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Potential of olivine melilitite as a soil remineralizer according to particle size and rates

Abstract – The objective of this work was to evaluate the potential of olivine melilitite rock powder, in two particle sizes and in increasing rates, to improve the chemical properties of the soil and the growth and nutrient accumulation of soybean (*Glycine max*) and sorghum (*Sorghum bicolor*) plants. The treatments consisted of three rates of the rock powder, equivalent to 2.5, 5.0, and 10 Mg ha^{-1}, in the powder and filler particle sizes of the commercial product. Physicochemical and mineralogical analyses were carried out using, as a basis, the Brazilian normative ruling on rock powder as a soil remineralizer. The soybean and sorghum plants were cultivated for 60 and 45 days, respectively, in a greenhouse on a Humic Dystrudept and a Typic Hapludult. The olivine melilitite rock powder applied in the tested increasing rates and two particle sizes improved soil chemical properties and promoted plant growth. However, the filler particle size is more efficient than that of the powder to improve soil chemical properties and plant growth and nutrient accumulation.

Index terms: agromineral, natural inputs, plant nutrition, rock powder, soil fertility.

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Potencial do pó da rocha olivina melilitito como remineralizador de solos de acordo com tamanho de partículas e doses

Resumo – O objetivo deste trabalho foi avaliar o potencial de pó da rocha olivina melilitito, em duas granulometrias e em doses crescentes, para melhorar as características químicas do solo e o crescimento e o acúmulo de nutrientes em plantas de soja (*Glycine max*) e sorgo (*Sorghum bicolor*). Os tratamentos consistiram de três doses de olivina melilitito, equivalentes a 2,5, 5,0 e 10 Mg ha^{-1}, nas granulometrias de pó e filler do produto comercial. Foram realizadas análises físico-químicas e mineralógicas, tendo-se utilizado, como base, instrução normativa para pó de rocha como remineralizador de solos. As plantas de soja e sorgo foram cultivadas por 60 e 45 dias, respectivamente, em casa de vegetação, em Cambissolo Háplico Alumínico e Argissolo Vermelho Distrófico sômbrico. O pó da rocha olivina melilitito aplicado nas doses crescentes e nas duas granulometrias testadas melhorou as características químicas dos dois solos estudados e promoveu o desenvolvimento das plantas. No entanto, a granulometria filler é mais eficiente que a do pó para melhorar as características químicas dos solos e o desenvolvimento e o acúmulo de nutrientes nas plantas.

Termos para indexação: agromineral, insumos naturais, nutrição de plantas, rochagem, fertilidade do solo.

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Introduction

Although Brazil stands out in agricultural production worldwide due to the great size of its territory and high crop yields associated to favorable climatic conditions, most soils of the country are highly weathered and acidic and have a low nutrient availability (Barbosa et al., 2017; Rabel et al., 2018).

To improve the production capacity of these soils, in conventional agriculture, high amounts of soluble fertilizers are used, which is linked to a great dependency on external sources of raw materials (Manning & Theodoro, 2020). An alternative for the country to increase its autonomy in supplying nutrients for its own crops is the application of rock powders, whose effects, however, still need to be further researched for the adequate use of each rock for this purpose in agriculture (Manning, 2015; Silva et al., 2017; Beerling et al., 2018; Manning & Theodoro, 2020; Brito et al., 2019).

Researches in Brazil and abroad have shown that, when rock powders are applied to a soil as a source of nutrients, the agronomic responses are comparable to those obtained with soluble fertilizers (Manning et al., 2017; Zhang et al., 2018; Silva et al., 2019; Aguilera et al., 2020). Despite this positive result, there are important limitations to the wider use of rock powders, especially related to the scarcity of scientific studies evaluating their effects on improving soil quality and crop yield. Therefore, it is necessary to identify, according to their composition and solubility, the rocks that are most effective in each soil and crop condition, as well as the best products to be used, to improve soil chemical properties for a suitable plant development (Theodoro, 2017; Beerling et al., 2018; Manning & Theodoro, 2020). Another challenge is that, in Brazil, since the legislation for the use of rock powders is still recent, there are not yet adequate requirements for estimating the amount and rate of nutrient release from these rocks to plants.

Considering this scenario and the interest of companies in the commercial production of soil remineralizers, a possible material to be tested for this use is the ultrabasic rock olivine melilitite, which presents high contents of calcium and magnesium and expressive contents of potassium and phosphorus, with a localized occurrence in the highlands of Southern Brazil, especially in the alkaline complex of the municipality of Lages, in the state of Santa Catarina (Scheibe, 1986). As other rock powders, this one should be evaluated to determine its most adequate particle size distribution, nutrient content, solubility and reaction rate in the soil, as well as its effectiveness as an alternative to soluble fertilizers in crops (Beerling et al., 2018; Zhang et al., 2018; Silva et al., 2019; Aguilera et al., 2020).

For a more detailed characterization of the melilitite olivine rock and identification of its benefits for both soil and plants, the hypotheses of the present study were: the filler particle size of the olivine melilitite rock powder improves the chemical properties of two soils from Santa Catarina, when compared with the powder particle size; nutrient accumulation by soybean [*Glycine max* (L.) Merr.] and sorghum [*Sorghum bicolor* (L.) Moench] plants is higher in the filler than in the powder particle size; nutrient release from the rock powder in both particle sizes provides an adequate nutrition for soybean and sorghum; and the response of soils and plants subjected to the conventional treatment will be better than that under the different particle sizes of the olivine melilitite rock powder.

The objective of this work was to evaluate the potential of olivine melilitite rock powder, in two particle sizes and in increasing rates, to improve the chemical properties of the soil and the growth and nutrient accumulation of soybean and sorghum plants.

Materials and Methods

The experiment was conducted from November 2017 to February 2018, using a commercial product of olivine melilitite rock powder (Dinamisa Agrominerais, Curitiba, PR, Brazil) with two levels of grinding: powder, preliminary grinding, with 100% of the rock particles passed through a 2.0 mm sieve, 87% through a 0.84 mm sieve, and 60% through a 0.3 mm sieve; and filler, fine grinding, with 100% of the particles passed through a 0.3 mm sieve, as recommended in Instrução Normativa Nº 5 (IN5) of Ministério da Agricultura, Pecuária e Abastecimento (Brasil, 2016), the Brazilian normative ruling for plant remineralizers and substrates. For its characterization, the olivine melilitite rock was subjected to petrographic, chemical, and mineralogical analyses.

The petrographic characterization was done through analyses of thin sections of the rock in the Axio Imager.

A2m petrographic microscope, using the AxioVision system of image capture and processing (Carl Zeiss Microscopy, LLC, White Plains, NY, USA). The analyses showed that the rock was a dark-gray color, with a very fine to thick granulation, grain size from 0.1 to 1.5 mm, a massive structure, a very fine to thick inequigranular phaneritic texture, and submillimeter fractures with different orientations, probably filled with clay minerals. The mineral composition of the rock included 40% melilitite, 35% clinopyroxene (diopside), 15% phlogopite, 5% olivine, and 5% opaque minerals, as well as traces of apatite, altering minerals, and clay minerals.

For the chemical characterization of the olivine melilitite rock, analyses were first carried out using the X-ray fluorescence (XRF) analyzer as described in Heberle (2017). Then, in a laboratory with ALS Global certification, chemical analyses were performed to quantify the present elements through plasma atomic emission spectrophotometry induced by argon.

The values obtained by XRF for the oxides of Si (SiO_2), Ca (CaO), Mg (MgO), K (K_2O), and P (P_2O_5) of the tested rock powder were similar to those found by the chemical analyses, except those of P, which were higher (Table 1).

The elemental chemical analyses revealed low contents of SiO_2 in the rock, confirming its classification in the ultrabasic group. However, the levels of CaO and MgO were very high and those of K_2O were expressive, meeting the criteria of IN5 (Brasil, 2016). In addition, the tested rock powder showed relatively high levels of total P (1.18% P_2O_5) (Table 1), which may contribute to the release of low amounts of the element to the plants during the process of rock dissolution. A complementary and independent sample of crude rock was also analyzed in the laboratory, showing similar values to those of the tested rock powder, in order to guarantee the reliability of the obtained results.

Regarding potentially toxic elements, the tested material showed levels of 2.5, >0.5, 0.01, and 13 ppm arsenic, cadmium, mercury, and lead, respectively, which are below the allowed maximum limits of 15, 10, 0.1, and 200 ppm (Brasil, 2016).

For the mineralogical analysis of the rock, X-ray diffraction (XRD) was carried out in the PW 3710 diffractometer (Philips/PANalytical, Almelo, Netherlands), equipped with a copper tube, with a compensation angle of θ/2θ, and a graphite monochromator with an angular variation from 3.2 to 42º2θ. The angular velocity was 0.02 ° 2θ/s in step mode, with a reading time of 1 s per step. The diffractogram was made in the X'Pert Highscore Plus, version 3.0, software (PANalytical, Almelo, Netherlands). The criteria used for the interpretation of the diffractogram and for the identification of the minerals of the rock powder were based on the interplanar spacing and behavior of the diffraction reflexes presented by Jackson (1969), Brindley & Brown (1980), and Whittig & Allardice (1986), as well as on the complete tables containing the peaks of various minerals in the RRUFF database (Lafuente et al., 2015).

The mineralogical analysis revealed a mineral assemblage very similar to that found by the petrographic analysis, besides identifying the characteristic peaks of the following minerals: melilitite, clinopyroxene of the diopside type, olivine, and phlogopite (Figure 1). Small

Table 1. Characterization of two samples of olivine melilitite rock (OM4 and OM DIN 7) by chemical analyses and by X-ray fluorescence (XRF).

Method	SiO_2	CaO	MgO	K_2O	P_2O_5
	(%)				
			ICP-AES[(1)]		
OM4[(2)]	38.2	13.55	15.05	2.84	1.11
OM DIN 7[(3)]	35.7	14.85	17.4	2.73	1.18
			XRF		
OM DIN 7	37.7	15.28	14.91	3.59	1.55
	Content (%) of element in the rock[(4)]				
	16.7	10.6	10.4	2.3	0.52

[(1)]Plasma atomic emission spectrophotometry induced by argon. [(2)]Supplementary sample of rock powder. [(3)]Sample of rock powder particle size range. [(4)]Calculated from the values obtained by OM DIN 7.

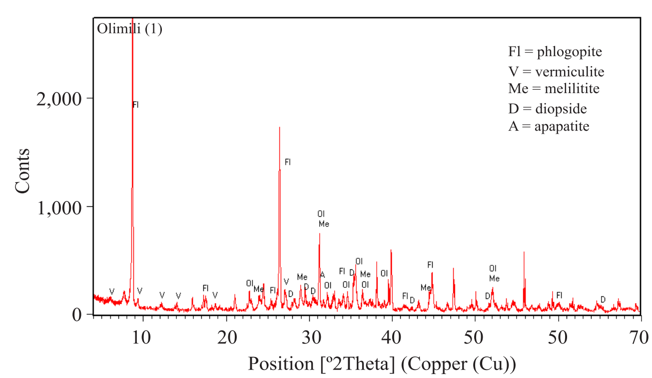

Figure 1. X-ray diffractogram of the applied olivine melilitite rock powder.

amounts of vermiculite were also detected by XRD, indicating a possible transformation of the phlogopite in solid state to vermiculite, which is consistent with the results of the petrographic analysis, showing a small amount of clay minerals in the submillimetric fractures of the rock. Moreover, the low-intensity peak around 2.81 A indicated the presence of small amounts of apatite in the rock, compatible with the relatively high levels of P (around 1.2% P_2O_5) confirmed by the elemental analysis. Although the most intense peaks in the diffractogram were those of the phlogopite, which could indicate that it was the dominant mineral in the studied sample, the chemical and petrographic analyses showed, respectively, low amounts of K and phlogopite (Table 1). Therefore, there must have been segregation and/or orientation of the phlogopite mineral particles on the surface portion of the sample holder during the powder analysis. According to Dunworth & Wilson (1998), the presence of relatively high quantities of phlogopite and apatite are unusual in the olivine melilitite characterized in other environments.

For the study, besides the rock powder, two very acidic soils, in a unfertilized natural condition, were tested: a Cambissolo Háplico Alumínico típico, i.e., a Humic Dystrudept, with a clayey texture, 4.69 pH in water, 2.97 mg kg^{-1} P, and 0.18 $cmol_c$ kg^{-1} K, obtained from the municipality of Lages, in the state of Santa Catarina; and an Argissolo Vermelho Distrófico sômbrico, i.e., a Typic Hapludult, with medium/clayey texture, 4.60 pH in water, 3.40 mg kg^{-1} P, and 0.20 $cmol_c$ kg^{-1} K, from the municipality of Içara, located in the same state. Samples from both soils were collected at a depth of 0–20 cm from the surface horizon, air dried in a greenhouse, crushed, milled, sieved with a 4.0 mm mesh, and then incubated separately in a greenhouse for 60 days, being homogenized every 10 days.

Before incubation, the soils were characterized by chemical analyses for pH in water, pH in the 1:1 soil:solution ratio, and SMP pH, in order to calculate the rate of limestone to be used. Both soils were then corrected to pH 5.5 by applying 33.6 and 76.8 g dolomite limestone filler (Silva et al., 2016), respectively, calculated for 16 kg soil (dry basis). The organic carbon content was obtained by wet oxidation according to Tedesco et al. (1995), whereas P and K were extracted with the Mehlich-1 solution and quantified, respectively, by colorimetry (Murphy & Riley, 1962) and flame photometry (Tedesco et al., 1995). Field capacity was determined as described in Casaroli & Jong van Lier (2008).

The experimental design was completely randomized in a (3x2+2)x2x2 factorial arrangement, with three rates olivine melilitite rock powder x two particle sizes + control + limestone and soluble fertilizers x two soils x two plant species.

The treatments consisted of the three rates of olivine melilitite rock powder, equivalent to 2.5, 5.0, and 10 Mg ha^{-1}, in two particle size ranges, called powder and filler, which were applied to the two different soils, on which the soybean and sorghum plants were cultivated. The control were the soils in natural and unfertilized condition, which was used, as a basis, to stipulate the chosen rock powder rates. Each treatment was carried out with four replicates, and the rates were homogenized in 16 kg soil, to which distilled water was applied to increase water content up to 80% field capacity throughout the experiment, which was done by replacing daily the amount of water lost after weighing the experimental units; the weight corresponding to plant growth in each soil and treatment was included in the water replacement.

The experimental unit was a 5.5 L pot containing 4.0 kg of each incubated soil (dry basis) used to cultivate the soybean and sorghum plants. Seven to eight seed of each species were sown, without pre-germination, per pot in both soil types. Ten days after emergence, plants were thinned out to two soybean and four sorghum plants per pot. The pots were randomized every ten days so that the plants had the same growth conditions. Furthermore, both the soybean and sorghum plants received sources of the conventional N, P, and K soluble fertilizers (Resende et al., 2012).

The soils subjected to the conventional treatment (limestone + soluble fertilizers) and cultivated with sorghum were fertilized with 2.09 g P (triple superphosphate) and 0.9 g K (potassium chloride), as recommended in the protocol for the agronomic evaluation of rock powders and derived products as sources of nutrients to plants or as soil conditioners (Resende et al., 2012). This procedure was necessary since it was a greenhouse experiment, where the volume of root exploitation was limited by the volume of the pot. The same amounts of P and K were applied to both soils before soybean cultivation, but not to the soils in the treatments with the rock powders. In addition, nitrogen (0.35 g urea) was only applied to the soils cultivated with sorghum, also according to Resende et al. (2012), regardless of the treatment (limestone + soluble fertilizers and rock powder alone), totaling eight applications (0.044 g N per week) during the experiment with this plant species. Urea was not applied to soybean because its seeds were inoculated with rhizobia.

For sampling, all plants were collected on the same day but in different stages: soybean, when most plants were in the full-bloom phenological stage; and sorghum, in stage four (visible flag leaf), in the treatments with the two particle sizes of olivine melilitite rock powder, and, in stage five (booting, when all leaves were completely developed), in the treatments corrected with limestone and fertilized with N, P, and K.

From the plant samples, aboveground biomass was collected, kept in paper bags, and dried in a forced-circulation oven, at 65°C, until constant weight. After weighing, the dry matter of the aerial part (APDM) was obtained. Plant roots were separated manually, washed in running water, and dried as the aerial part to obtain root dry matter (RDM). The total dry matter (TDM) produced by the soybean and sorghum plants was considered the sum of the APDM and RDM; only the results of TDM were presented.

After the APDM and RDM were determined, the plant tissue of both soybean and sorghum was ground and then the samples were digested as described in Tedesco et al. (1995). The concentrations of Ca and Mg in the plant tissue were quantified in the Optima 8300 inductively coupled plasma emission optical spectrometer (PerkinElmer Inc., Waltham, MA, USA). Colorimetry (Murphy & Riley, 1962), flame photometry, and steam distillation in the semi-micro Kjeldahl equipment (Tedesco et al., 1995) were used to obtain P, K, and N concentrations, respectively.

From TDM and the N, P, K, Ca, and Mg contents, the accumulated amounts of these nutrients in the plant tissue were calculated according to the equation: N_{Amacro} (mg) = TDM (mg) x nutrient concentration (%) / 100 (Cunha et al., 2019), where N_{Amacro} corresponds to the amount of macronutrient accumulated in the vegetal tissue (aerial part + roots) of the tested plants.

After the collection of the aerial part and roots, the soils were homogenized for sampling, being air dried, crushed, milled, and sifted through a 2.0 mm mesh sieve to obtain the air-dried fine earth (ADFE).

In the ADFE samples, pH in water and in $CaCl_2$ 0.01 mol L^{-1} (1:1 soil:solution ratio) was determined according to Tedesco et al. (1995), as well as the contents of exchangeable Ca^{2+}, Mg^{2+}, K^+, and Al^{3+}. The P, K^+, and Na^+ elements were extracted using the Mehlich-1 solution. Moreover, P was quantified by colorimetry (Murphy & Riley, 1962), and K^+ and Na^+ by flame photometry (Tedesco et al., 1995).

Soil chemical properties, TDM production, and the nutrient contents accumulated in the vegetal tissue of the soybean and sorghum plants were subjected to the analysis of variance with the aid of the SISVAR, version 5.6, software (Ferreira, 2014). For plant yield results, means were compared by the F-test for orthogonal contrasts, at 5% probability. These contrasts aimed at comparing the following treatments: control with the rock powder at different rates and particle sizes; limestone + soluble fertilizers with the rock powder at different rates and particle sizes; and filler and powder at different rates and particle sizes. The data obtained for the soils were subjected to the Scott-Knott test, also at 5% probability.

Results and Discussion

In most cases, when compared with the control treatments, the use of limestone and rock powder in the two particle size ranges, regardless of the plant species, soil type, and applied rates of the tested products, increased the values of pH in water and in $CaCl_2$ 0.01 mol L^{-1}, as well as the contents of Ca^{2+}, Mg^{2+}, Na^+, and P and the sum of bases and saturation, with a concomitant decrease in H+Al, exchangeable Al^{3+}, and Al saturation (Table 2). These results are indicative that the applied products, even in a short period of time, were efficient in improving the fertility of the two evaluated soils.

Higher values were found for pH in water especially after the cultivation of soybean in the Typic Hapludult, probably because this soil is less acidic and buffered. As this is a less buffered soil, the measured pH was higher in the treatments with limestone + PK for soybean and limestone + NPK for sorghum, when compared with those with the rock powder in the two particle size ranges. In the Humic Dystrudept, the pH values in water, at the highest rate and finer particle size of the rock powder, were superior to those obtained in all other treatments, regardless of the plant species,

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soil types, and rates of the used products (Table 2). However, in general, pH values in water in both soils decreased throughout the experiment (Table 2), which was an unexpected behavior.

The sum of Ca^{2+} and Mg^{2+} in the treatments with limestone was 7.0 $cmol_c$ kg^{-1} for both soils, an amount much higher than that of 5.0 $cmol_c$ kg^{-1} recommended for these cations by Comissão de Química e Fertilidade do Solo do Rio Grande do Sul e de Santa Catarina (Silva et al., 2016). This same behavior was observed in the treatments that received the highest rate of olivine melilitite rock powder in the finest particle size

Table 2. Chemical properties of two soils after the cultivation of soybean (*Glycine max*) and sorghum (*Sorghum bicolor*) plants under greenhouse conditions, with the application of limestone plus fertilizers and olivine melilitite rock powder in the filler and powder particle size ranges.

Soil	Treatment	pH (1:1)		Al^{3+}	H+Al	Ca^{2+}	Mg^{2+}	K^+	Na^+	S[(2)]	T[(3)]	V[(4)]	m[(5)]	P
		Water	$CaCl_2$[(1)]	----------------------------------(cmol$_c$ kg^{-1})----------------------------------								----(%)----		(mg kg^{-1})
							Soybean							
Humic Dystrudept	0	4.69e	4.14e	3.93a	8.81a	1.14e	0.34f	0.18a	0.04g	1.69f	10.50e	16g	70a	2.97e
	Limestone + PK	5.60b	4.70b	1.40d	6.55b	6.09a	1.61a	0.09c	0.10f	7.88a	14.43a	55b	15f	28.67a
	2.5 Mg ha^{-1} filler	5.46c	4.37d	2.74b	7.86b	1.73d	0.58e	0.12b	0.18e	2.62d	10.47e	25e	51c	3.17e
	5.0 Mg ha^{-1} filler	5.57b	4.57c	2.00c	6.85b	2.18c	1.02c	0.13b	0.30c	3.65c	10.49e	35c	35e	5.30d
	10 Mg ha^{-1} filler	5.82a	4.79a	1.08d	5.83e	5.64b	1.41b	0.17a	0.58a	7.79a	13.62b	57a	12f	8.97b
	2.5 Mg ha^{-1} powder	5.31d	4.24e	2.93b	9.23a	1.24e	0.51e	0.15b	0.16e	2.06e	11.29d	18f	59b	4.00e
	5.0 Mg ha^{-1} powder	5.34d	4.32d	2.52b	9.16a	1.89d	0.60e	0.14b	0.26d	2.89d	12.06c	24e	47d	7.07c
	10 Mg ha^{-1} powder	5.58b	4.51c	1.72c	8.24b	2.35c	1.04c	0.17a	0.44b	4.01b	12.26c	33d	30e	8.82b
	CV (%)	1.14	0.96	11.33	4.53	7.87	9.21	8.27	8.48	5.91	4.14	3.37	6.89	11.39
Typic Hapludult	0	4.50f	3.97f	1.61a	6.01a	0.23f	0.02e	0.04c	0.06e	0.35f	6.37d	6h	82a	2.51d
	Limestone + PK	6.58a	6.15a	0.03e	1.02f	6.32a	2.18a	0.04c	0.09e	8.63a	9.65a	89a	0e	22.14a
	2.5 Mg ha^{-1} filler	5.61d	4.45d	0.64c	4.66c	0.78e	0.46d	0.02d	0.18d	1.44e	6.10d	24f	31c	3.61d
	5.0 Mg ha^{-1} filler	5.79c	4.74c	0.32d	4.16d	1.40c	0.71c	0.05c	0.30c	2.46c	6.62c	37d	11d	5.78c
	10 Mg ha^{-1} filler	6.16b	5.29b	0.04e	3.08e	2.12b	1.32b	0.09a	0.55a	4.09b	7.17b	57b	1e	10.62b
	2.5 Mg ha^{-1} powder	5.37e	4.23e	1.14b	5.30b	0.75e	0.35d	0.03d	0.18d	1.31e	6.61c	20g	47b	4.09d
	5.0 Mg ha^{-1} powder	5.51e	4.40d	0.74c	4.86c	1.10d	0.48d	0.04c	0.27c	1.90d	6.76c	28e	28c	4.15d
	10 Mg ha^{-1} powder	5.74c	4.70c	0.32d	4.05d	1.56c	0.61c	0.06b	0.40b	2.62c	6.67c	39c	11d	10.61b
	CV (%)	1.77	0.95	19.92	4.97	7.52	11.59	17.44	14.13	5.30	3.71	3.89	13.85	15.77
							Sorghum							
Humic Dystrudept	0	4.60c	4.08e	4.03a	10.63a	1.23f	0.44d	0.20a	0.03e	1.90f	12.53b	15f	68a	3.40c
	Limestone + NPK	5.58a	4.79a	1.39e	7.13d	5.81a	1.87a	0.07e	0.05e	7.80a	14.94a	52a	15g	30.09a
	2.5 Mg ha^{-1} filler	4.60c	4.17d	2.77b	9.85b	1.76e	0.83d	0.20a	0.18c	2.97d	12.82b	23d	48c	4.40c
	5.0 Mg ha^{-1} filler	4.82b	4.36c	2.05c	8.77c	2.25d	1.21c	0.16c	0.29c	3.91b	12.68b	31b	34e	5.50c
	10 Mg ha^{-1} filler	5.78a	4.73a	0.87f	7.34d	5.45b	1.61b	0.14d	0.46a	7.66a	15.00a	51a	10h	8.77b
	2.5 Mg ha^{-1} powder	4.37c	4.11e	2.95b	9.99b	1.69e	0.58d	0.20a	0.15c	2.62e	12.60b	21e	53b	4.60c
	5.0 Mg ha^{-1} powder	4.46c	4.16d	2.80b	9.74b	2.05d	0.87d	0.19a	0.26c	3.38c	13.12b	26c	45d	5.99c
	10 Mg ha^{-1} powder	4.96b	4.43b	1.72d	8.74c	2.49c	1.07c	0.19a	0.40b	4.14b	12.88b	32b	29f	11.34b
	CV (%)	4.07	1.06	8.44	4.58	5.22	11.45	7.16	10.76	4.92	3.66	4.38	5.17	20.17
Typic Hapludult	0	4.67e	4.04f	1.52a	5.84a	0.28g	0.08d	0.05b	0.06c	0.47f	6.31d	7h	76a	6.02e
	Limestone + NPK	6.46a	6.08a	0.04e	0.74e	6.61a	2.20a	0.05b	0.11c	8.97a	9.71a	92a	0e	19.95a
	2.5 Mg ha^{-1} filler	5.06c	4.42d	0.63c	4.91b	0.93e	0.54c	0.04b	0.23b	1.74d	6.65d	26f	27c	3.81f
	5.0 Mg ha^{-1} filler	5.35b	4.66c	0.30d	4.50c	1.49d	0.78c	0.03b	0.42a	2.72c	7.22b	38d	10d	6.39e
	10 Mg ha^{-1} filler	5.39b	4.99b	0.09e	3.65d	2.16b	1.32b	0.09a	0.22b	3.80b	7.45b	51b	2e	11.36b
	2.5 Mg ha^{-1} powder	4.91d	4.26e	0.85b	5.23b	0.74f	0.34d	0.03b	0.18b	1.29e	6.52d	20g	40b	4.32f
	5.0 Mg ha^{-1} powder	5.01c	4.44d	0.61c	3.85d	1.10e	0.51c	0.03b	0.22b	1.86d	5.71e	33e	25c	8.53d
	10 Mg ha^{-1} powder	5.39b	4.79c	0.26d	3.99d	1.81c	0.71c	0.05b	0.39a	2.96c	6.95c	43c	8d	9.12c
	CV (%)	1.33	2.03	20.78	8.13	8.78	22.61	30.05	33.17	9.31	6.47	4.59	16.54	4.69

(1)Calcium chloride at 0.01 mol L^{-1}. (2)Sum of bases. (3)Cation exchange capacity (CEC) at pH 7. (4)Base saturation. (5)Aluminum saturation.

range, but only in the Humic Dystrudept (Table 2), in which the levels of those elements increased, reaching values comparable to those obtained with liming. This finding can be considered very positive since, in the comparison between a product that dissolves relatively quickly (limestone) and a less soluble one (silicate rock), a similar effect was found in a short experimental period.

Although the levels of Ca^{2+} and Mg^{2+} were more pronounced in the Humic Dystrudept, an increase in these nutrients was observed in both tested soils regardless of the used powder particle size range and rate (Table 1). This increase may be related to the high levels of CaO (14.85%) and MgO (17.40%) present in the minerals that constitute the olivine melilitite rock powder (Table 1). Therefore, the increase in the contact time between the rock powder and the soils during the conduction of the experiment possibly favored the dissolution and release of those nutrients to the soils, also increasing their percentage in the cation exchange capacity (CEC) of these soils (Table 2).

Higher levels of Ca^{2+} and Mg^{2+} were found in other basic cations in the Humic Dystrudept, which is attributed to the greater acidity and high organic matter (OM) content of this soil. Together, these two factors may have been crucial for the increase in the decomposition of the rock, regardless of the particle size ranges and rates used (being more pronounced in the filler particle size at the highest tested rate), as well as for the release of these nutrients in the Humic Dystrudept (Table 2).

The contents of Al^{3+} and H+Al and Al saturation decreased with the treatments, regardless of the used product. The Al saturation values decreased below the threshold of 20–30% considered critical for most crops (Smyth & Cravo, 1992; Hashimoto et al., 2010; Cunha et al., 2018a, 2018b) in the treatments with limestone and rock powder at the maximum rate and in the two particle size ranges, especially in the Typic Hapludult (Table 2). In this condition, Al^{3+} exerted little or no toxicity effect on the evaluated plants.

Acidity decreased in both the Typic Hapludult and Humic Dystrudept, probably due to the high levels of basic cations in the products added to these soils, which already had high levels of these cations in their chemical composition (Table 1). After the solubilization of the applied products, the cations corrected soil acidity by increasing both the pH values and the sum and saturation of bases (Table 2), which, consequently, increased soil fertility. These results, therefore, show the corrective power, particularly of the olivine melilitite rock powder, a product of low solubility compared with limestone. These findings are supported by the studies carried out by Tavares et al. (2018), Miranda et al. (2018), Brito et al. (2019), and Manning & Theodoro (2020).

The K^+ content decreased in the Humic Dystrudept, most likely due to the expressive presence of 2:1 clay minerals such as hydroxy-Al interlayers, which can hold more K (Almeida et al., 2018). In the Typic Hapludult, however, the contents of this element remained similar when compared with the control. There were also no significant changes in the extractable K^+ concentrations in the treatments with increasing rates of the tested rock powder, which can be attributed to the low contents of K_2O present in the rock (Table 1). This does not mean, however, that the rock was not releasing K^+, whose concentration and accumulation could have increased in the soil solution and in the plant tissue, respectively. Another possibility is that this nutrient, when released to the soil, may have been adsorbed by the exchange sites in the soil or precipitated as a secondary mineral, as reported by Renforth et al. (2015).

In general, the K^+ contents were lower in the treatments in which lime and soluble fertilizers were applied to both evaluated soils, regardless of the plant species cultivated, although, in some cases, they were similar to those found for the control and the treatments with the olivine melilitite rock powder (Table 2). This result may have been due to the increase in the number of negative electrical charges from the soils (Bortolanza & Klein, 2016; Gabriel et al., 2018), causing part of the K^+ of the solution to migrate to the negative charges created (Ernani et al., 2007). Another possible explanation may be related to the greater absorption of this nutrient by the plants subjected to the conventional treatment, leading to a superior TDM production and nutrient accumulation in comparison with the other treatments (Table 3).

The Na^+ concentrations increased in all treatments (Table 2), being more pronounced in those with olivine melilitite rock powder in its different rates and particle size ranges, which may be directly related to the Na_2O content (3.29%) already present in the chemical composition of this rock. The increase in the applied rates and in the time of contact between the product and the soils may also have contributed to the increased Na^{+} in the soils throughout the experiment (Table 2). However, even at the highest applied rates of the filler and powder particle sizes, sodium saturation at CEC still remained below the levels that could have been considered critical, i.e., above 6.0% (Silva et al., 2016).

No significant changes were observed in the CEC values at pH 7 since the increase in Ca^{2+} and Mg^{2+}

Table 3. Total dry matter (TDM) production and nutrient accumulation (Ca, Mg, K, P and N) in the tissue of soybean (*Glycine max*) and sorghum (*Sorghum bicolor*) plants on two different soils, under greenhouse conditions, with the application of limestone plus fertilizers and olivine melilitite rock powder in the filler and powder particle size ranges.

Treatment	Soybean						Sorghum					
	TDM	Ca	Mg	K	P	N	TDM	Ca	Mg	K	P	N
	(g)	--------------------(mg g^{-1})--------------------					(g)	--------------------(mg g^{-1})--------------------				
							Humic Dystrudept					
0	2.82	11.22	8.84	33.50	3.79	110.1	0.69	1.28	0.91	4.61	0.43	15.07
Limestone + PK for soybean - limestone + NPK for sorghum	43.4	353.26	142.10	442.61	106.33	1099.3	35.1	66.7	91.4	565.6	81.6	398.6
2.5 Mg ha^{-1} filler (F2.5)	10.0	56.91	29.93	45.47	13.86	224.3	1.64	4.19	3.18	23.19	2.35	39.8
5.0 Mg ha^{-1} filler (F5.0)	16.69	126.78	56.77	84.96	25.61	449.2	4.95	11.7	12.1	152.9	8.66	138.1
10 Mg ha^{-1} filler (F10)	21.45	190.60	70.74	115.85	42.24	596.6	12.4	23.7	24.6	340.1	17.9	234.0
2.5 Mg ha^{-1} powder (P2.5)	7.86	38.93	23.53	48.49	12.25	184.2	0.91	2.2	1.47	11.4	1.24	22.0
5.0 Mg ha^{-1} powder (P5.0)	11.74	73.82	37.90	67.86	22.08	303.6	1.35	3.84	2.63	26.4	3.50	35.0
10 Mg ha^{-1} powder (P10)	16.26	120.14	52.27	86.22	25.92	440.7	3.87	9.56	8.93	121.5	7.99	114.7
							F-test – orthogonal contrasts					
Control (0) x F2.5; F5.0; F10; P2.5; P5.0; P10	**	**	**	**	**	**	**	**	**	**	**	**
Limestone x F2.5; F5.0; F10; P2.5; P5.0; P10[(7)]	**	**	**	**	**	**	**	**	**	**	**	**
F2.5; F5.0; F10 x P2.5; P5.0; P10	**	**	**	*	ns	**	**	**	**	**	**	**
F2.5 x F5.0; F10	**	**	**	**	**	**	**	**	**	**	**	**
F5.0 x F10	**	**	**	**	*	**	**	**	**	**	**	**
P2.5 x P5.0; P10	**	**	**	**	ns	**	*	**	ns	**	**	*
P5.0 x P10	**	*	**	*	ns	**	*	**	ns	**	*	**
CV (%)	10.12	13.09	13.78	10.36	33.34	12.84	16.92	15.01	25.96	16.67	15.71	26.32
							Typic Hapludult					
0	0.60	0.73	0.81	2.05	1.11	30.03	0.51	1.06	1.41	2.58	0.61	17.92
Limestone + PK for soybean - limestone + NPK for sorghum	27.48	277.93	148.30	227.29	84.49	668.18	32.48	90.59	142.1	374.99	78.00	401.56
F2.5	8.51	37.60	22.58	59.92	13.56	164.79	0.51	1.18	1.47	1.24	0.73	18.53
F5.0	8.71	51.18	25.32	84.65	16.71	197.57	2.27	6.50	7.79	45.05	4.56	90.97
F10	9.72	57.71	27.09	107.83	14.62	188.67	2.17	6.28	5.78	56.20	3.30	65.91
P2.5	5.68	24.76	17.42	33.14	9.92	169.71	0.14	0.31	0.28	0.86	0.29	3.25
P5.0	6.80	32.18	20.35	42.85	12.39	164.46	0.29	0.96	0.90	3.50	0.46	9.84
P10	7.54	48.25	25.22	77.55	10.78	197.53	1.86	4.89	5.36	47.01	4.27	74.34
							F-test – orthogonal contrasts					
Control (0) x F2.5; F5.0; F10; P2.5; P5.0; P10	**	**	**	**	**	**	ns	ns	ns	ns	ns	ns
Limestone x F2.5; F5.0; F10; P2.5; P5.0; P10[(7)]	**	**	**	**	**	**	**	**	**	**	**	**
F2.5; F5.0; F10 x P2.5; P5.0; P10	*	**	ns	**	ns	ns	ns	*	ns	ns	ns	*
F2.5 x F5.0; F10	ns	*	ns	**	ns	ns	ns	**	ns	ns	ns	**
F5.0 x F10	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
P2.5 x P5.0; P10	**	*	ns	**	ns	ns	ns	ns	ns	ns	ns	*
P5.0 x P10	ns	ns	ns	**	ns	ns	ns	*	ns	ns	ns	**
CV (%)	24.39	17.71	17.17	19.78	24.15	13.75	42.91	18.58	28.04	60.09	92.69	34.64

* and **Significant at 5 and 1% probability, respectively. ^{ns}Nonsignificant.

was stoichiometrically similar to the decrease in H+Al. However, the effective CEC increased with the application of the evaluated products to the soils, as expected (Table 2).

The P contents increased in the two soils and in all treatments (Table 2), particularly in the treatment with limestone, in which P was applied to both soils in the form of a rapidly soluble fertilizer, i.e., the triple superphosphate. The content of P also increased with increasing rates of the rock powder, both in the filler and powder particle size ranges. Furthermore, at the highest rate of 10 Mg ha^{-1}, P contents were about three times higher than the values originally found in the two soils (Table 2). This result is indicative that the rock shows potential to release P to the soil despite its relatively low P_2O_5 contents of 1.18% (Table 1); however, it should be noted that the acid extraction by Mehlich-1 overestimates the availability of P for plants when less soluble sources of this element are used (Mumbach et al., 2020), such as rock powders and natural phosphates.

The improvement in soil fertility with the use of the tested products (Table 2), in general, led to positive responses in terms of TDM production (Table 3) and nutrient accumulation by the soybean and sorghum plants cultivated on the Humic Dystrudept and Typic Hapludult. The effects of the treatments, as well as the visual differences between them, may be observed by comparing the height and size of the soybean (Figure 2) and sorghum (Figure 3) plants in each treatment to which the soils were subjected.

Regardless of the plant species and used product, TDM and nutrient accumulation (Ca, Mg, K, P, and K) were higher in the fertilized treatments in the Humic Dystrudept, when compared with the control. For soybean plants, a similar behavior was observed in the Typic Hapludult. Therefore, there was increase in soybean TDM and nutrient accumulation in the two soils treated with the different particle size ranges and rates of the olivine melilitite rock powder, likely due to the improvement in the fertility of both soils, whose acidity decreased with the application of this product (Table 2).

For sorghum, however, TDM production and nutrient accumulation in the Typic Hapludult did not differ, in general, between the control and the treatments with the rock powder in the two particle size ranges (Table 3). In addition, on this soil, sorghum TDM production and nutrient accumulation were higher when the rates of 5.0 and 10 Mg ha^{-1} of the filler particle size and the highest rate of the powder particle size were added, probably because, at these rates, the applied products improved soil chemical properties and, consequently, the response of the plants in comparison with the other rates and particle size (Tables 2 and 3, and Figure 3). These findings suggest that, regardless of the particle size, in soils with chemical and physical characteristics similar to those of the Typic Hapludult evaluated in the present study, higher rates of the rock powder must be used for plants to express their yield potential, which can be attributed to the slower dissolution and release of nutrients from this product in more fertile soils as this one, when compared with poorer soils, as the Humic Dystrudept (Table 2).

The obtained results are indicative that the rock powder was efficient in releasing substantial amounts of nutrients to the soils, with a possible immediate absorption by the soybean plants, whose nutritional requirements were met in each phenological stage during the conduction of the experiment. For the same reason, a similar behavior was observed for sorghum when cultivated on the Humic Dystrudept (Tables 2 and 3).

When comparing limestone with the rock powder in the two particle size ranges and at the different rates applied, TDM production and nutrient accumulation differed between the two plants species in both evaluated soils. Despite these differences, the highest values for these plant variables were observed in the treatment with limestone plus soluble fertilizers (Table 3 and Figures 2 and 3). In the Humic Dystrudept, for example, the TDM production of soybean in the treatment with 10 Mg ha^{-1} of the filler particle size was half of that obtained with limestone, although it was about eight times greater than that with the control (Table 3 and Figure 2). In the same soil, sorghum TDM production was lower at the highest rate of the filler particle size, being equivalent to 35% of the value found with limestone plus soluble fertilizers, but still about 18 times higher than that with the control.

In the Typic Hapludult, the effect of the application of the rock powder on TDM production was less expressive, although still superior to that of the control, but only for the soybean plants (Table 3 and Figure 2). Therefore, a higher TDM production and nutrient accumulation were obtained under the limestone and

NPK treatment due to the high rates of the product applied to both soils, which were three times higher than the recommended for field cultivation (Silva et al., 2016). This behavior was already expected, since the soluble fertilizers are characterized by a fast release of nutrients to the soil solution, allowing their greater absorption and subsequent accumulation by the plants (Cunha et al., 2019). Contrastingly, the release of nutrients by rock powders is slower and, therefore, would only have an effect in the medium term or over the subsequent crop cycles (Manning & Theodoro, 2020; Silva et al., 2019).

In the treatments with the rock powder, TDM production (except of soybean that did not differ significantly) and nutrient accumulation (except of P in soybean) showed significant differences in the Humic Dystrudept, increasing with the increasing rates of the rock powder, regardless of the particle size range used. However, in the Typic Hapludult, the TDM production with the increase in the rock powder rate differed only for the soybean but not for the sorghum plants (Table 3 and Figures 2 and 3).

There was a difference in the accumulation of Ca and K in soybean and of Ca and N in sorghum in the Typic Hapludult. However, unlike the observed in the

Figure 2. Development of soybean (*Glycine max*) plants grown on a: Humic Dystrudept (A) and Typic Hapludult (B) subjected to the control, 2.5 Mg ha^{-1} filler, 5.0 Mg ha^{-1} filler, 10 Mg ha^{-1} filler, and limestone + PK treatments; and Humic Dystrudept (C) and Typic Hapludult (D) subjected to the control, 2.5 Mg ha^{-1} powder, 5.0 Mg ha^{-1} powder, 10 Mg ha^{-1} powder, and limestone + PK treatments. Photos by Danel Alexandre Heberle.

Humic Dystrudept, there was no difference in the accumulation of Mg, P, and N in the tissue of soybean and of Mg, K, and P in that of sorghum even with the increase in the rates of the rock powder. It is important to note that the highest absolute values were found in the treatments that received the filler particle size (Table 3).

When the filler particle size was applied at the rate of 2.5 Mg ha^{-1}, TDM production and nutrient accumulation differed between soybean and sorghum plants in the Humic Dystrudept; a similar behavior was observed when comparing the rates of 5.0 and 10 Mg ha^{-1} (Table 3). However, in the Typic Hapludult, among the three rates of the filler particle size, there was no difference in the TDM production of either plant species, only in the accumulation of Ca and K in soybean and of Ca and N in the sorghum plants. In contrast, when only the two highest rates of the filler particle size were compared in this same soil, there was no difference in TDM production and nutrient accumulation in the two plants species. These results are indicative that the TDM production and nutrient accumulation of the tested plants increased with the increase in the rate of the filler particle size only in the Humic Dystrudept, when compared with the other treatments with rock powder and with the control.

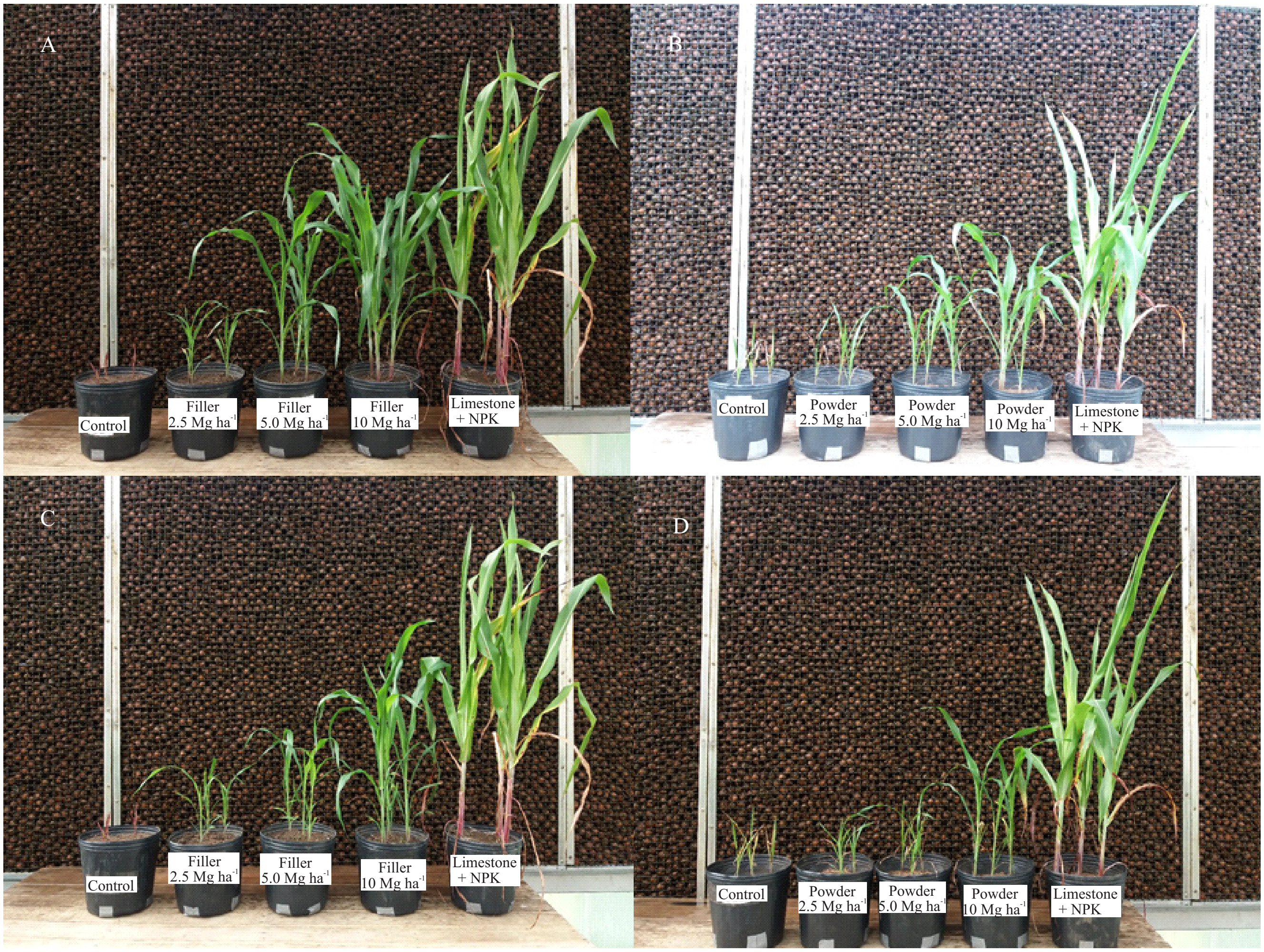

Figure 3. Development of sorghum (*Sorghum bicolor*) plants grown in a: Humic Dystrudept (A) and Typic Hapludult (B) subjected to the control, 2.5 Mg ha^{-1} filler, 5.0 Mg ha^{-1} filler, 10 Mg ha^{-1} filler, and limestone + NPK treatments; and Humic Dystrudept (C) and Typic Hapludult (D) subjected to the control, 2.5 Mg ha^{-1} powder, 5.0 Mg ha^{-1} powder, 10 Mg ha^{-1} powder, and limestone + NPK treatments. Photos by Danel Alexandre Heberle.

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Plant TDM production and nutrient accumulation (except of P in soybean and Mg in sorghum) differed between the lowest and the two highest rock powder rates within the same particle size range in the Humic Dystrudept. A similar behavior was observed between the two highest rates of the rock powder. Conversely, in the Typic Hapludult, when the lowest rate was compared with the two highest ones, there was a difference in the TDM production and in the accumulation of Ca and K by soybean and of N by sorghum. However, in the comparison of the two highest rates, no significant difference was found for TDM production and nutrient accumulation between plant species (Table 3).

These results are indicative that, regarding TDM production and nutrient accumulation, the best responses of the soybean and sorghum plants were observed with the filler particle size (Figures 2 and 3). Therefore, it is possible that smaller particles of rock dust, as those of the filler, in contact with the soil (soil moisture) for a longer time, favor a greater solubilization of the rock, with a consequent release of substantial amounts of nutrients (macro- and micronutrients and silicon) that are responsible both for reducing soil acidity and for supplying plant demands at different stages of development. In short, plants cultivated in soils with better chemical conditions (greater nutrient supply) tend to show a higher TDM production and nutrient accumulation.

Therefore, the differences in the results obtained for soil chemical analyses, TDM production, and nutrient accumulation between the powder and filler particle size ranges (Tables 2 and 3 and Figures 2 and 3) may be related to particle size, which is responsible for reducing the speed of rock solubilization, affecting the efficiency of the product and the release of nutrients to the soils in the short term. This allows of inferring that the rock powder in the powder particle size needs more time to dissolve and subsequently release nutrients.

Despite these differences due to the two particle size ranges of the rock powder, the nutrient content in both soils, TDM production, and nutrient accumulation by the soybean and sorghum plants were increasing and significant, exceeding the values of the control (Tables 2 and 3 and Figures 2 and 3). In addition, during plant development, no nutritional deficiencies were identified in soybean or sorghum and the levels of nutrients determined in the index leaves were in the range considered adequate by Tedesco et al. (1995) and Vargas et al. (2018).

As in the present study, Welter et al. (2011), when evaluating the application of basalt powder in two particle sizes (0.05 and 0.10 mm) and at six increasing rates, found that the smallest size was the best for the initial development of camu-camu [*Myrciaria dubia* (Kunth) McVaugh] seedlings. Melo et al. (2012), also using increasing rates of ground powder from basalt rock, concluded that the highest applied rate significantly reduced the acidity and increased the basic cations of a Latossolo Amarelo distrófico (Oxisol), highlighting that the analyzed rock can be considered an alternative source for fertilizers and soil correction. Moreover, Toscani & Campos (2017) reported that the basalt, phosphorite, and dolomite rock powders, applied in different particle size ranges as remineralizers of weathered soils, showed positive effects on soil fertility and plant yield.

Still according to the literature, increasing rates of rock powders also had a significant effect on soybean response. Silva et al. (2019) found that soybean yield increased with increasing rates (total of ten) of the basalt gabbro rock powder. Almeida Júnior et al. (2020) evaluated several yield indexes of soybean grown in an Argissolo Vermelho, i.e., a Red Argisol, subjected to increasing rates of rock powder and concluded that the tested organic fertilizer was efficient in maintaining both crop yield above the national average and all agronomic characteristics at high levels. Aguilera et al. (2020), analyzing the effect of the application of four rates of basalt rock powder on soybean yield, observed improvements in the yield components of this crop when grown on a Latosol Rojo distrófico.

Therefore, although rock powders show a low solubility compared with limestone plus soluble fertilizers, under adequate management conditions, most of them can be considered promising to replace the conventional products used in agriculture. This conclusion is further supported by the results obtained both for the chemical analyses of the soil and for the TDM production and nutrient accumulation by the plants on the soils treated with the filler particle size of the rock powder, notably at the highest rate of 10 Mg ha^{-1}, with some values close to or even above those found for the treatments with limestone plus soluble fertilizers (Tables 2 and 3 and Figures 2 and 3). This finding could be attributed to the slow but continuous release by the rock powder of the nutrients required by the plants in each phenological stage until the completion of their cycle (Ramos et al., 2014; Pereira et al., 2019; Manning & Theodoro, 2020).

In acid soils, such as the Humic Dystrudept, with high OM contents, the addition of rock powder in association with manure or organic residues or in a pre-composting with the used products may further increase the dissolution of the rock minerals due to the action of the organic acids present in the OM, as reported by Wolschick et al. (2016), Tavares et al. (2018), and Pereira et al. (2019). In the present study, this was observed with the application of the rock powder in the two particle size ranges (mainly the filler at the highest rate), being confirmed by the higher nutrient contents released in the Humic Dystrudept, whose OM (6.0%) is higher than that of the Typic Hapludult (2.9%). Therefore, in soils with characteristics similar to those of the Typic Hapludult, a source of OM should be added to potentiate the beneficial effects of the rock powder.

The results of the present study are, therefore, indicative that the application of the olivine melilitite rock powder is an interesting alternative to increase soil fertility, showing positive effects both on plant yield and nutrient accumulation. However, future studies are still necessary to evaluate the potential of the rock powder in improving soil chemical properties and plant growth, when applied in the two analyzed particle size ranges, pure or combined, associated or not with a source of OM, in field experiments and/or in a greenhouse, as well as to determine the residual effect of these products after crop succession or rotation.

Conclusions

1. The olivine melilitite rock powder applied in the powder and filler particle size ranges improves the chemical properties of the two studied soils and increases total dry matter (TDM) production and nutrient accumulation by soybean (*Glycine max*) and sorghum (*Sorghum bicolor*) plants.

2. The soils treated with the filler particle size show the best response in terms of improved soil chemical characteristics and plant yield and nutrient accumulation.

3. The most positive effects of the olivine melilitite rock powder, in both particle size ranges, on soil chemical characteristics and plant yield is observed in the Humic Dystrudept.

4. TDM production and nutrient accumulation by the soybean and sorghum plants in the treatments with limestone plus soluble fertilizers surpass those obtained with the powder of the olivine rock melilitite in the two particle size ranges at increasing rates.

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