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Geological viability and nutrient availability of andesitic basalt rock powder as a soil remineralizer

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Abstract

Brazilian soils are prone to a gradual decline in fertility due to intensive agricultural activity combined with the natural process of weathering. However, the use of conventional fertilizers results in a series of negative environmental impacts and limited access for smallholder farmers, as these products are typically imported. Over the past two decades, the development and improvement of techniques aimed at meeting crop nutritional needs with lower environmental impact have intensified significantly. Soil remineralization consists of supplying macro- and micronutrients through the addition of ground rock from specific lithologies. Law No. 12,890/2013 marked a milestone in the dissemination of this technique in Brazil by including remineralizers in the category of agricultural inputs. This law was later complemented by Normative Instruction No. 5/2016 from the Ministry of Agriculture, Livestock, and Supply, which established the technical criteria required for a rock to be commercialized as a soil remineralizer. The present study aimed to assess the geological viability and efficiency of ground andesitic basalt, occurring in southern Brazil, for use as a soil remineralizer. The methodology included mineralogical and geochemical characterizations, along with a leaching test to evaluate nutrient availability. Geochemical analysis showed that the lithology contains more than 15% of total base-forming oxides (K_2O, MgO, and CaO), with K_2O exceeding 1%, and lacks significant concentrations of potentially toxic elements (As, Cd, Hg, and Pb), thus complying with current legislation. Likewise, the leaching test using a 2% citric acid solution demonstrated the release of 36.25 mg/L of Ca, 24.95 mg/L of Mg, and 12.06 mg/L of K, confirming the nutrient availability under simulated acidic soil conditions. These findings confirm the geological viability of this lithology for use as a soil remineralizer. However, further field studies are recommended, as the current results are based exclusively on laboratory-scale experiments.

Highlights

- 1. Andesitic basalt powder supplies abundant macro and micronutrientes.
- 2. Soil remineralizers align with the 2nd UN Sustainable Development Goal.

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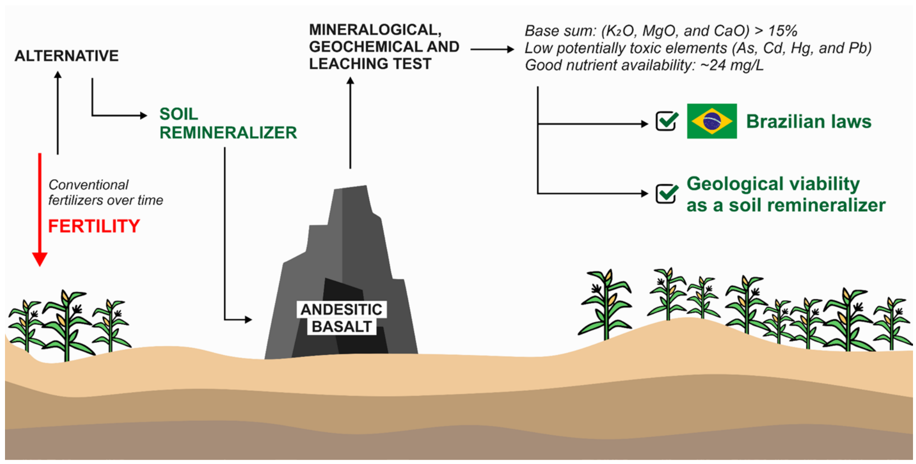
- 3. Soil remineralization has low environmental impact and reduces chemical fertilizer use.

Keywords Alternative fertilizers, Sustainable agriculture, Environmental geology, Sustainable development goal (SDG)

Graphical Abstract



1 Introduction

Over the past two decades, there has been a global surge in the consumption of inorganic fertilizers. In 2020, the use of phosphorus, nitrogen, and potassium-based fertilizers reached 201 million tons, with Brazil accounting for 8% of global consumption [1, 2]. In 2024, the import of intermediate fertilizers and NPK-based formulations reached 41.35 million tons, accounting for 90.64% of all fertilizers delivered to the Brazilian market. Between 2018 and 2024, NPK imports showed an average annual increase of 7.51% [3]. The nutrient with the highest import index is potassium, as approximately 95% of it comes from foreign sources, particularly from Russia, China, Morocco, and Belarus [2].

Conflicts in Eastern Europe, coupled with economic sanctions imposed on Belarus, the primary supplier of potassium fertilizers to Brazil, highlighted the vulnerability of the Brazilian agricultural sector. Despite being the fourth-largest grain producer globally, Brazil heavily relies on foreign raw materials [2, 4].

Brazilian soils are prone to a gradual decline in fertility, largely due to the country's development model and land-use practices. According to Nearing et al. [5] and Theodoro et al. [6, 7], the extensive expansion of agricultural and mining activities, combined with inadequate land-use planning, leads to high erosion and degradation rates. In this scenario, to maintain agricultural productivity, there is a progressive increase in the demand for fertilizers, with soybean, corn, and sugarcane crops accounting for 72% of national fertilizer consumption in 2020 [2].

Growing interest in sustainable agriculture and reduced dependency on imported fertilizers has increased attention to Soil Remineralizers (REMs), which involve the application of comminuted rocks, commonly known as stone meal [7, 8]. The effectiveness of REMs is influenced by climatic conditions, in tropical countries such as Brazil, intense weathering processes, particularly hydrolysis, enhance nutrient release from these materials [9].

On a global scale, the use of REMs emerges as a promising alternative for mitigating the effects of climate change, due to the mineral carbonation process. This process involves the absorption of atmospheric carbon dioxide (CO_2) by minerals, resulting in the formation of stable solid carbonates. Although it is a natural process, the reduction of rock particles significantly increases the surface area, intensifying this process. Campe et al. [10] estimate that this technique has the potential to remove approximately four gigatonnes of CO_2 from the atmosphere annually, equivalent to 11% of annual emissions.

Li et al. [11] found that the incorporation of rock powder into the soil over a period of two years resulted in a 120% and 187% increase in the fruit yield of an apple orchard located in Jiangsu Province, China. Similarly, the addition of basalt to a clay agricultural soil in the United Kingdom led to a 21% increase in Sorghum bicolor yield, without causing the accumulation of potentially toxic elements in the seeds. This effect was associated with a 26% increase in silicon content in the aerial parts of the plants, enhancing their resistance to both biotic and abiotic stresses [12].

Brazil is a pioneer in regulating REM use; Law No. 12.890/2013 categorizes REM as agricultural inputs [13]. These are defined as mineral materials that have undergone only mechanical reduction and size classification processes, altering soil fertility indices by making macro and micronutrients available to plants, thereby improving soil physical, physicochemical, or biological properties. In 2016, the Ministry of Agriculture, Livestock and Food Supply (MAPA) published Normative Instruction No. 5 (IN 5/2016), establishing criteria and minimum guarantees for lithologies intended for soil remineralization [14]. The main lithologies used for this purpose are volcanic rocks, as they are natural sources of phosphorus, potassium, calcium, magnesium, and micronutrients, with greater susceptibility to weathering [15].

In Brazil, the Serra Geral Group (SGG) is of particular interest due to its extensive territorial coverage, spanning an area equivalent to 917,00 km² in the southeastern region of South America [16]. The SGG is predominantly composed of volcanic rocks (97.5%) associated with plutonic rocks (2.5%), showcasing a diverse occurrence of minerals, particularly global-scale amethyst and agate geode deposits [17, 18]. The state of Rio Grande do Sul (RS) stands out as the world's largest exporter of amethysts and agates, with extraction concentrated in the mining districts of Ametista do Sul, Salto do Jacuí and Quaraí [16, 18].

Mining is a pivotal economic activity, but it comes with environmental and social issues, ranging from project implementation to the generated environmental liabilities [19]. Concerning amethyst and agate mining, the primary negative environmental impact is the substantial generation of waste constituting disposal piles. Most of these wastes are volcanic rocks occurring alongside the exploited deposit, lacking economic value. Recent research has confirmed the viability of these lithologies for soil remineralization [20–26].

Soil remineralization presents a cost-effective, high-yield, and environmentally sustainable technique in the medium to long term, enabling a reduction in Brazil's dependence on imported chemical fertilizers and a cleaner food production. This technique is aligned with the second and 13th Sustainable Development Goals proposed by the United Nations' Agenda 2030, which pertain to Zero Hunger and Sustainable Agriculture, and Climate Action, respectively [27]. This study aims to determine the viability and geologic efficiency of andesitic basalt powder extracted from the western region of

RS, considering this lithology as a potential by-product of amethyst and agate mining, with potential to reduce the consumption of soluble chemical fertilizers.

2 Materials and methods

2.1 Study area location

The study area is located in the municipality of Quaraí, in the western part of the state of RS, where samples Q1 and Q2 were collected. Geologically, this region is part of the SGG, characterized by a succession of volcanic flows. In the mining district of Quaraí, there are several volcanic flows, including Mata Olho, Muralha, Cordilheira, Catalán, and Coxilha [28]. The Muralha flow stands out from the others due to its significant occurrence of amethyst and agate geodes. The map presented in Fig. 1 was created using the open-source QGIS software version 3.20.2. Cartography work adopted the Coordinate Reference System and the Geodetic Reference System for the Americas (SIRGAS 200)

2.2 Analytical procedures

2.2.1 Characterization of the andesitic basalt samples

For the determination of the mineralogy of the andesitic basalt samples, the analysis of two thin sections was conducted. These thin sections were prepared by the Sample Preparation Laboratory at the Center for Petrology and Geochemistry Studies of the Federal University of Rio Grande do Sul. The quantification of free SiO_2 (quartz) involved counting quartz crystals incident in the rock matrix and in the form of phenocrysts in the two thin sections. For this purpose, a binocular polarized petrographic microscope with an attached chariot (model LM510-PTR) from the Petrography Laboratory of the Federal University of Pelotas was utilized.

The geochemical analysis of samples Q1 and Q2 was conducted using the technique of inductively coupled plasma optical emission spectrometry (ICP-OES) for quantification of oxides and inductively coupled plasma mass spectrometry for the determination of

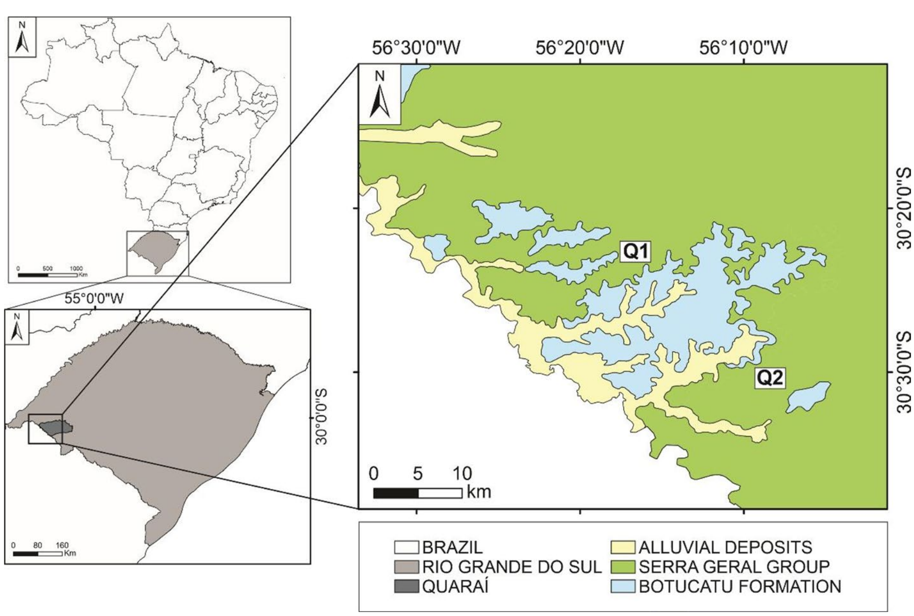


Fig. 1 Study area location on a national and state scale and local geological context. Adapted from SGB [29].

potentially toxic elements (PTE). The geochemical results obtained were compared with the data presented by De Medeiros et al. [25], Dalmora et al. [24], and Ramos [21], which are associated with lithologies applicable to remineralization.

Additionally, a comparison was made between the lithology examined in this study and the geochemical parameters established by regulation IN 5/2016. According to this regulation, for a rock to be considered for remineralization, it must contain a minimum of 1% K_2O and 9% sum of bases ($CaO + MgO + K_2O$). Concerning PTE IN 5/2016 specifies that the limit for arsenic (As) is 15 ppm, for cadmium (Cd) is 10 ppm, for mercury (Hg) is 0.1 ppm, and for lead (Pb) is 20 ppm.

To determine the geochemical mobility of the rock's constituent elements, the analysis of availability of nutrients was conducted with two dilution levels, in a neutral medium [30] and an acidic medium [31]. Two samples of volcanic rock, Q1 and Q2, outcropping in distinct locations belonging to the Muralha volcanic flow, were used for this purpose.

2.2.2 Sample preparation procedure of the andesitic basalt samples

Samples were crushed, ground, and sieved to obtain a particle size smaller than 0.075 mm. All analyses were conducted in duplicate. For the assessment of nutrient availability in a neutral medium, a 1:10 ratio was employed, where 1 g of rock powder was mixed with 10 mL of deionized water in a 250 mL Erlenmeyer flask. The solution was agitated at 30 rpm for 24 h in a temperature-controlled shaker incubator (model NL-343-01) set at 25 °C.

The nutrient extraction for the acidic medium was carried out using a 2% citric acid solution ($C_6H_8O_7$) to simulate natural soil conditions [32]. In a 250 mL Erlenmeyer flask, 1 g of rock powder was mixed with 10 mL of the 2% citric acid solution (pH 2.11, total dissolved solids: 1114 ppm, electrical conductivity: 1633 μS). The mixture was incubated at 25 °C for 30 min in a shaker incubator (model NL-343-01) operating at 30–40 rpm. The leachates from both extraction procedures were stored for 10 days to allow complete sedimentation of solid particles before filtration. Nutrient concentrations were determined using Microwave Plasma Atomic Emission Spectroscopy (MP-AES), with nitrogen plasma (Agilent 4200 MP-AES), at the Chemical Metrology Laboratory of the Federal University of Pelotas. All geochemical analyses were performed in duplicate to ensure reproducibility. Procedural blanks and calibration standards were used to verify analytical accuracy.

3 Results and discussion

3.1 Mineralogy

The andesitic basalt of the Muralha volcanic flow exhibits a hypocrystalline texture with a grain size ranging from fine to very fine. The glomeroporphyritic texture is secondary, characterized by phenocrysts of quartz, alkaline feldspar (K-feldspar), and plagioclase embedded in an aphanitic matrix. The essential minerals in this lithology include plagioclase, K-feldspar, clinopyroxene, quartz, and opaque minerals. Quartz predominantly occurs in the form of subhedral phenocrysts with dimensions around 0.3 mm (Fig. 2A and B). The quartz content in the samples ranges from 8% to 10%, in accordance with the stipulations of Brazilian normative IN 05/2016, which mandates that for a rock to be deemed suitable for soil remineralization, its quartz content must not exceed 25%.

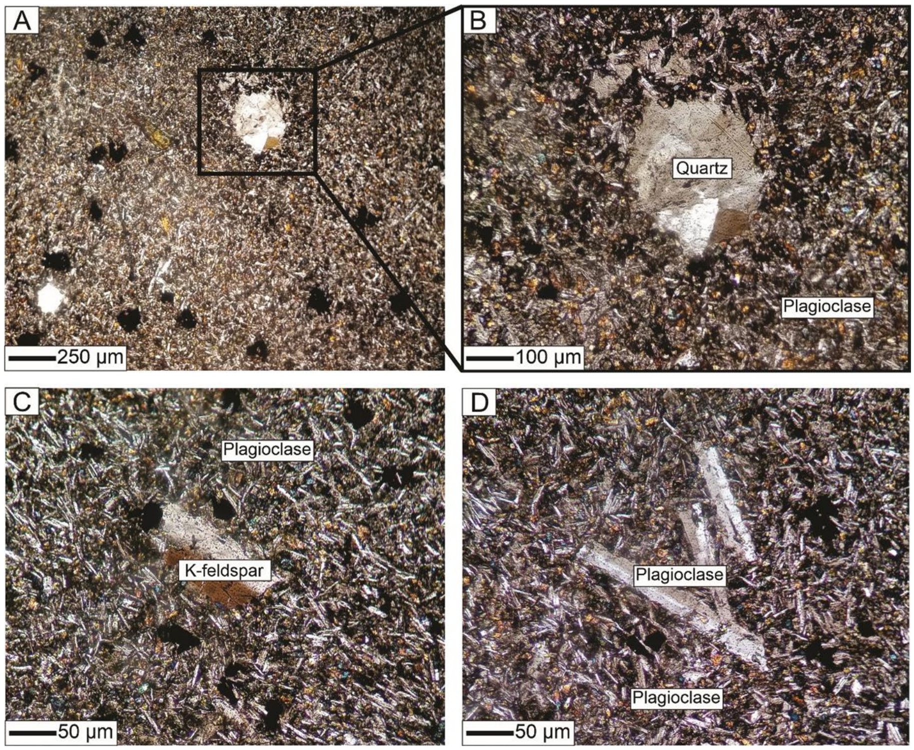


Fig. 2 Photomicrographs of volcanic rocks from the Muralha volcanic flow; **A** and **B** Quartz phenocryst embedded in an aphanitic matrix composed of plagioclase, pyroxene, K-feldspar, and opaque minerals; **C** K-feldspar phenocryst; **D** Ripiform crystals of plagioclase

The K-feldspar exhibits variable shapes ranging from subhedral to euhedral with dimensions smaller than 0.1 mm (Fig. 2C). Plagioclases are present in the form of crystals and ripiform phenocrysts. Plagioclases within the matrix display a pronounced process of clay alteration, imparting reddish hues to them (Fig. 2D). The pyroxenes occur primarily in the rock matrix. According to Gillman [33], these highly reactive silicate minerals promote nutrient availability in the soil and enhance Cation Exchange Capacity (CEC). The inequigranular opaque minerals are dispersed in the matrix with diverse shapes (prismatic, square, and anhedral) and dimensions ranging from 0.01 to 0.03 mm.

3.2 Geochemistry

The application of rock powder is founded on the principle of supplying the soil with a wide range of macro and micronutrients available to the soil, positively altering fertility indices, and providing plants with resistance to biotic and abiotic stresses [34, 35]. The primary macronutrients supplied by remineralization techniques are potassium, phosphorus, calcium, and magnesium [36]. However, the supplementation of other elements is also necessary, such as silica, which, despite not being an essential macronutrient, has beneficial effects, including increased resistance to pest and disease attacks [37]. The analysed andesitic basalt has a silica (SiO_2) content ranging from 52.14% to 57.55% in the two samples (Table 1). According to Keeping [38], Beerling et al. [39] and Dalmora et al. [24], excessive absorption of SiO_2 does not pose a potential risk to plants. Therefore, the high silica content in the samples may prove advantageous for the soil, potentially enhancing productivity.

Table 1 Chemical composition of andesitic basalt from the Muralha volcanic flow

Sample	Q1	Q2		Q1	Q2
	%				
SiO_2	52.14	54.5	CaO	9.58	9.05
Al_2O_3	14.01	13.69	Na_2O	2.09	2.31
Fe_2O_3	11.26	11.28	K_2O	0.9	1.12
MnO	0.158	0.167	TiO_2	1.093	1.085
MgO	6.17	5.55	P_2O_5	0.13	0.12
	ppm				
Sc	38	37	La	14.8	15.2
Be	1	1	Ce	30.1	30.6
V	325	317	Pr	3.62	3.78
Ba	257	261	Nd	15.4	15.4
Sr	204	188	Sm	3.7	3.7
Y	24	23	Eu	1.01	1.04
Zr	112	113	Gd	3.5	3.5
Cr	80	70	Tb	0.6	0.6
Co	41	41	Dy	3.8	3.8
Ni	60	50	Ho	0.7	0.8
Cu	160	70	Er	2.2	2.2
Zn	80	80	Tm	0.29	0.33
Ga	17	17	Yb	1.9	2
Ge	2	2	Lu	0.29	0.31
As	< 5	< 5	Hf	2.3	2.2
Rb	24	38	Ta	0.4	0.4
Nb	7	7	W	< 1	< 1
Mo	< 2	< 2	Tl	0.1	0.2
Ag	< 0.5	< 0.5	Pb	< 5	5
In	< 0.2	< 0.2	Bi	< 0.4	< 0.4
Sn	1	1	Th	3.5	3.6
Sb	< 0.5	< 0.5	U	0.7	0.9
Cs	0.7	1.1			

The high content of Al_2O_3 is common in acidic volcanic rocks due to alumino-potassic feldspars ($KAlSi_3O_8$). This element is toxic to plants and can result in nutritional deficiencies [21]. The average content of Al_2O_3 in the lithology targeted in this study is 13.53%, considered high. However, aluminium is highly stable in the crystal structure of minerals, resulting in low release in the soil [21, 24].

The suitability of a lithology for commercialization as a soil remineralizer is determined by the criteria specified in Brazilian normative IN 05/2016. Within the volcanic lithology of the Muralha volcanic flow, the average K_2O content is 1.01%, while the sum of bases content is 15.72% for sample Q2 and 16.65% for sample Q1. These values comply with the standards set forth in IN 05/2016. Furthermore, the volcanic lithology of the Muralha volcanic flow exhibits levels of potentially toxic elements (PTEs) that are below the maximum limits established by the legislation [14].

The geochemical composition of the andesitic basalt from Quaraí revealed the presence of barium (257–281 ppm), chromium (70–80 ppm), cobalt (60–70 ppm), nickel (50–60 ppm), and uranium (0.7–0.9 ppm), which suggests caution regarding the agricultural application of this lithology to soils. Although these concentrations are below the limits established by Brazilian Normative Instruction No. 5/2016 (MAPA) for fertilizers and soil amendments, the potential bioavailability and chemical speciation of these elements may negatively affect crops that are sensitive to trace metals, even at low concentrations, such as vegetables. On the other hand, crops with greater tolerance to trace metals, such as maize, eucalyptus, coffee, and pasture species, may benefit from the use of this lithology.

As demonstrated by Rodrigues et al. [40], basalt powder was effective in promoting the growth of Brachiaria (Urochloa brizantha), with higher application rates, particularly 96 Mg ha^{-1}, significantly increasing biomass production and nutrient accumulation in the aerial parts of the plant. However, this benefit depends on a combination of physiological, biochemical and molecular mechanisms, as well as pedological aspects [41, 42].

Figure 3 presents a comparison of K_2O, MgO, and CaO content in the analysed lithology with that of rocks found in the northern and northeastern regions of the state of Rio Grande do Sul, which are recognized as soil remineralizers. As shown in Fig. 3, the andesitic basalt samples exhibit higher levels of CaO and MgO compared to the lithologies from the northern region of Rio Grande do Sul, specifically from the municipalities of Nova Prata and Estância Velha.

The latter lithologies have been proven viable for soil remineralization [21, 24, 25]. The CaO content varies between 9.05% and 9.58%, while MgO ranges from 5.55% to 6.17%. The deficiency of these elements in the soil is one of the limiting factors for the performance and productivity of crops. They play crucial roles in neutralizing soil acidity and are essential for processes such as photosynthesis, respiration, organic compound synthesis reactions, ion absorption, and the root system's growth and expansion [43].

3.3 Analysis of availability of nutrients

The determination of macro- and micronutrient availability, in light of simulating the effects of chemical weathering, is crucial for evaluating the effectiveness of remineralizers. The rock constituents in the neutral medium solution (pH 7.3) demonstrated low solubility in both samples (Table 2). It can be observed that iron and manganese minerals are the least affected by the neutral solution, while magnesium and potassium are the most affected. These findings support the use of acidic conditions to enhance mineral

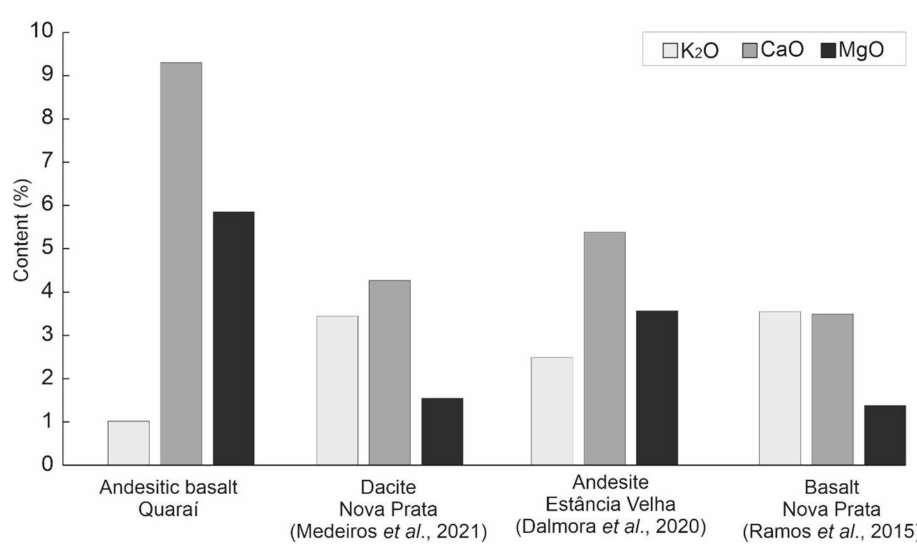


Fig. 3 Comparison of K_2O, MgO, and CaO content in the analysed lithology with the rocks outcropping in the northern and northeastern regions of the state of Rio Grande do Sul, known as soil remineralizers

Table 2 Nutrient extraction from samples Q1 and Q2 in a neutral solution

	Ca	Mg	K	Fe	Mn
Q1 (mg/L)	0.13	3.38	4.18	0	0.09
Q2 (mg/L)	2.06	3.74	4.60	0.05	0.16

Table 3 Concentration of ca, K, mg, fe, mn, na, al, Cu and Zn in the leachate

	Ca	Mg	K	Fe	Mn	Na	Al	Cu	Zn
Q1 (mg/L)	45.50	28.00	13.30	2.60	9.35	8.75	6.25	5.88	0.00
Q2 (mg/L)	27.00	21.90	10.82	12.50	15.45	4.88	7.38	3.25	0.00

dissolution and nutrient release from the rock, leading to efficient soil remineralization [26].

Table 3 presents the concentrations of calcium, magnesium, potassium, iron, manganese, sodium, aluminum, copper, and zinc in the leachate. It can be observed that, under acidic conditions, the pH of the leachate obtained from samples Q1 and Q2 was 2.29 and 2.40, respectively. This led to the extraction of several essential nutrients for the productivity of various crops, including Ca, K, Mg, Fe, Mn, Na, Al, Cu and Zn. As shown in Table 3, the average concentrations of Ca and Mg were 36.25 mg/L and 24.95 mg/L, respectively. The availability of K ranged from 10.82 mg/L to 13.30 mg/L.

The differentiation in nutrient availability between samples Q1 and Q2 is intrinsically linked to the mineralogy of the analysed lithology. The Ca content in sample Q1 and Q2 is directly related to the occurrence of minerals from the plagioclase group, especially labradorite (50 – 30% $NaAlSi_3O_8$ + 50–70% $CaAl_2Si_2O_8$). The release of potassium was similar in both samples, supporting the study presented by Dalmora et al. [24], in which the author suggests that rock powder has the potential to act as a substitute for soluble potassium fertilizers, as it presents immediate release and continuous availability of this nutrient upon acid attack. The high availability of Fe in sample Q2 is estimated to be correlated with the index of ferromagnesian minerals, especially pyroxenes, whose susceptibility to weathering contributes to a rapid release of Fe.

The dissolution of silicate minerals through the use of organic acids, such as citric acid, oxalic acid, and humic acid, initially leads to the availability of potassium, magnesium, iron, aluminium, and silicon oxide [44]. Although the nutrient content made available is relatively low compared to soluble fertilizers, rock amendment techniques have a long-term residual effect, allowing for a gradual release of nutrients [34]. This leads to an improvement in soil chemical properties and an increased supply of essential nutrients for the development of various crops [45].

3.4 Outcomes and challenges in soil remineralization

The mineralogical and geochemical characterization of andesitic basalt outcropping in the Quaraí region suggests that this lithology holds significant potential as a soil remineralizer. However, several conditions must be addressed to ensure the widespread adoption of rock amendments. A key challenge is the availability of these materials near the application area, as the high costs associated with transportation can render this technique economically unfeasible [36, 46]. Furthermore, increased attention should be devoted to the potential presence of potentially toxic elements (PTEs) within these materials. The accumulation of such elements could pose significant risks to soil health and hinder the practical application of this method in soil remineralization, limiting its practicality and sustainability in specific contexts.

According to Swoboda et al. [9], using rock amendments is a promising alternative for correcting fertility indices of soils degraded by weathering actions in tropical climate countries, providing a financially accessible source of Ca and K to small rural producers and being environmentally safe. Moreover, seven of the ten most produced crops worldwide are silicon accumulators, resulting in a deficiency of this nutrient. The use of silicate lithologies implies significant amounts of Si added to the soil [9].

Furthermore, minerals rich in calcium and magnesium that constitute silicate rock powder, when incorporated into the soil, react with CO_2 present in the atmosphere, forming stable carbonate compounds through the geological process of mineral carbonation [47–49]. Although mineral carbonation is a natural process, rock powder accelerates this reaction due to its low particle size and high surface area, optimizing CO_2 capture. Studies conducted by Taylor et al. [50] and Ramos et al. [47] demonstrate that the widespread use of rock amendments in countries such as China, India, the United States, and Brazil can capture up to 2 billion tons of CO_2 annually. This approach proves to be promising for mitigating the effects of climate change.

4 Conclusion

This study highlighted that the andesitic basalt from the Muralha flow has the potential to be used as a soil remineralizer. Mineralogically, this lithology is essentially composed of plagioclase, alkali feldspar, clinopyroxene, quartz, and opaque minerals, with a free SiO_2 content between 8% and 10%. The andesitic basalt samples have levels of K, Ca, and Mg and do not contain significant amounts of potentially toxic elements (As, Cd, Hg, and Pb), in accordance with the parameters established by IN 5/2016 for a lithology to be marketed as a remineralizer. Similarly, the leaching test using 2% citric acid showed the release of 36.25 mg/L of Ca, 24.95 mg/L of Mg, and 12.06 mg/L of K.

Although total concentrations of trace elements are below regulatory limits, further investigation on their chemical speciation and bioavailability under soil conditions is recommended to better assess potential agronomic and environmental risks. Some limitations are intrinsic to the scope of the research. The fact that a purely laboratory approach was used, with a 2% citric acid solution to simulate soil conditions, may not fully represent the effects in natural environments. In addition, the short-term laboratory analysis contrasts with the long-term effects of rock powder in the field. Finally, the economic aspects of producing the powder and applying it to surrounding areas must be considered. However, this study provides promising results that can guide future research and additional analyses.

Additionally, by promoting the use of local, sustainable resources such as basalt rock powder, this study contributes to discussions aligned with the achievement of SDG 12 (Responsible Consumption and Production) and SDG 15 (Life on Land). The use of natural fertilizers in agriculture is an important strategy to reduce land degradation and support intelligent land management, and is therefore a relevant tool in the context of current climate challenges.

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Author contributions

Emanuélle Cardozo – Conceptualization, Methodology, Validation, Data curation, Formal analysis, Visualization, Investigation, Writing – original draft, Writing – review & editing.Johny Barreto Alves – Conceptualization, Methodology, Validation, Writing – original draft.Viter Pinto – Conceptualization, Methodology, Validation.Pascal Silas Thue – Investigation, Writing – original draft, Writing – review & editing.Willian Nadaleti – Conceptualization, Methodology, Validation.Pascal Silas Thue – Investigation, Writing – original draft, Writing – review & editing.Maele Santos – Writing – review & editing.Cassiana Michelin – Methodology, Resources.Charlie Guimarães Gomes – Methodology, Resources.Anderson Schwingel Ribeiro – Methodology, Resources.Jones Machado – Writing – review & editing.Melissa Johner – Methodology, Resources.Bruno Vieira – Supervision, Project administration, Funding acquisition.

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Data availability

All data generated or analyzed during this study are included in this published article.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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