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AGRONOMIC POTENTIAL OF USING ORNAMENTAL STONES WASTE AS A SOURCE OF AGRICULTURAL FERTILIZATION

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Summary: *The volume of waste (by-products) generated in the production process of ornamental stones is the main environmental problem of the sector, while the import limitations and increase in fertilizer prices highlight the vulnerability of the Brazilian agricultural production system and put the world food supply at risk. Alternatives for the use of mining by-products and agricultural fertilization are essential for the sustainability of these activities, and this is the objective with this research. The by-products used in this study include three syenites (CB, CI, and MG), one alkali-granite (OI), and one varvite (AR), evaluated for their agronomic potential to improve soil quality. In the analysis of the results, the by-products meet the requirements of the legislation, and are considered potential soil remineralizers. After 150 days of soil incubation with the different by-products under study, RA showed the best agronomic potential, followed by CB, OI, CI and MG.*

Key words: *agrominerals, soil remineralizer, rock powder, sustainable development.*

Introdução

The fourth largest food producer in the world, representing one-fifth of the Gross Domestic Product (GDP) and 48% of exports (IBGE, 2020; CNA, 2021), Brazil is an agribusiness powerhouse.

Considering the world trend of growing food consumption at about 6% per year, for agricultural production to keep up with demand, it will be necessary to increase the production and productivity of crops, which are directly related to the fertility of the soil-plant system. However, in the conventional cultivation system, it becomes necessary to import soluble fertilizers, which today correspond to approximately 80% of the national annual requirement, resulting in high production costs, loss of competitiveness, and vulnerability to other countries (SANTOS; GLASS, 2018; GLOBALFERT, 2021).

The dependence on the national agricultural production system can be exemplified by the limitations on the shipment of fertilizers from Russia to Brazil, as an indirect consequence of the diplomatic conflicts established between Russia and Ukraine in the year 2022. According to the Brazilian Ministry of Economy (COMEXSTAT, 2022), about 23% of chemical fertilizers imported by Brazil in 2021 came from Russia. If added to the dependence on fertilizers coming from Belarus, the seventh largest exporter of fertilizers to Brazil and an ally of Russia, the degree of national dependence rises to 26%. Thus, the search for alternative sources acquires great importance for the future of Brazilian agricultural production (BRITO et al., 2019).

As Brazil is the fifth largest producer and exporter of ornamental stones in the world (ABIROCHAS, 2021a;b), the use of waste generated in this production chain, estimated nationally at 18.0 million tons in 2019 (ABIROCHAS, 2020), meets the Circular Economy and can, about product innovation, provide more sustainable and competitive economic development for industries in the mining sector concomitant to the supply of alternative sources of agricultural fertilization (CAMARA et al., 2021).

Given this scenario, studies that recommend the use of different waste products from the production chain of ornamental stones together with the search for alternatives that accelerate the solubilization of nutrients present in the rocks, become necessary so that the production chain of ornamental stones can become more sustainable, as well as the Brazilian agribusiness less dependent on external inputs.

Considering the hypotheses that the materials under study have: (i) potential for use as soil remineralizers, meeting the requirements set out in the NI; (ii) ability to release potassium to the soil; and (iii) greater solubilization of nutrients when inoculated with different microorganisms, this study aimed to analyze the potential for agronomic use of coarse waste generated by the processing of different types of ornamental stones as soil remineralizers.

After the characterization of the materials, the results of the incubation process are presented, according to the agronomic protocol provided in the Brazilian Normative Instruction (IN) No. 05, of March 10, 2016, of the Ministry of Agriculture, Livestock and Supply (MAPA) (BRASIL, 2016), which will be referred to as either Normative Instruction or NI throughout this material.

Material and methods

The rocks selected for this study include three syenites (CB, CI, and MG), one alkali granite (OI), and one varvite (AR), collected from coarse residues (by-products) generated in quarries or sawmills (non-standard blocks, rock fragments, hulls, drill cores, etc.). The characterization of each rock is described in the results and discussion topic.

The sequence of the methodology presented below complies with the guidelines provided by Normative Instruction, which recommends that studies conducted to evaluate the potential use of certain rocks as soil remineralizers include the requirement of geochemical and mineralogical analyses that prove the suitability and efficiency of the material. Thus, they are presented in the following order: comminution of by-products, physical characterization, determination of the chemical composition by X-Ray Fluorescence (XRF), loss on ignition (LOI), analysis of the hydrogen potential (pH), determination of the mineralogical composition by X-Ray Diffraction (XRD), quantification of the free silica content by Rietveld Analysis, analysis of potentially toxic elements by solubilization and incubation test.

For the comminution of by-products, the samples were sent to the Center for Mineral Technology - Regional Center of Espírito Santo (CETEM - NRES) and fragmented with the aid of a sledgehammer. Subsequently, the fragments were comminuted in a jaw crusher and sieved in a vibrating sieve with a 28 mesh (0.06 mm) screen. The material retained on the sieve was taken to a roller mill for grinding, again sieved on a 28 mesh screen and the material retained on the sieve was ground in a disc mill and mixed with the material passing the sieve for further homogenization and quartering, following methodology adapted from Góes et al. (2010).

The physical characterization of the by-products was determined from the particle size distribution. For this, a laser granulometer model Mastersize Hydro 2000SM from Malvern Instruments was used. 500 mL of water were added to the device's container, keeping it under agitation of 1700 rpm for 30 minutes until it reached the necessary obscuration to perform the measurement. Then, the sample was gradually added until it reached the ideal obscuration index for reading.

The determination of the chemical composition of the samples was performed at CETEM - NRES using an X-ray Fluorescence Spectrometer (XFR), Bruker S2 Ranger model. We used 10 grams of each by-product powder sample, with particles smaller than 0.105 mm, manually comminuted in agate mortar and pressed at 20 tons for 15 min in a manual press (Mauthe Maschinenbau, PE-011 model). The loss on ignition (LOI) of each sample was also determined by heating at a temperature of 1000 ºC for 2 hours in a muffle furnace, INTI, model FL1300/20, with a heating ramp of 5 ºC per minute.

For analysis of hydrogen potential (pH), an aliquot of each ground sample was mixed in distilled water at a ratio of 1:1 by weight, according to the methodology proposed by MAPA (BRASIL, 2017), the mixture was homogenized in a Quimis magnetic stirrer (model Q5261) and then the pH was measured in a pH meter Marte (model MB 100).

The determination of the mineralogical composition of the samples was performed via X-ray diffraction (XRD) using a Bruker-AXS Model D8 Advance Eco diffractometer. The following operating conditions were adopted: Cu Kα radiation (40 kV/25 mA), with 0.01° 2θ step, 92 seconds counting time per step with a state-of-the-art silicon drift type position sensitive linear detector (with energy discrimination) LynxEye XE, collected from 5 to 80° 2θ. Qualitative spectrum interpretation was performed by comparison with standards contained in the PDF 4+ relational database (ICDD, 2020) in Bruker Diffrac.EVA software.

Aiming to quantify the free silica content (silicon dioxide - SiO_2) in the samples submitted to XRD analysis, the Rietveld method (Rietveld, 1969) was applied. The analysis and interpretation of the XRD results and the Rietveld analysis were performed at the Technological Characterization Sector (TCS) of the Mineral Analysis Coordination (COAMI) of the Mineral Technology Center in Rio de Janeiro, Brazil (CETEM - RJ).

To assess the solubilization of the metals Arsenic (As), Cadmium (Cd), Mercury (Hg), and Lead (Pb), a waste solubilization test was conducted using the methodology described in the ABNT NBR 10006:2004 standard (ABNT, 2004). The extracts were quantified using an inductively coupled plasma optical emission spectrometer (ICP-OES).

For the incubation test, soil samples were collected from the experimental area of the Center of Agricultural Sciences and Engineering (CCAE) at the Federal University of Espírito Santo (UFES), Alegre Campus, at a depth of 0 to 0.30 m. The soil has a clayey texture (46% clay + 36% coarse sand + 10% fine sand + 8% silt).

To accelerate the solubilization of nutrients in the studied by-products, two solutions of microorganisms known as plant growth-promoting inoculants were used. The first solution, identified by the acronym BF, was composed of a combination of *Pseudomonas fluorescens* and *Azospirillun brasiliense* at a concentration of $1x10^{11}$ colony-forming units per liter (CFU/L). The second solution, identified by the acronym BT, was composed of a combination of *Bacillus subtilis*, *Bacillus amyloliquefaciens*, and *Bacillus pumilus* at a concentration of $1x10^{11}$ CFU/L. Inoculation was performed using a graduated pipette, and the volume of inoculum followed the manufacturer's recommendation.

A 5x3x2+3 factorial experiment was used for the incubation test. Specifically, the experiment included 5 by-product samples (MG, CB, CI, OI and AR), 3 different doses of each by-product (0%, 40% and 60%), 2 different microbial solutions (BF and BT), and 3 additional control treatments, with 3 replicates for each sample unit. Each unit consisted of 300 grams of sieved soil homogenized with the respective treatments. The samples were packed in transparent plastic bags, placed on metal shelves in a controlled environment with an average temperature of 25 °C and indirect sunlight, and evaluated at different incubation periods (0, 30, 60, 90, 120 and 150 days) for a total of 33 treatments in 594 sampling units. The soil moisture of each sample unit was maintained at 80% of field capacity, and all sampling units had a small opening for gas exchange with the medium. The experiment was repeated 6 times with different sets of soil samples.

Every 30 days, for a period of 150 days, the experimental units were analyzed for the following parameters: routine analysis, including available Calcium (Ca), Magnesium (Mg), exchangeable Aluminum (Al), Phosphorus (P), Potassium (K), total acidity (H + Al), pH, base saturation (V), Aluminum saturation (m), exchangeable base sum (SB), and cation exchange capacity at pH 7.0 (T); analysis of micronutrients Iron (Fe), Copper (Cu), Zinc (Zn), and Manganese (Mn); and analysis of Remaining Phosphorus (Prem). The soil analyses were performed by the Soil Laboratory of UFES, which is accredited and certified by Embrapa Solos (Brazilian Agricultural Research Corporation).

The obtained results were subjected to variance analysis. Whenever the variables evaluated were significant, the Scott-Knott test was conducted with the aid of R software, version 4.1.2 (R CORE TEAM, 2021), at a 5% probability of error.

Results

To evaluate the potential of the different waste rocks studied in this work, to act as remineralizers for soils intended for agriculture, the results obtained were analyzed and compared with the rules on the definition, classification, specifications, guarantees, and tolerances provided for in Normative Instruction.

By-product characterization

The by-products of ornamental stones, collected in the form of rock fragments, were prepared for the incubation tests by means of grinding. After this procedure, the samples became a particulate material whose granulometry is described in Table I. In the by-products MG, CB, CI, and OI, the predominant fractions are fine sand and coarse sand, unlike the RA, where the silt fraction predominates.

All materials studied are composed mostly of Si, followed by Al, which are normally present in the crystal structure of silicate minerals (Table II). In third place come Fe, Ca, and K, followed by Mg and Na, also very common constituents of silicate minerals present in rocks. The other elements present can be considered 'trace' or of little significance. The sum of bases, involving CaO, MgO, and K_2O contents, should be greater than or equal to 9%, and K_2O content greater than or equal to 1%, according to Normative Instruction. The by-products have a similar alkaline nature, with pH values ranging between 7.57 and 8.48, with the AR by-product having the highest value.

The silicon (Si) contents presented in Table 2 do not refer to the so-called "free silica" but to the total silica, including that present in all minerals of the silicate group. The quantification of free silica (quartz - SiO_2), necessary to meet the proposed Normative Instruction, was done using Rietveld analysis with the data obtained by X-ray diffractometry (XRD) (Table III).

The minerals present in higher concentrations are quartz, albite, microcline, oligoclase, muscovite, orthoclase, and augite, with smaller fractions of others. For the free silica content, all by-products showed values equal to or less than 25%, which is the maximum value allowed by Normative Instruction, for a material to be considered a soil remineralizer. Thus, all the samples of the residues studied fit the free silica content set by the NI.

Table I. Granulometric distribution of the studied residues, after grinding.

	Distribuição Granulométrica (%)*				
	MG	**CB**	**CI**	**OI**	**AR**
Silte	1.03	0.46	0.99	1.20	98.26
Areia Fina	54.74	32.74	44.26	48.72	1.74
Areia Grossa	44.23	66.80	54.75	50.08	0.00

*The silt fraction comprises particles with diameters between 0.002 mm and 0.06 mm and the sand fraction has a grain diameter ranging from 0.06 mm to 2.0 mm, with 0.06 mm to 0.20 mm corresponding to the fraction of thin sand; 0.20 to 0.60 mm of medium sand and 0.60 to 2.0 mm of coarse sand (ABNT NBR 6502:1995).

Table II. Chemical composition and pH of the studied residues.

By-product	Chemical Composition (%)												pH
	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	MgO	Na_2O	TiO_2	P_2O_5	Outros	LOI[(1)]	SB[(2)]	
MG	60.9	14.1	4.,27	3.43	7.97	2.98	3.73	0.56	0.72	0.93	0.41	14.38	7.57
CB	58.1	17.6	6.08	3.06	5.16	1.09	6.02	1.21	0.53	0.99	0.16	9.31	7.75
CI	56.8	14.0	5.10	5.40	8.15	3.48	2.45	1.24	1.45	1.64	0.29	17.03	7.98
OI	59.6	18.0	4.73	4.01	6.65	1.96	2.36	1.01	-	1.44	0.24	12.62	8.06
AR	60.4	17.7	5.89	1.34	3.47	4.64	2.12	0.88	-	0.64	2.92	9.45	8.48

*[1] LOI - loss on ignition; *[2] SB - Sum of Bases (sum of CaO, MgO and K_2O contents).

Table III. Mineralogical composition of residues and percentage of minerals calculated by the Rietveld method.

MINERAL	% *RIETVELD*				
	MG	CI	CB	OI	AR
Quartz	4.46	1.96	-	3.51	29.10
Albite	17.86	9.38	19.19	-	24.48
Microcline	31.28	22.61	8.38	-	13.66
Actinolite	9.39	2.57	5.09	4.59	-
Oligoclase	7.58	15.26	29.45	45.52	-
Muscovite	2.18	5.85	2.49	3.74	19.11
Fluorapatite	1.24	2.50	1.42	1.44	-
Dolomite	-	0.18	0.21	-	1.57
Kaolinite	0.27	0.12	0.15	0.16	2.61
Orthoclase	18.05	18.31	18.71	36.23	-
Nepheline	-	0.55	5.42	-	-
Sodalite	-	0.21	1.08	-	-
Augite	6.82	17.47	5.83	3.60	-
Cancrinite	-	1.28	0.97	-	-
Titanite	0.88	1.74	1.61	1.22	-
Chlorite	-	-	-	-	9.47

In Brazil, the solubility of elements and substances from a solid waste (by-product) is predicted using the solubilization test according to the Brazilian Association of Technical Standards - ABNT (ABNT, 2004). The results obtained from the application of this test to the by-products studied (Table IV) allow us to consider them inert for the elements As, Cd, Hg, and Pb, as provided in the NI.

Table IV. Element contents in the obtained solubilized extracts.

Content in the solubilized extract (mg L^{-1})	By-products					
	MG	CB	CI	OI	AR	T-IW(*)
As	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.01
Cd	< 0.003	< 0.003	< 0.003	< 0.003	< 0.003	0.005
Hg	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.001
Pb	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.01

T-IW(*): threshold for inert wastes (ABNT, 2004).

Analysis of the use of by-products as potential soil remineralizers by the incubation method

Significant differences were observed among the treatments studied, regardless of the inoculation of microorganisms BF and BT, for the variables pH, P, K, Na, Ca, Mg, Fe, Cu, Zn, Mn, H+Al, SB, T, V, and Prem.

Due to the large amount of statistical information to be presented, a table of notes was created to show the average variation of each of the analyzed variables in comparison to the control, at 30, 60, 90, 120, and 150 days after the application of treatments (DAA). In other words, the variation observed in the treatments, which were soil + by-products (T2 to T11), soil + microorganisms (T12 and T13), and soil + by-products + microorganisms (T14 to T33), was calculated by discounting the naturally occurring variation in the control (T1). This was done to ensure a clear understanding of the effect of using the by-products on the chemical and physical aspects of the soil.

To construct the table of scores, initially, the statistical groupings defined after variance analysis and the Scott-Knott test at 5% probability were analyzed for the mean variation of each variable and within each evaluation period. Zero scores were assigned for the results referring to the control group (T1) and, from this, other scores were established according to the groupings. For example score '3' for group 'a', '2' for group 'b', '1' for group 'c', '0' for group 'd' (T1 - witness), and '-1' for group 'e'. In the end, we quantified the scores given for each variable at 30, 60, 90, 120, and 150 days, allowing us to see, in a single table, which were the best treatments within each of the variables analyzed (Table V).

Table V. Final grades attributed to the average variation of the soil variables analyzed in comparison with the control, after 150 days of treatment application.

TREATMENT	DESCRIPTION	ANALYZED VARIABLE															FINAL GRADE
		pH	P	K	Na	Ca	Mg	Fe	Cu	Zn	Mn	H+Al	SB	T	V	Prem	
T1	Control	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T2	MG 40%	8	10	0	0	-3	-4	0	1	-4	0	11	-1	-6	9	2	23
T3	MG 60%	9	13	0	0	-3	-5	0	3	-4	0	11	-1	-7	11	4	31
T4	CB 40%	8	4	10	6	-4	-2	0	0	9	-4	11	9	6	11	3	67
T5	CB 60%	9	6	17	11	-4	-3	0	0	10	-4	11	11	9	11	3	87
T6	CI 40%	7	17	0	0	-4	-2	0	9	-2	0	8	-1	-6	8	1	35
T7	CI 60%	9	23	0	0	-4	-4	0	10	-4	0	11	-1	-7	11	4	48
T8	OI 40%	9	4	0	0	-1	-3	6	1	3	4	11	0	-6	10	2	40
T9	OI 60%	11	9	0	0	-1	-7	8	2	3	5	11	-1	-6	11	3	48
T10	AR 40%	13	4	1	0	4	6	11	17	6	13	11	3	-1	11	-4	95
T11	AR 60%	14	7	1	0	5	7	18	22	6	21	11	3	-1	11	-3	122
T12	BF Microorganism	1	0	1	0	-1	-1	0	2	0	0	1	0	0	1	0	4
T13	BT Microorganism	1	0	1	0	-2	0	0	1	-2	0	1	-1	0	0	1	0
T14	MG 40% + BF	6	9	0	0	-3	-4	0	4	-4	0	6	-1	-4	4	3	16
T15	MG 60% + BF	8	13	0	0	-4	-5	0	7	-4	0	10	-3	-8	9	3	26
T16	MG 40% + BT	7	10	0	0	-2	-2	0	6	-4	0	8	-1	-5	6	3	26
T17	MG 60% + BT	8	13	0	0	-2	-4	0	6	-4	0	11	0	-5	9	3	35
T18	CB 40% + BF	8	6	12	7	-3	-1	0	0	8	-4	10	15	13	10	3	84
T19	CB 60% + BF	9	10	13	15	-2	-4	1	-3	13	-4	11	15	14	11	2	101
T20	CB 40% + BT	9	3	9	10	-3	-4	0	-3	8	-4	10	12	10	11	1	69
T21	CB 60% + BT	10	7	12	13	-3	-4	0	-4	13	-4	11	13	10	11	2	87
T22	CI 40% + BF	9	20	0	0	-1	-3	0	5	-3	1	11	-1	-6	11	0	43
T23	CI 60% + BF	10	22	0	0	-4	-6	0	5	-5	1	11	-2	-7	11	4	40
T24	CI 40% + BT	9	14	0	0	-2	-4	0	3	-5	-1	11	-2	-7	11	3	30
T25	CI 60% + BT	9	18	0	0	-3	-6	0	5	-5	0	11	-2	-7	11	4	35
T26	OI 40% + BF	9	6	-2	0	1	-5	5	-3	0	4	11	-1	-6	11	2	32
T27	OI 60% + BF	14	9	0	0	1	-6	9	-3	1	4	11	-1	-6	11	3	47
T28	OI 40% + BT	9	7	0	0	2	-5	4	-3	0	3	11	-1	-6	11	3	35
T29	OI 60% + BT	12	7	0	0	2	-5	6	-4	-1	3	11	0	-4	11	3	41
T30	AR 40% + BF	14	4	0	0	7	4	13	14	7	16	11	4	0	11	-3	102
T31	AR 60% + BF	14	6	0	0	7	5	16	18	7	22	11	5	1	11	-3	120
T32	AR 40% + BT	14	4	0	0	5	5	10	12	6	14	11	4	0	11	-3	93
T33	AR 60% + BT	14	4	0	0	8	7	20	18	8	24	11	5	2	11	-3	129

Regarding the availability of Al and aluminum saturation (m), no significant quantitative differences were observed between the different treatments under study, regardless of the inoculation of microorganisms BF or BT.

Discussion

The comparison of the results obtained from the analysis of the by-products as potential soil remineralizers with the rules on the definition, classification, specifications, guarantees, and tolerances provided in Normative Instruction, showed that all meet the minimum and maximum requirements provided in the legislation, among which: (i) the physical nature specifications of the remineralizers (Table 1); (ii) the chemical nature specifications of the remineralizers (Table 2); (iii) the free silica contents (Table 3); and (iv) the presence of potentially toxic elements (Table 4).

None of the analyzed residues meet the provisions of the NI concerning the minimum contents of P and micronutrients, which does not prevent their use but restricts the declaration of these as guarantees of the marketed product, through labeling.

In the analysis of the agronomic protocol, in which the objective is to understand the potential of the different by-products in the release of macro and micronutrients, as well as in the improvement of several soil variables, the methodology proposed in this work meets the provisions of the current Brazilian legislation, proposed by EMBRAPA (SILVEIRA et al., 2019a,b).

The sum of the scores assigned after 150 DAA points out the AR by-product as the best material, among those analyzed, to be used agronomically (661 points), followed by the residues CB (495 points), OI (286 points), CI (188 points) and MG (157 points).

The naturally finer particle size of the AR waste may have contributed to its better score for agronomic use, as also observed by Basak et al. (2018) in studies with alkaline volcanic rock waste at different particle sizes and by Dalmora et al. (2020) in nutrient release studies from Andesito and Dacito rocks. According to Priyono and Gilkes (2008), in studies on the dissolution kinetics of multinutrients from silicate rocks, the dissolution rate of cations, for example, increases the smaller the particle size. This fact is important, because the changes resulting from the comminution process in the surface area of the particles assist in the release of elements that were previously fixed in the crystalline structure of minerals (DUARTE et al., 2021).

All by-products analyzed have agronomic potential for soil pH correction, known as 'liming effect', being the by-product AR the most promising also in this case. The pH elevation with the use of the residue was also reported by Aquino et al. (2020) in studies with alkaline rocks from the volcanic province of Fortaleza (Brazil). The AR by-products also stood out for the variables 'total soil acidity' and 'base saturation index'.

The availability of phosphorus (P) was observed in all analyzed by-products, with CI showing the highest release. It is worth noting the importance of P for plant growth as it participates in essential processes, such as respiration, photosynthesis, root growth, energy storage and transfer, cell division, and fruit and seed formation, as well as precocity of production (TELES et al., 2017).

All analyzed by-products, except for AR, obtained positive results for the Prem variable. Remaining Phosphorus (Prem) is related to the soil's retention capacity of P, and the higher the retention capacity, the lower the value of Prem, which is related to the soil's clay content.

Since Brazil is the world's largest importer of potassium (K) (COMEXSTAT, 2022), a nutrient highly demanded by plants for maintaining and increasing crop productivity (CARVALHO et al., 2018), it becomes crucial to obtain new materials that can be widely used in the agricultural production system, aiming to reduce external dependence and production costs. Among the by-products analyzed in this study, only CB was found to have the ability to make K available to the soil-plant system, as observed for the 'cation exchange capacity at pH 7.0'.

The presence of sodium (Na) in the soil nutrient solution can benefit plant growth when present in small concentrations but can lead to soil salinization and sodification when in higher concentrations (AQUINO et al., 2020). Among the by-products analyzed in this study, only the CB by-product can make Na available to the soil-plant system. Similar results were obtained by Duarte et al. (2021) in studies on the release of nutrients from by-products of ornamental stone processing, including one quartzite, two quartz-diorite, and one syenogranite. The recommended concentration of this by-product will depend, for example, on the management of tillage, especially with regard to the nutrient content of the soil and the presence or absence of irrigated crops.

Regarding the availability of Ca in the soil, an element responsible for regulating the transport of nutrients and present in various enzymatic functions (GILLIHAM et al., 2011), the by-products OI and AR obtained satisfactory results, with emphasis on the AR by-product. The same occurs for the availability of Fe and Mn.

Copper (Cu) is a cofactor in numerous biochemical and physiological reactions of plants. However, excess Cu can reduce root vigor and growth, decrease P uptake, and cause Fe deficiency. In this study, all by-products, except CB, showed release of this nutrient, with AR exhibiting the highest release.

The AR by-product was the only one to release Mg, an essential nutrient in the photosynthetic process (GUO et al., 2016). Positive results were also found for the availability of Zn and the 'sum of bases' variable, with emphasis on CB, OI, and AR by-products.

The use of BF or BT microorganisms did not significantly affect the solubilization of mineral nutrients present in the by-products under study. This may be attributed to the absence of plants in the incubation study system. All the aforementioned microorganisms are scientifically recognized as plant growth-promoting inoculants, and they depend on plants for proper colonization and development in the soil-plant system through complex inoculant-plant and inoculant-microbiota interactions.

The existing relationship between the soil microbiota and the solubilization of nutrients present in rocks was also reported by Basak et al. (2018) in studies on the significant positive correlation existing between K uptake by plants and K release by different chemical and biological processes, indicating that the rhizosphere of plants can accelerate the release of K from rocks for further uptake by plants, requiring an additional understanding of the biogeochemical processes existing in the rock-soil-plant system for the desired agronomic effectiveness to be achieved.

A relevant concern in the use of rock dust in agricultural soils, from the technique known as rock farming, is the potential availability of toxic elements naturally present in some rocks, which would represent environmental risks (RAMOS et al., 2017; 2019). This was verified in the analysis of potentially toxic elements (Table 4) provided in Normative Instruction, showing that the contents of As, Cd, Hg and Pb in the samples, all below the detection limit, ensure that the use of the different types of by-products does not offer risks to human and animal health.

No traces of potentially toxic elements were identified in any of the by-products analyzed in this study, demonstrating compliance with Normative Instruction and highlighting the potential use of these by-products as soil remineralizers.

Conclusions

All by-products analyzed in this research meet the minimum and maximum requirements outlined in Normative Instruction MAPA No. 05/2016 (BRASIL, 2016). The results obtained during the incubation stage, inherent to the Agronomic Protocol, show the potential use of the by-products MG, CB, CI, OI, and AR as soil remineralizers.

The CB by-product was the only one to make K available to the soil.

The sum of the scores assigned to the by-products after 150 DAA reveals, in general, AR as the most efficient by-product to be used agronomically, followed by CB, OI, CI, and MG.

The use of by-products incorporated into the soil has a high agricultural potential, which was not favored in the incubation stage with the inoculation of microorganisms 'BF' or 'BT.

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