	0
T4 – By-product 50% and NPK 50%	3000	3300	115	330

3. Results and discussion

3.1. Petrography

Optical microscope observations revealed that the andesite has an intermediate composition between basalt and granite featuring a microcrystalline to glassy matrix with a microporphyritic texture of granulation less than 1 mm (Fig. 3A and B). Plagioclase microphenocrysts, comprising less than 30% of the volume of the rock, appear isolated or glomerophyritic (Fig. 3A). Vesicles surrounded by zeolites were observed (Fig. 3C and D). The minerals identified in the matrix were plagioclase, opaque minerals, and laumontite zeolite with apatite as an accessory mineral. Opaque minerals appear associated with the interstitial mesostasis and occur as dendritic and cruciform crystals (Fig. 3B). Apatite crystals have needle shapes up to 0.05 mm and are associated with the interstitial-domain. The microphenocrysts of plagioclase and zeolite are of 1.2 and 8 mm. The interstitial domains of andesite are weakly anisotropic indicating partial devitrification, oxidation is frequent where the matrix is replaced by iron hydroxide. The occurrence of all these minerals that are susceptible to weathering is a good indication that the vesicular andesite rock by-product can release macronutrients and micronutrients into the soil.

3.2. Mineralogy

The XRD pattern of the by-product is shown in Fig. 4. It can be seen that the main three peaks correspond to quartz (SiO_2), andesine ($(Na,Ca)(Si,Al)_4O_8$), and montmorillonite-chlorite ($(Na,Ca)_{0,3}(Al,Mg)_2Si_4O_{10}(OH)2{\bullet}n(H_2O)$). It was also possible to detect orthoclase ($KAlSi_3O_8$), laumontite ($CaAl_2Si_4O_{12}{\bullet}4(H_2O)$), enstatite ($Mg_2Si_2O_6$), and hematite ($Fe_2O_3$). This corresponds to

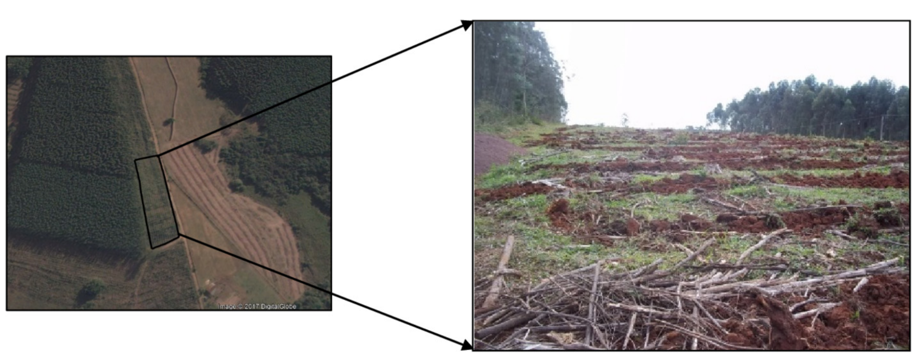

Fig. 1. Experimental overview. Source: Google Earth, 2015.

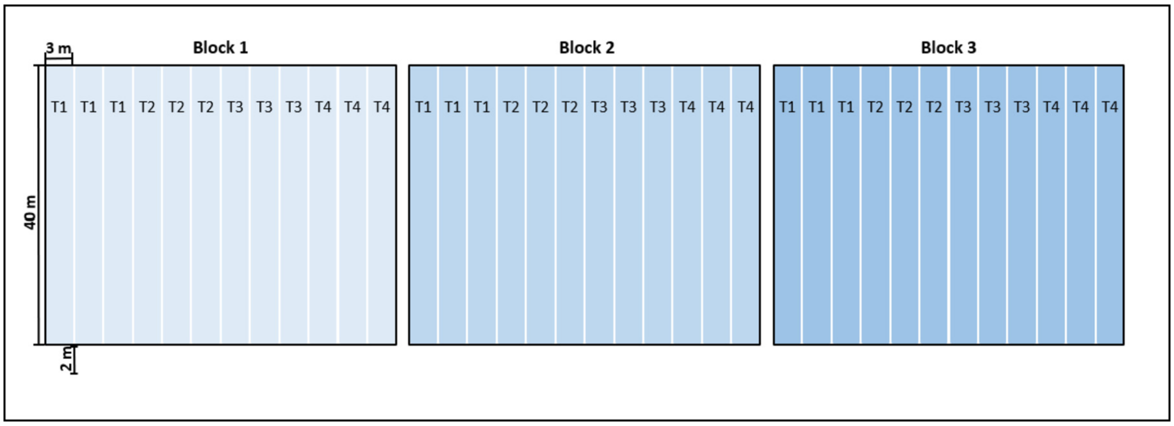

Fig. 2. Treatments distribution.

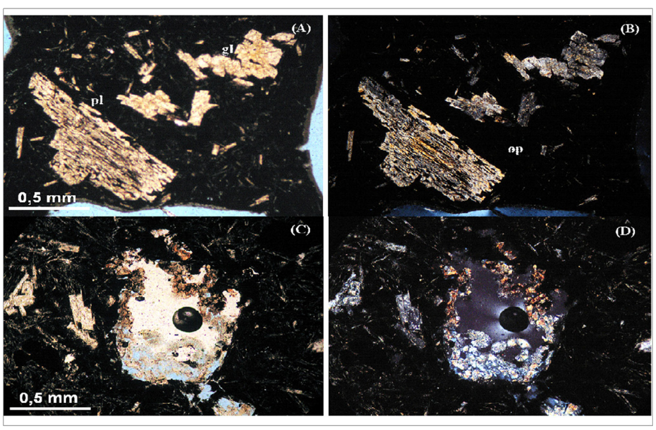

Fig. 3. Petrographical images of by-product. (A) plagioclase microphenocrysts isolated (pl) or glomerophyritic (gl) (NL); (B) opaque minerals (PL); (C) vesicles surrounded by laumontite zeolite (NL); (D) vesicles surrounded by laumontite zeolite (PL).

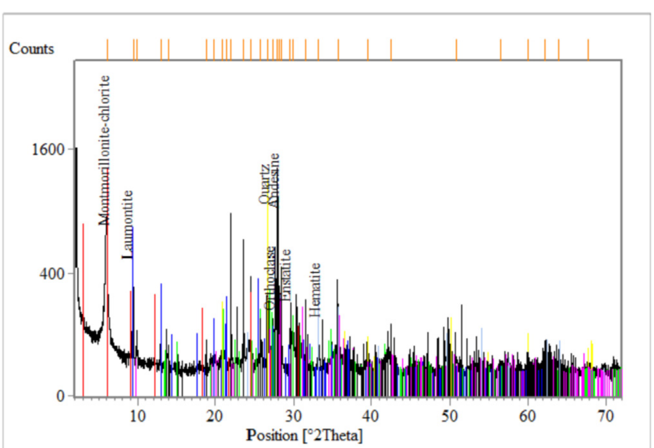

Fig. 4. X-ray diffractogram from by-product sample.

minerals most common volcanic rock-forming minerals (Deer et al., 2013).

Smectites (montmorillonite-chlorite mixed layer) are important in soils due to their high cation exchange capacity (Huggett, 2015). This indicates a possible ability to change cations into soil suspensions.

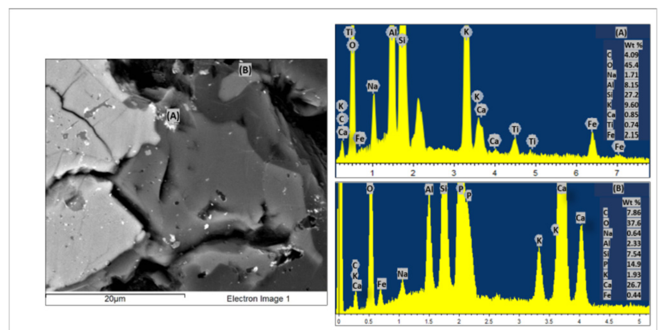

Fig. 5. SEM image of apatite and orthoclase detected in the by-product. (A) EDS spectrum of orthoclase; (B) EDS spectrum of apatite.

Scanning electron microscope/EDS analysis confirm the occurrence of orthoclase in the by-product (Fig. 5A). Orthoclase, a K-feldspar, when added to soil can release K more easily due to the action of weathering (Manning et al., 2017). Potassium is very necessary nutrient for enhance the productivity of many crops (Carvalho et al., 2018).

Fig. 5B shows that the apatite makes up the by-product sample. Apatite is an accessory phosphate mineral that occurs in almost all igneous rocks and is known to be partially resistant to weathering (Piccoli and Candela, 2002), with slow dissolution and P release. This interpretation is contradictory to studies of Ramos et al. (2015), which showed recovery up to 93% of the P in leaching tests using similar rock powder to this study. This fact indicates that the P may be of great potential in aiding several processes of plant growth through remineralization.

The by-product is mainly composed of aluminosilicates, which mean that besides of its application as a fertilizer, it also could be used in ceramic production. This is a relevant possibility to study in a future work, since the predominance of these components suggests the fabrication, for example, refractory materials (Sánchez-Peña et al., 2018).

The agricultural use of by-product in tropical soils suggest replacing soluble fertilizers because the aluminosilicates have nutritional properties significantly influence soil fertilization (Tubana et al., 2016).

3.3. Chemical composition

According to Table 2, the by-product is primarily composed of SiO_2 along with a high presence of other silicates. These results

Table 2
Chemical composition in percentage weight of oxides of the by-product sample.

Oxides	Andesite
SiO_2	57.1
TiO_2	1.17
Al_2O_3	14.1
Fe_2O_3	9.50
MnO	0.17
MgO	3.57
CaO	5.38
Na_2O	3.22
K_2O	2.49
P_2O_5	0.26
LOI[a]	2.70
Total	99.7

[a] Loss on ignition.

concur with those obtained by Nunes et al. (2014), who characterized four similar rocks and their application as a soil remineralizer.

Silicon is essential to crop growth, although it is not regarded as an essential nutrient. According to Epstein (1999) Si-deficient plants have generally structurally weaker and more prone to growth, development and reproduction irregularity. Silicon is the only nutrient that is not harmful when over-absorbed. In addition, it helps to control pests and increase the productivity and quality of agricultural products (Keeping, 2017; Beerling et al., 2018).

Aluminum oxide (Al_2O_3) was another compound noted to has significant concentration in by-product analyzed. Although the by-product particles contained important fractions of Al, a low release of this element is expected to the soil. Aluminum is very stable within the crystalline structure of the by-product particles; this is very important because Al may be toxic to the plants. The toxicity by Al dissolution is not considered to be an environmental concern. This interpretation was proven by the investigations of Ramos et al. (2019), who studied the potential use of volcanic rock powder as soil remineralizer in black oats and, sequentially maize crops. These authors showed ameliorations in soil attributes, like high levels of Ca, K and P and low levels of exchangeable Al and Al saturation.

In terms of potential (based on content) for the macronutrient K, the by-product could be proposed as a soil remineralizer according to the Brazilian normative instruction nº 05 (Brazil, 2016). The by-product presents the sum of chemical compounds ($CaO + MgO + K_2O$) higher than 9% and K_2O content is higher than 1%, in compliance with the Brazilian normative instruction nº 05 (Brazil, 2016). From these results, the criteria for a remineralizer are satisfied by the by-product studied here. This is a positive characteristic that represents good potential for agricultural use, especially in nutrient-poor soil such as USoil. The average P concentration of the Earth's upper crust is approximately 0.1% P_2O_5 (Cordell and White, 2011). According to Table 2, the P_2O_5 content of

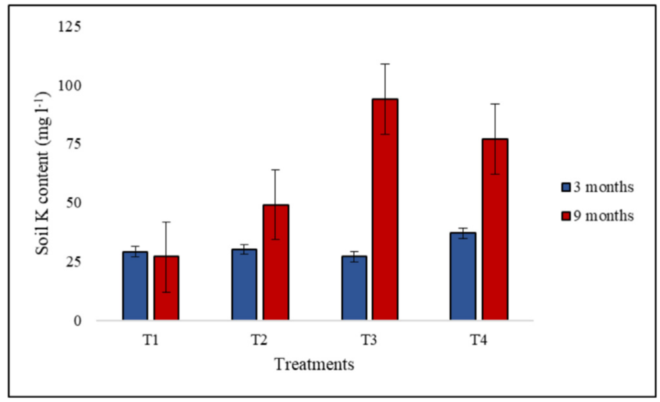

Fig. 6. Treatment effects on the K content in soils after three and nine months of ESS planting.

the by-product is almost three-times above the crustal average. This result may be attributed to the occurrence of apatite, identified by optical microscopy and by SEM/EDS (Fig. 5B), in the by-product. Apatite is the most abundant phosphate mineral, accounting for more than 95% of all P in the Earth's crust and is found as an accessory mineral in volcanic rocks (Ptáček, 2016). Phosphorous and K are important nutrients to obtain high productivity in several crops, for example, in tropical soils (Carvalho et al., 2018).

In the characterization of rocks destined for the remineralization of soils, it is important to quantify major elements, as well as PTEs, which may be necessary and beneficial to plant physiology, but cannot extrapolate the limits established by environmental legislations.

The limits maximum of PTEs in soil remineralizers allowed by Brazilian normative instruction nº 05 (Brazil, 2016) are 15 ppm arsenic (As), 10 ppm cadmium (Cd), 0.1 ppm mercury (Hg), and 200 ppm lead (Pb). The results of analysis by ICP-MS demonstrates that the by-product sample has low concentrations of PTEs <1 ppm As, 0.6 ppm Cd, 0.01 ppm Hg, and 15.6 ppm Pb, which do not represent an environmental risk (Table 3).

As the Brazilian normative instruction nº 05 is restricted to PTEs such as As, Cd, Hg, and Pb, the PTEs maximum values allowed by Brazilian National Environmental Council (Brazil, 2009) in Resolution nº 420, were used to protect the soil quality. The maximum levels allowed by Brazil (2009) are 35 mg kg^{-1} As, 3 mg kg^{-1} Cd, 150 mg kg^{-1} chromium (Cr), 200 mg kg^{-1} copper (Cu), 12 mg kg^{-1} Hg, 180 mg kg^{-1} Pb, and 300 mg kg^{-1} zinc (Zn). This interpretation

Table 3
Chemical composition results obtained by ICP-MS of the by-product sample.

PTEs	By-product mg kg^{-1}/ppm
As	<1
Cd	0.60
Cr	30.8
Cu	42.5
Hg	0.01
Pb	15.6
Zn	112.6

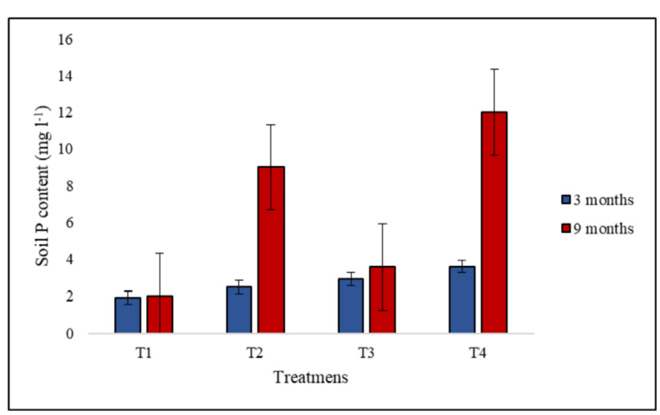

Fig. 7. Treatment effects on the P content in soils after three and nine months of ESS planting.

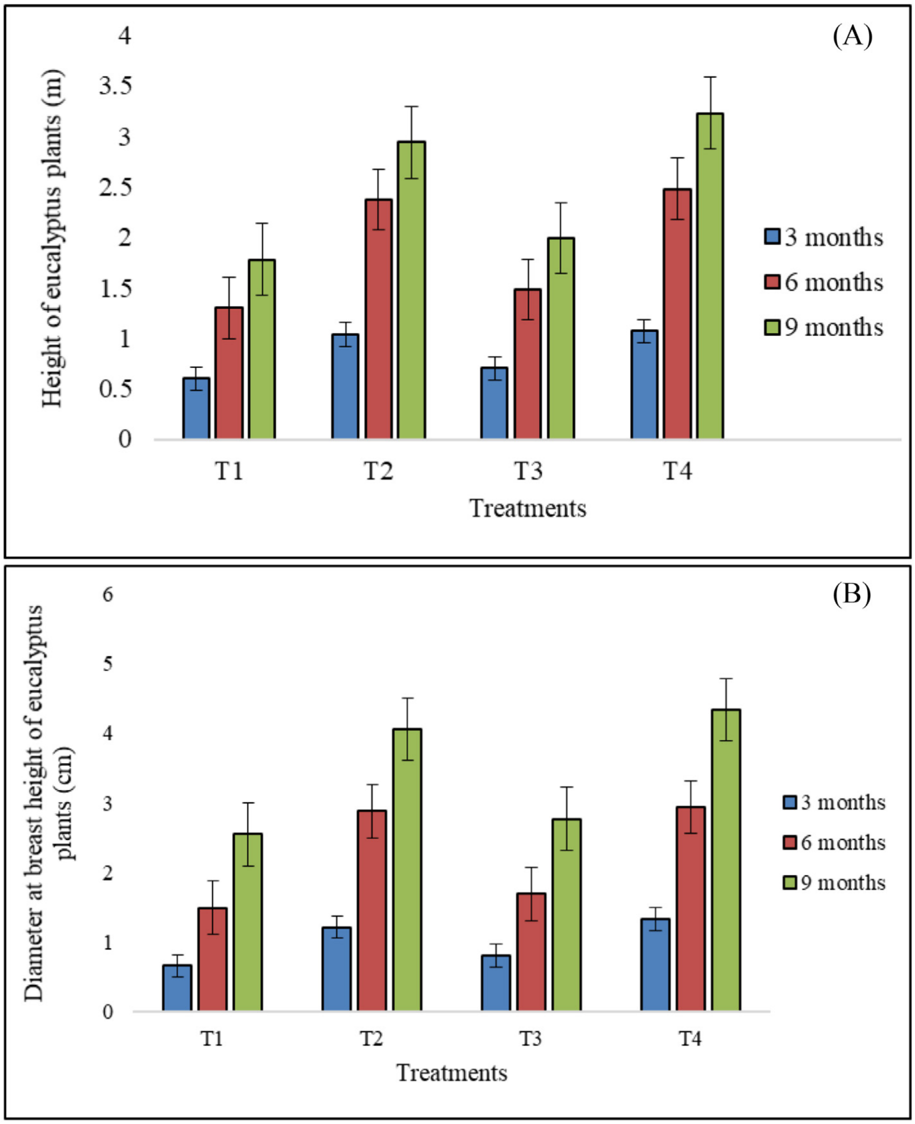

Fig. 8. Treatment effects. (A) on the height and (B) on diameter at breast height of eucalyptus plants.

agrees with Hartmann et al. (2015) that the use of rock by-products as a soil remineralizer can be a safe alternative for their reuse.

Table 3 shows that the PTEs concentration of by-product it is well below the limits established by Brazilian normative instruction nº 05 (Brazil, 2016) and Resolution nº 420 (Brazil, 2009). Similar results were obtained by Ramos et al. (2017) with a by-product from the same region of this study. These authors carried out leaching tests in five acid solutions and concluded that very low levels of potentially toxic elements were made available to extraction solutions. These results indicate that the addition of by-product to the soil will not cause toxicity risks to plants or to the environment.

3.4. Potassium and phosphorus availability to the USoil

Fig. 6 shows the average K concentrations in soils after three and nine months of eucalyptus planting. After nine months, the soil K content of T3 treatment (100% by-product) was significantly higher ($p = 0.002$) than all other treatments. In T4 treatment (50% by-product and 50% NPK) the average K concentration ins soil was significantly higher ($p = 0.02$) than in T2 treatment (100% NPK). T2 treatment did not reach the adequacy level of 60 mg l^{-1} for eucalyptus cultivation (SBCS, 2004). In contrast, treatments with by-product (T3 and T4) provided K content above than 60 mg l^{-1}. The high content of K in T3 treatment was exclusively due to the presence of orthoclase. This mineral has 14.05% of K in it is composition and was detected in by-product via XRD analysis (Fig. 4). The by-product 6600 kg ha^{-1} dose has the potential to totally replace soluble K fertilizers. Similar results were obtained by Ramos et al. (2019), who investigated the plant availability of Ca, Mg, K and P in dacite rock by-product by growing black oats and maize for 70 d each, with different by-product doses. The authors showed that the K supplied by by-product was available to the plants.

Fig. 7 shows the average P concentrations in soils after three and nine months of eucalyptus planting. Tropical soils usually have low concentrations of available P and high potential for fixation of P applied by using soluble fertilizers (Schütz et al., 2018). This context places P, along with N, as one of the most limiting nutrients in crop production in Brazil (Withers et al., 2018). In clayey soils, as in the present study, the critical level, i.e. sufficiency level, of P for eucalyptus production is 9 mg dm^{-3} (SBCS, 2004). The eucalyptus clones are nutritionally more demanding and are more subject to deficiency of this nutrient. Unlike K, it was found that after nine months, fertilization with 100% by-product (T3) provided lower soil P values than T2 and T4 treatments. The latter presented levels of P in the soil above the critical level for the development of the plants (Fig. 7). The T4 treatment with combined fertilization with by-product and NPK presented higher P contents than all other treatments (Fig. 7). This fact suggests that the addition of NPK favored the weathering of apatite, with 18.43% P, thus releasing the P faster in the soil.

The results of the T3 treatment were superior to those obtained by Toscani and Campos (2017). They applied 300 t ha^{-1} of basalt powder composed of 1.15% K_2O and 0.379% P_2O_5. The concentrations of experimental soil were of 74 mg dm^{-3} of K and 5.9 mg dm^{-3} of P. After twelve months of common bean planting, the soil K content was 35 mg dm^{-3} and P was 1.7 mg dm^{-3}.

The by-product combined with NPK added in T4 treatment proved to be a promising alternative source for the supply of P in the studied soil. The T4 treatment have potential to partially replace P fertilizers.

Despite low P release observed in T3 treatment compared to highly soluble fertilizers in T4 treatment, results using by-products as a soil remineralizer are promising (Nunes et al., 2014; Ramos et al., 2017). According to Beerling et al. (2018), the by-products of rock mining (considered an environmental problem) could supply the demand for highly soluble fertilizers and provide subsidies to farmers to use the technique globally.

The results obtained in this study conform to those of Theodoro et al. (2010) that rocks can provide nutrients that are important for crops. The by-product of this study presented notable reactivity in soils of treatments T3-T4.

3.5. *Eucalyptus saligna Smith growth*

In this experiment, there was no substitution of ESS seedlings because all of them survived. Size responses in terms of DBH and H of ESS at three, six, and nine months after planting are shown in Fig. 8A and B.

During the all evaluations, the highest DHB and H were observed in T4 and T2 treatments. Trees in the T3 treatment were similar in H and DBH to the control treatment that received no fertilization. The same behavior was noted in the T2 and T4 treatments (Fig. 8A and B).

At nine months, the response of H in T4 treatment was significantly higher than all treatments ($p < 0.05$). There was a H gain of 45% and DBH of 42% compared to control (Fig. 8A and B). Height and DHB responses to all treatments were directly proportional to tree age (Fig. 8A and B).

Similar results to those of this study were found only in an experiment conducted by Leonardos and Theodoro (1999) at the Água Limpa farm in Brasília, Brazil. These authors used three forms of fertilization over 13 years in latosols (volcanic rock powder, NPK combined with volcanic rock powder, and NPK). According to the authors, the growth of the eucalyptus plants grown in the NPK-fertilized plot was rapid until the fourth year. After this period, tree growth decreased significantly as compared to the growth of plants treated only with rock dust, which grew linearly, although more slowly at the beginning.

In this study, the development of ESS plants grown in USoil treated with combined doses of by-product and NPK (T4) was initially favored since the NPK acted as a catalyzer and the subsequent growth may be maintained by the released nutrients from by-product minerals.

4. Conclusions

This study indicated that by-product of vesicular andesite rock contains macronutrients such as Ca, K, Mg, and P, jointly with micronutrients like Cu and Zn. The low potentially toxic elements concentrations from by-product do not represent environmental risk what shows a good potential to be used as a soil remineralizer.

The amount of K release in soil was significantly higher in T3 treatment with by-product dose of 100% suggesting that the mineral powder could act as an immediate release K source, being to a potential total substitute of soluble K fertilizer.

The amount of P release in soil, and DHB and H measures of the eucalyptus plants were significantly higher in soil mixture with doses of 50% by-product and 50% NPK (T4 treatment). This suggest that the vesicular andesite by-product can be a partial substitute of soluble P fertilizer.

A further understanding of the underlying biogeochemical processes is needed so that mineral materials and conditions can be modified to achieve desired agronomic effectiveness. Further subsequent evaluations of K and P in soils, DHB and H measures of the eucalyptus plants at long-term are needed to assess the quantitative K and P supply behaviors of the rock mineral powder in order to support sustainable agricultural production.

The use of vesicular andesite powder as a soil remineralizer in agriculture may be suitable for solving the problem of by-products deposited outside the mines and to decrease the consumption of highly soluble fertilizers.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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