Sustainable Release of Macronutrients to Black Oat and Maize Crops from Organically-Altered Dacite Rock Powder

Claudete Gindri Ramos, Adilson Celimar Dalmarka, Rubens Muller Kautzmann, James Hower, Guilherme Luiz Dotto, and Luis Felipe Silva Oliveira

By-products from the dairy industry and mining activities represent a great environmental overload, which justify research for value-added reuse of these by-products (dairy sludge and dacite rock powder). Dairy sludge is generated at a rate of about 0.2–10 l per liter of processed milk, and dacite powder, from rock mining extraction and processing, is generated for about 52,400 m³ per year in Nova Prata city, Southern Brazil. For both by-products, the compositions of calcium (Ca), magnesium (Mg), potassium (K) and phosphorous (P), arsenic (As), cadmium (Cd), chromium (Cr), mercury (Hg), and lead (Pb) were determined by using appropriate analytical techniques. A greenhouse experiment was conducted to determine release of macronutrients, such as Ca, K, Mg, and P, from by-products to support black oat (Avena strigosa) and maize nutrition. Twelve by-products doses were blended with a typical Hapludox soil and were applied to pots with five replications each. Black oat (first cultivation) and, sequentially, maize (second cultivation) were cultivated for 70 days each. Ameliorations in soil chemical attributes, leaf dry matter yield, and plant nutritional status were evaluated at the end of each cultivation. There was a significant (p < 0.05) increase in all parameters evaluated in a dose of 7251 kg ha⁻¹ of dacite rock powder and 20,594 kg ha⁻¹ of dairy sludge. Compared to the control treatments, both crops grew well better on all mixtures. The presence of potentially toxic elements in both by-products was irrelevant, indicating that effective blending of dacite rock powder along with dairy sludge could be a potential source of Ca, K, Mg, and P in agriculture without posing a risk of contamination to the environment.

KEY WORDS: Dairy sludge, Dacite rock powder, By-products, Soil fertilization.
INTRODUCTION

The dairy industry requires large amounts of water for washing pipes, machinery, and floors, but the liquid residue of a dairy product originates mainly from the manufacturing process, generating a large volume of wastewater, about 0.2–10 l per liter of processed milk (Balannec et al. 2005). The high production and proper sludge disposal are problematic issues for the dairy industry (Bhadouria & Sai, 2011). The main negative impacts of these by-products are not only the contamination of drinking water but also the harm to aquatic ecosystems, which can lead to death of fish and other animals, besides emitting unpleasant odors into the atmosphere and accumulation of waste (Qasim & Mane, 2013). In addition, sludge generated in the flotation treatment of the dairy industry, generally a source of N, could also contribute significant amounts of phosphorus (P), calcium (Ca), potassium (K), sodium (Na), magnesium (Mg), sulfur (S), zinc (Zn), and other important nutrients for crops (Qasim & Mane, 2013). In natura application of dairy sludge is suitable for the environmental outlook, and it shows a beneficial property in the recovery of degraded land. Sludge utilization favors plant yields and can reduce the use of highly soluble fertilizers (Oszust et al. 2015). The application of sludge produced by the dairy industry in agricultural soils is an attractive option for their reuse because several nutrients are provided and the physical attributes of the soil can be ameliorated (Frac et al. 2017). Several studies with these types of sludge demonstrated an increase in agricultural productivity (Macono et al. 2002) and ameliorated soil fertility (Suárez et al., 2004). This is because plants can modify the pH values of the rhizosphere, but they also exude organic acids and other strategies, increasing solubilization of insoluble compounds, which can increase nutrient availability (De Conti et al. 2019).

The main negative aspect of the use of dairy sludge is the low K content (López-Mosquera et al. 2002). Still, the dairy sludge is very rich in organic material, so it is expected that it has high bioactivity. This characteristic may be advantageous for blending with another less bioactive by-product, but with a larger nutrient diversity, such as dacite rock dust (Ferrari et al. 2019). The association of high biological activity materials, such as dairy industry sludge, with rocks may influence the process of alteration of rock minerals (Stranghoener et al. 2018). According to Anjanadevi et al. (2016), the release of rock nutrients can be hastened by blending the rocks with organic by-products, thereby promoting mineral dissolution by biological process.

Given the complex nature of rock minerals, appropriate analytical procedures need to be defined to satisfactorily characterize the composition and bioavailability of existing rock elements, as crop responses may be associated not only with K from rocks, but also with synergistic factors and effects arising from its composition (Ramos et al. 2017).

Rock minerals and industrial minerals typically do not generate environmental impacts such as acid drainage and environmental contamination. The survey carried out by Toscan et al. (2007) revealed that in 2005, an amount of approximately 52,400 m³ of rock mining by-product was generated in Nova Prata, Rio Grande do Sul, Brazil. As they are sometimes found in more populated areas or near cities, the mining industry faces the challenges of avoiding landscape damage and properly disposing the processing tailings. In addition, they compete for physical space with the community in their surroundings, due to the opportunity cost of using the areas (Lins, 2008).

In Brazil, volcanic rocks present good potential as a source of K. According to Santos et al. (2016), the rock powder addition can be an effective K fertilizer for cultivation of eucalyptus, maize, and grass. Rock powder has been reported as a soil remineralizer and a source of plant nutrients in several countries such as Australia and India (Basak, 2019; Basak et al. 2020), Brazil (Dalmora et al. 2020; Ramos et al. 2019), and the UK (Manning, 2018; Mohammed et al. 2014). Theodoro and Leonardos (2006) showed that the rock powder application blended with organic by-product achieved better productivity crop yields than the application of just rock powder. The combined application of dacite rock powder with dairy sludge can be a promising approach because insoluble nutrients in mineral rocks can be made available by the action of organic acids produced during organic-matter decomposition (Basak et al. 2017). These point to the possibility of converting by-products with environmental contamination potential to inputs to be used in agriculture. This may be an alternative means of combating the waste problems of the dairy and rock mining industries. It is necessary to conduct more research to verify the fertilizing property of these by-products compared to high-solubility fertilizers. It is also relevant that their use as agricultural input is properly planned to maximize benefit of their
qualities and minimize the potential environmental risks.

A relevant factor that makes the use of dairy sludge and rock mining by-products attractive in agriculture is the abundance of elements such as nitrogen (N), Mg, Ca, and P. However, it is extremely relevant to monitor the soils that receive these materials to detect possible long-term accumulation of harmful elements (Cavallaro et al. 1993; López-Mosquera et al. 2000). López-Mosquera et al. (2000) showed that the application of sludge from the dairy industry to acidic soils did not accumulate potentially toxic elements (PTEs) during the experimental period of four years.

In a previous study, Ramos et al. (2019) performed a detailed granulometric, petrographic, chemical, and mineralogical characterization of the dacite rock powder and its potential use as soil remineralizer in the growth of black oat (Avena strigosa) and, sequentially, maize crops. The use of dacite rock powder and dairy sludge by-products is still an unexplored research field. The aims of this present work were to assess the inorganic by-product (dacite rock powder) and the organic by-product (dairy sludge) blended with tropical soil as fertilizer to determine the ideal proportions of these three components for the production of black oat and maize. It is possible to state that the present study stands out for its contribution to the mitigation of by-product production, since it is the first study to reuse these by-products as soil fertilizer.

MATERIALS AND METHODS

Samples of Dacite Rock Powder, Dairy Sludge, Soil, and Seeds

Fifty kilograms of dacite rock powder passing an ASTM Series #10 sieve, 2 mm fraction, was supplied by the Sindicato da Indústria de Extração de Pedreiras quarry, Nova Prata city, Rio Grande do Sul state (RS), Brazil. The dairy sludge was obtained from the dairy industry of Nova Petrópolis city, RS, Brazil. An amount of 200 l of dairy sludge was collected in 20-l-capacity plastic containers directly from maturation ponds, after having undergone maturation for 7 days. A 5-l portion of the dairy sludge sample was oven-dried at 40 °C until reaching constant weight and sent for chemical composition analysis.

The typic Hapludox soil (USDA, 1999) was collected from the region of Nova Santa Rita, RS, at depths of 0–20 cm (A-horizon), in an amount weighing 800 kg. This material was air-dried, homogenized, sieved, and quartered. For soil fertility analysis and granulometric distribution, an amount of approximately 1 kg of soil was used. Soil fertility analysis was performed according to Donagema et al. (2011), before and after plants harvesting. Table 1 shows the results of soil fertility analyses.

Black oat is a grass recommended for fall–winter green manure and successfully used in the rotation and/or succession of soybean, bean, and sunflower crops. Black oat cultivation “breaks” the cycle of pests, diseases, and nematodes and reduces weed infestation, as well as producing “mulch” for direct planting of grains and vegetables. It is also an excellent fall–winter forage and can be eaten by sheep, goat, and cattle in direct grazing, hay, and silage (Velazco, 2013). Maize, the most important commercial plant originating in the Americas, is a highly polyispecific species, with about 300 breeds and thousands of varieties. Its culture is widely spread around the world, featuring specific races and varieties adapted to different ecological conditions (Fornasieri Filho, 2007).

Analytical Procedures

A detailed procedure, including thin-section petrographic description, mineralogical characterization, and chemical analysis, in percentage weight

### Table 1. Attributes of the typic Hapludox soil collected from the top 0–20 cm layer and used in the experiment

| Attributes                              | Unit       | Soil  |
|-----------------------------------------|------------|-------|
| pH in H$_2$O                            |            | 5.2   |
| H + Al                                  | cmol dm$^{-3}$ | 3.5   |
| CEC$^*$                                 |            | 4.0   |
| Al exchangeable (extractor KCl 1 mol l$^{-1}$) |          | 0.3   |
| Ca exchangeable (extractor KCl 1 mol l$^{-1}$) |          | 2.6   |
| Mg exchangeable (extractor KCl 1 mol l$^{-1}$) |          | 0.7   |
| Saturation                              | %          |       |
| Al                                      |            | 7.8   |
| Base                                    |            | 49    |
| Clay                                    |            | 21    |
| Organic matter                          |            | 1.6   |
| P available (extractor Mehlich-1)        | mg dm$^{-3}$ | 6.2   |
| K (extractor Mehlich-1)                 |            | 62    |

$^*$Cation exchange capacity
of oxides, of the dacite rock powder, was performed by Ramos et al. (2019). X-ray diffraction (XRD), and X-ray fluorescence (XRF) techniques, were used by the authors.

A combination of HNO₃, HCl, HClO₄, and HF acids, in accordance with García-Delgado et al. (2012), was used for dairy sludge and dacite rock powder sample digestions before quantification by inductively coupled plasma–mass spectrometry (ICP–MS) of the PTEs such as arsenic (As), cadmium (Cd), chromium (Cr), mercury (Hg), lead (Pb), and selenium (Se). Calcium, K, Mg, and P were determined by using inductively coupled plasma–atomic emission spectrometry (ICP–AES).

Soil pH was measured in soil–water (1:1) suspension. Soil P and K were extracted according to the Mehlich 1 method, and exchangeable Ca and Mg were extracted with 1 mol l⁻¹ KCl and were all analyzed by ICP–AES.

Experimental Site and Preparation

In 2013, two-pot experiments were conducted in a plastic greenhouse, located at Environmental Research Center of La Salle University in Nova Santa Rita, RS. Different soil mixtures were studied in 12 dm³ pots. The treatments in Table 2 were defined according to the Brazilian Society of Soil Science (SBCS 2004).

Experimental Design

In experiment 1, black oat was cultivated on increasing doses of dacite rock powder in experimental soil and on increasing doses of the mixtures of dacite rock powder and dairy sludge in experimental soil. Five replicates of each treatment were performed, resulting in 60 pots. Nine seeds of black oat were planted in pots containing 10 dm³ of soil; these were the only three plants grown for 70 days. The black oats were harvested, and the fresh matter was dried at 40 °C until it reached a constant weight, weighed, and milled for analysis of the dry matter. Soil samples were collected of all for chemical and physical analyses in an amount of 500 cm³ from each pot at depths of 0–20 cm. The chemical analyses were performed on composite soil samples representing all replicate pots of each treatments.

In experiment 2, the remaining soil samples were homogenized, sieved in a 4-mm mesh sieve, and put in the same pots. Nine seeds of maize were planted, and only three plants were grown for 70 days. The maize was harvested on January 30, 2014, and fresh matter and soil samples were treated as a described above for black oat.

The effect on soil amelioration, growth, and dry matter production of black oat, of increasing doses of dacite rock powder blended or not with dairy sludge in soil was compared with each other and between the control treatments (Table 2). These experiments allow the comparison of the fertilization efficiency of the dacite rock powder and the dacite rock powder blended with dairy sludge and their application for the fertilization of black oat and maize. In addition, to evaluate the immediate and residual effects of the by-products, all results were evaluated statistically by using of Tukey test at a significance level of 5% (p < 0.05) using the statistical software SAS Enterprise Guide 6.1.

RESULTS AND DISCUSSION

Chemical Composition of Dacite Rock Powder and Dairy Sludge

The chemical compositions of the dacite rock powder and the dairy sludge, determined by ICP–MS and ICP–AES, as well as the limits of allowed PTEs in sewage sludge (SS), for application in agricultural soils, by legislations of Brazil (2006), European Union (EU, 1986), and USA (USEPA, 1999), are presented in Table 3.

The data in Table 3 show that Ca, K, and Mg concentrations in the dacite rock powder were higher than in the dairy sludge. The function of Ca is to control nutrient transport, and to assist various enzymatic functions of plants (White & Broadley, 2003). Potassium is an essential nutrient for plant development, which acts on activation of enzymes in the formation of organic substances, in the synthesis of protein and starch, and in regulation of respiration and photosynthesis (Rawat et al. 2016). Magnesium promotes the activation of enzymes in photosynthesis, supplies adenosine triphosphate as an energy source, and is involved in the transport of photosynthates between the plant organs (Kwano et al. 2017). In contrast, the P content in the dairy sludge was higher than in the dacite rock powder. Phosphorus is fundamental for all forms of life (Vance et al. 2003). The levels of PTEs in the dairy sludge were below the levels permitted for sewage
| Treatments                  | *DL (kg ha\(^{-1}\)) | Dacite (kg ha\(^{-1}\)) | KCl (kg ha\(^{-1}\)) | Sludge (kg ha\(^{-1}\)) | **TSP (kg ha\(^{-1}\)) | K\(_2\)O Dacite (kg ha\(^{-1}\)) | K\(_2\)O Sludge (kg ha\(^{-1}\)) | CaO Dacite (kg ha\(^{-1}\)) | CaO Sludge (kg ha\(^{-1}\)) | MgO Dacite (kg ha\(^{-1}\)) | MgO Sludge (kg ha\(^{-1}\)) | P\(_2\)O\(_5\) Dacite (kg ha\(^{-1}\)) | P\(_2\)O\(_5\) Sludge (kg ha\(^{-1}\)) |
|----------------------------|-----------------------|---------------------------|-----------------------|--------------------------|--------------------------|---------------------------------|---------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|---------------------------------|---------------------------------|
| PK-Absolute control        | 3300                  | 0                         | 0                     | 0                        | 0                        | 0                               | 0                               | 0                             | 0                             | 0                             | 0                             | 0                               | 0                               |
| P-Standard control         | 3300                  | 0                         | 0                     | 0                        | 238                      | 0                               | 0                               | 0                             | 0                             | 0                             | 0                             | 0                               | 0                               |
| K-Control                  | 3300                  | 0                         | 100                   | 0                        | 0                        | 0                               | 0                               | 0                             | 0                             | 0                             | 0                             | 0                               | 0                               |
| PK-Standard control        | 3300                  | 0                         | 100                   | 0                        | 238                      | 0                               | 0                               | 0                             | 0                             | 0                             | 0                             | 0                               | 0                               |
| R906                       | 3300                  | 906                       | 0                     | 0                        | 238                      | 30                              | 0                               | 32                            | 0                             | 21                            | 0                             | 2                               | 0                               |
| R1813                      | 3300                  | 1813                      | 0                     | 0                        | 238                      | 60                              | 0                               | 65                            | 0                             | 41                            | 0                             | 5                               | 0                               |
| R3625                      | 3300                  | 3625                      | 0                     | 0                        | 238                      | 120                             | 0                               | 129                           | 0                             | 82                            | 0                             | 9                               | 0                               |
| R7251                      | 3300                  | 7251                      | 0                     | 0                        | 238                      | 240                             | 0                               | 258                           | 0                             | 165                           | 0                             | 19                              | 0                               |
| R906 + S2574               | 3300                  | 906                       | 0                     | 2574                     | 0                        | 30                              | 1.3                             | 32                            | 15                            | 21                            | 2.5                           | 2                               | 50                              |
| R1818 + S5149              | 3300                  | 1813                      | 0                     | 5149                     | 0                        | 60                              | 2.6                             | 65                            | 30                            | 41                            | 5                             | 5                               | 100                             |
| R3625 + S10297             | 3300                  | 3625                      | 0                     | 10,297                   | 0                        | 120                             | 5.2                             | 129                           | 60                            | 82                            | 10                            | 9                               | 200                             |
| R7251 + S20594             | 3300                  | 7251                      | 0                     | 20,594                   | 0                        | 240                             | 10.4                            | 258                           | 120                           | 165                           | 020                           | 19                              | 400                             |

* Dolomitic limestone (DL) with total neutralization relative power (TNRP) of 72%; **Triple superphosphate (TSP)
sludge by all studied legislations (Table 3). The results concur with the studies of López-Mosquera et al. (2002), who reported similar concentrations of elements in dairy sludge of Spain.

In Brazil, there is a legislation with well-defined specifications for the use of rock powder in soil fertilization. These include the maximum permitted limits for PTEs, which are 15, 10, 0.1, and 200 ppm for As, Cd, Hg, and Pb, respectively (Brazil, 2016). According to Table 3, the levels of PTEs in the dacite rock powder were below the limits allowed for its application in Brazilian agricultural soil. According to Tikariha and Sahu (2014), dairy sludge, in addition to low PTE content, has high levels of easily degradable carbon, which can avoid the loss of soil nutrients and promote the increase in agricultural production. This indicates that there will be no risk of environmental contamination or to human health due to the application of both by-products to soil.

### Table 3. Chemical compositions of dacite rock powder and dairy sludge samples

| Elements | Sludge (mg kg⁻¹) | Dacite (mg kg⁻¹) | Brazil (2006) SS limit (mg kg⁻¹) | USEPA (1999) SS limit (mg kg⁻¹) | E.U. (1986) SS limit (mg kg⁻¹) |
|----------|-----------------|-----------------|---------------------------------|---------------------------------|---------------------------------|
| Ca       | 4790            | 16,919          | –                               | –                               | –                               |
| K        | 1019            | 15,713          | –                               | –                               | –                               |
| Mg       | 640             | 5210            | –                               | –                               | –                               |
| P        | 8370            | 705             | –                               | –                               | –                               |
| As       | < 0.60          | 3.0             | 41.0                            | 75.0                            | –                               |
| Cd       | < 0.10          | 0.08            | 39.0                            | 85.0                            | 40.0                            |
| Cr       | < 0.02          | 7.0             | 1000                            | 3000                            | 1000                            |
| Hg       | < 0.10          | < 0.01          | 17.0                            | 57.0                            | 25.0                            |
| Pb       | 7.78            | 18.7            | 300                             | 840                             | 1200                            |
| Se       | 0.53            | 0.08            | 100                             | 100                             | –                               |

Improvement in Soil Chemical Attributes

Figure 1 shows that after application of the treatments, soil chemical attributes such as pH and Al saturation were altered significantly by the application of R3625 + S10297 and R7251 + S20594 mixtures (p < 0.05) when analyzed at 70 days after incorporation into the soil. In control treatments, there were an increase in Al saturation and reduction in soil pH (Fig. 1) at 140 days after treatments.

Acid soils limit plant growth in many parts of the world. According to Goulding (2016), soil acidity occurs due to a set of factors, including deficit of macronutrients such as Ca, K, Mg, N, P, and of the micronutrient molybdenum (Mo) besides toxicity by hydrogen, Al, and manganese (Mn). Acidity can reduce nitrogen fixation in the soil, making it susceptible to erosion and compaction. The use of by-products with potential to soil pH increase is essential for agricultural production. This interpretation is reinforced by results presented in Figure 1, which proved that the blended by-products have potential to increase soil pH in the short term (140 days).

Considering the technique proposed in the two experiments, it can be inferred that they presented an equal or greater performance than soluble fertilization with P and K (P-Standard control, K-Control, and PK-Standard control) (Fig. 1). In soils without added dairy sludge, all chemical attributes were significantly lower than in mixtures of dairy sludge and dacite rock powder (p < 0.01). However, the dacite rock powder alone elevated all fertility parameters in the soils to levels higher than the control treatments at 140 days (Fig. 1).

Figure 1 shows that the application of the by-products, besides raising pH and reducing Al saturation, increased the levels of exchangeable Ca and Mg in the soil, especially after the maize cultivation. In treatments with mixed dacite rock powder and by-products, the concentrations of these nutrients increased linearly, whereas they decreased in all control treatments. This can be explained by the fact that the dacite rock powder has high Ca and Mg contents, which are constituent elements of the mineral augite ((Ca,Na)(Mg,Fe,Al,Ti)(Si,Al)₂O₆), and when mixed with the dairy sludge and the soil, was able to release Ca and Mg, indicating that the by-products have immediate release potential of these nutrients. After maize harvesting, the levels of
Figure 1. Soil chemical attributes after addition of different mixtures of dacite rock powder (R) and dairy sludge (S). Vertical bars (I) represent standard errors from five replications.
readily available K and P were significantly higher in soils with by-products mixtures than with the dacite rock powder alone \((p < 0.05)\), and increasing doses of dacite rock powder and dairy sludge readily provided increased K and P levels \((p < 0.01)\) (Fig. 1). According to Moura et al. (2016), the availability of K in the soil in most tropical plantation areas is very low, but it is not as low as it occurs with P. All control treatments presented lower K and P contents in the soil compared to the other treatments. This indicates that that dairy sludge contributed little to K concentrations in soils, in agreement with Hue and Ranjith (1994) and Suárez et al. (2004) that dairy sludge has low K content.

A relevant agronomic indicator of fertilizer efficiency is the solubility of K. High-solubility fertilizers are readily available to plants and can cause an increase in soil K level beyond the recommended range (Santos et al. 2016). Thus, a gradual release, such as what occurs with dacite rock powder, would be advantageous because K concentrations in the soils increased after both crops cultivation, evidencing the residual effect of dacite rock powder (Fig. 1). The gradual release may be an advantage also when used for organic agriculture (van Straaten, 2016). Solubilization of nonexchangeable K can occur by changing the pH value, but also by exudation of organic acids in the rhizosphere (Volf et al. 2018). The ability of roots to reduce the concentration of K in the soil solution accelerates the weathering of the mineral sanidine \((\text{K(AlSi}_3\text{O}_8))\) present in dacite rock powder, increasing its capacity to supply K to plants. The ability of black oat to reach maximum growth (Fig. 2) with lower K supply (Fig. 1) can be due to their less requirement for this nutrient compared to maize. Basak et al. (2020) showed that volcanic rock by-products can supply K and essential micronutrients such as Cu, Fe, Mn, and Zn when blended with organic materials. They considered volcanic rock to be a potential source of K as well as micronutrients to supply plants requirement without any contamination risk by PTEs.

Tropical soils typically have low concentrations of available P and high P-fixation potential, especially when soluble fertilizers are applied (Withers et al. 2018). This interpretation placed P, together with N, as the main limiting nutrients of Brazilian agricultural production (Fageria, 2009). Rosling et al. (2007) reported that P occurs as apatite needles in rock matrix. When apatites weather, which favors its dissolution, it releases P into the soil (Spohn et al. 2020). The soil pH is the variable that most affects the availability of P in the soil; a pH of 5.7 (Fig. 1) promoted higher availability of P in the soil solution and higher uptake by black oat and maize grown in the treatment R7251 + S20594 (Table 4). This result agrees with Fageria (2009) that most agricultural plants do best in soil with pH of around 6.0.

A synergistic effect was observed between the concentration of Mg in the soil (Fig. 1) and the absorption of P by maize leaves (Table 4), because Mg acted as a P loader. Control treatments (with P and K fertilizer) were lower than those obtained in the mixtures of dacite rock powder and by-products after the two crops (Table 4). This is because there was a reduction in P availability due to soil acidification. This result even on soils with high phosphate fixation can be attributed to the readily available P present in abundance in the dairy sludge (McLaughlin & Champion, 1987; Sommers & Sutton, 1980). Several authors (e.g., Furrer et al. 1984; Gupta & Hani, 1979; Haraldsen & Pedersen, 2003) observed that the release of P by sewage sludge is greater than or similar to that of soluble fertilizers, as was observed in this study. The gradual increases in available P content in the soils with dacite rock powder, and by-products mixtures (Fig. 1) demonstrate that such sources are adequate for succession of crops, especially in tropical soil that has potential for P to be lost by leaching.

**Effects of Treatments on Nutrients Uptake by Leaves of Black Oat and Maize**

In experiments 1 and 2, black oat and maize crops responded significantly \((p < 0.01)\) to increasing amounts of by-product mixtures compared to boosted
levels of dacite rock powder and PK fertilizer (control treatments) (Table 4). The difference in growth responses may be explained by oxidative processes (mineralization) of organic matter in the dairy sludge over dacite rock minerals (Turek et al. 2019), releasing their nutrients more rapidly into the soil.

The levels of Ca and K uptake were much higher than the sufficiency limits for leaves of both crops in all treatments with dacite rock powder and dairy sludge mixtures (Table 4). Magnesium was higher only in maize leaves in the treatments R1818 + S5149, R3625 + S10297 and R7251 + S20594. In the other treatments, the levels of this nutrient remained within the range of sufficiency.

Table 4 shows that in maize leaves, P suitability levels were achieved in all dacite rock powder doses and in all mixtures of by-products. In black oat leaves, only in R7251 + S20594 mixture did the P levels reach the appropriate range. Regarding the effect of dacite rock powder doses only on nutrient uptake by plant leaves, the results of this study are consistent with those obtained by Ramos et al. (2019). They suggested that dacite rock powder may be a source of Ca, K, Mg, and P and can replace high-solubility fertilizers.

### Table 4. Nutrient concentrations in leaves of black oats and maize, and levels of adequacy sufficiency according to Pauletti (2004)

| Treatments* | Black oats | Maize |
|-------------|------------|-------|
|             | Ca | Mg | K | P | Adequacy sufficiency (g kg⁻¹) | Ca | Mg | K | P |
| PK-Acontrol | 4.80 | 2.57 | 25.2 | 1.46 | 7.03 | 3.95 | 30.4 | 1.63 |
| P-Control | 4.98 | 2.70 | 28.4 | 1.33 | 7.94 | 4.87 | 30.4 | 1.56 |
| K-Control | 4.35 | 2.58 | 30.3 | 1.36 | 6.59 | 4.17 | 27.9 | 1.26 |
| PK-Scontrol | 4.07 | 2.48 | 32.1 | 1.43 | 7.47 | 4.84 | 33.4 | 1.63 |
| R906 | 5.66 | 2.66 | 30.8 | 1.73 | 8.66 | 4.41 | 46.6 | 2.33 |
| R1813 | 5.91 | 2.73 | 31.1 | 1.89 | 8.90 | 4.97 | 53.4 | 2.16 |
| R3625 | 5.83 | 2.59 | 28.8 | 1.79 | 9.52 | 4.84 | 56.3 | 2.73 |
| R7251 | 5.27 | 2.51 | 30.2 | 1.79 | 8.89 | 4.55 | 48.7 | 2.06 |
| R906 + S2574 | 5.93 | 2.46 | 35.5 | 1.46 | 10.7 | 4.49 | 40.5 | 2.43 |
| R1818 + S5149 | 6.30 | 2.67 | 37.3 | 1.56 | 11 | 5.65 | 45.1 | 2.13 |
| R3625 + S10297 | 6.97 | 2.67 | 38.3 | 1.73 | 12.70 | 5.89 | 44.8 | 2.09 |
| R7251 + S20594 | 6.58 | 2.51 | 39.5 | 2.46 | 13.38 | 6.87 | 46.2 | 3.73 |

*R represents dacite rock powder, and S dairy sludge

### Effects of Treatments on Growth of Black Oat and Maize

The dry matter production of black oat and maize leaves increased significantly in soils treated with dairy sludge and dacite rock powder (Fig. 2). The highest effect was observed with the highest dose of the combined by-products in relation to all treatments, including those that received soluble fertilizer, in which increases of more 100% were recorded for black oat and maize. These results agree with those obtained by Ramos et al. (2019), who concluded that the use of dacite rock powder increased the production of black oat and maize crops. The dry matter production of black oat and maize increased linearly with the addition rate of dacite rock powder and by-products mixtures (Fig. 2). Haraldsen and Pedersen (2003) also used different mixtures of soil, soluble fertilizer (NPK), sewage sludge, and crushed rock to evaluate the growth of ryegrass. They showed that the best blend for ryegrass was rock powder, soil, and sewage sludge.

According to Li et al. (2019), total yield is the most important factor to be considered when evaluating plant growth in response to applied fertilizers. Figure 3 shows the responses to treatments in nutrients accumulation by leaves of the crops. A significant linear increase ($p < 0.01$) in Ca, K, Mg, and P accumulation in black oat leaves was observed in higher doses of by-product mixtures (Fig. 3).

Table 4 shows that the maize extracted the maximum possible amount of Ca, K, Mg, and P from the soil, resulting in higher concentrations of these nutrients in all treatments with dacite rock powder and dairy sludge mixtures. As seen in Figure 3, this is evident when comparing the treatments that re-
received the by-products mixed with the control and with dacite rock powder only, demonstrating the high reactivity of the dairy sludge. This shows the importance of the organic source as a multielement nutrient supplier, and it can be stated that the release of its nutrients is as fast as for high-solubility fertilizers. This interpretation is reinforced by the work of Theodoro and Leonardos (2014) who used basalt, kamafugite, carbonate schist, and biotite gneiss, mixed or not with an organic source. They verified that P, K, Ca, and Mg availability increased in soil with rock powder treatments, as compared to control treatments, at one year after application. Increases in pH and cation exchange capacity were observed in soils treated with rock powder, mixed or not with an organic source. That study also suggested that the solubility of minerals in rock powder and the release of their nutrients increase over time, due to the interaction of minerals with organic acids produced by roots in the soil. It is evident that the solubility of minerals differs, and the addition of organic matter is advised in order to increase nutrient release by mineral breakdown (van Straaten, 2013).

There are few studies on plant cultivation in soil containing blended rock powder and dairy sludge. Haraldsen and Pedersen (2003) showed that sewage sludge addition to soil, in suitable quantity, can yield positive results on ryegrass growth. The gap in the literature about tropical soil fertilization with dairy sludge and dacite rock powder blend hindered the comparison between the results of this study with

Figure 3. Calcium, K, Mg, and P cumulative absorption in leaves of black oats and maize grown in soils after addition of different mixtures of dacite rock powder (R) and dairy sludge (S). Vertical bars (I) represent standard errors from five replications.
CONCLUSIONS

The results obtained in this study showed the potential use of the two combined by-products as a source of Ca, K, Mg, and P. The by-product mixtures contributed to the amelioration of nutrient concentrations in leaves of crops and in soil attributes. The by-product mixtures may provide an alternative to the use of soluble fertilizers at suitable dosages and times, especially for acid soils. In addition, the R7251 + S20594 treatment, which consisted of 7251 kg ha\(^{-1}\) dacite rock powder and 20,594 kg ha\(^{-1}\) dairy sludge mixtures produced with typic Hapludox soil, was responsible for the better black oat and maize development, showing that the dairy industry sludge has high reactivity and can be used to increase the solubility of rock minerals. Thus, the methodology used will be promising and feasible for application to small- and medium-sized farmers, who can benefit in terms of productivity.

The by-products of rock mining and the dairy industry can be considered for significant reduction of environmental hazards and the high costs of final disposal. This study opens perspectives for future research into the use of combined by-products in soil-building processes. Moreover, microbiological and maturity analyses applied to by-products were not performed here, but they can provide vital information for understanding how bioactivity favors the transformation of potentially polluting by-products in nutrients source for agriculture. To apply by-products to improve poor soils in nutrient, it will be important to select suitable rocks and organic matter according to climatic–edaphic conditions as well as to specific requirements of each crops. The use of different by-products in agriculture can solve a stranglehold on industrial activity, both mining and food, decreasing the risk of environmental pollution. Soil remineralization on a large scale using by-products is needed to address environmental mismanagement, which causes soil loss much faster than can be regenerated naturally. In addition, this innovative technique will contribute to increased carbon storage in soils and forests.

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