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Utilizing Marble Waste for Soil Acidity Correction in Colombian Caribbean Agriculture: A Sustainability Assessment

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Abstract: Agricultural industrial waste has demonstrated potential as a soil acidity corrector and fertilizer, in addition to reducing environmental impacts caused by inadequate waste disposal. Ornamental rock waste is a sustainable alternative as it contains essential elements for plant growth. (1) Background: this study aims to evaluate using marble waste in SENA and the Gallo Crudo Quarry in Colombia as an acidity mitigator in soils cultivated with maize (*Zea mays*) in a greenhouse. (2) Method: four treatments were applied: T0: without marble dust—MD; three doses of MD (T1: 1.1 Mg of MD ha^{-1}; T2: 2.2 Mg of MD ha^{-1}; and T3: 3.3 Mg of MD ha^{-1}). After 70 days, soil fertility analyses were carried out. (3) Results: The results show that the chemical properties of the soil improved with all treatments, mainly with T2, influencing the calcium (Ca), carbon (C), sulfur (S), and magnesium (Mg) contents. MD's pH and Al + H values were higher than conventional treatments. The T2 treatment reduced soil acidity from 0.2 cmol + kg^{-1} to 0.0 cmol + kg^{-1} and increased pH to 7.91 compared to the control (5.4). The maize plants in the T2 treatment developed better, indicating that the dose of 2.2 Mg of MD ha^{-1} can replace commercial limestone. (4) Conclusions: This agroecological technique is an innovative alternative in Colombia, replicable in areas with ornamental rock reserves, benefiting the agricultural economy and contributing to target the Sustainable Development Goals, which promote sustainability, responsible management of natural resources, and a reduction in environmental impacts.

Keywords: soil acidity correction; marble dust; maize cultivation; sustainability management; agribusiness management; sustainable development goals

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Citation: Puche, J.O.C.; Bodah, B.W.; Salas, K.E.M.; Palma, H.H.; Theodoro, S.H.; Neckel, A.; Moreno-Ríos, A.L.; Mores, G.; Silva, C.C.O.d.A.; Dal Moro, L.; et al. Utilizing Marble Waste for Soil Acidity Correction in Colombian Caribbean Agriculture: A Sustainability Assessment. *Sustainability* **2024**, *16*, 10076. https://doi.org/10.3390/su162210076

Academic Editor: Anna De Marco

Received: 18 October 2024
Revised: 14 November 2024
Accepted: 14 November 2024
Published: 19 November 2024

1. Introduction

Due to the expansion of mining activities and the resulting accumulation of waste, the depletion of mineral resources is exacerbated, making environmental concerns even more pressing globally [1,2]. Marín et al. [3] project that 19 billion tons of mining waste will amass on the Earth's surface by 2025, of which only 20% will be recyclable due to its complex composition. Estimates suggest that 7 billion additional tons of mining waste are generated annually [3].

A limited number of mining wastes have the potential to revitalize soil used for food production worldwide [4]. Growing global demand for quality food and water poses significant challenges to food security, requiring soils capable of providing high food productivity [5]. Projections indicate a 70% increase in food production globally and a 100% increase in developing countries will be required to feed growing populations by 2050 [6,7]. Food quantity and nutritional quality play a fundamental role in human health, with soil responsible for 95% of food production [4,5]. However, the need to maintain soil health to guarantee crucial ecosystem services supporting sustainable food and fiber supply stands out [8].

According to Echeverry-Vargas et al. [9], Colombia's agricultural sector contributes significantly to the consumption of natural resources; with extensive areas of land, it presents unfulfilled potential due to insufficient management of mineral waste. Consequently, large amounts of underutilized mineral waste exist due to a lack of technical knowledge, access to soil remediation markets, and innovation in generating value-added products [10]. The global priority is to enhance soil properties through alternative technologies that can effectively utilize mineralization residues [4]. In this relationship, several researchers have explored the application of residues generated when mining or shaping ornamental rocks as agricultural inputs, proposing a promising way to strengthen soil fertility to improve agricultural production [11–13].

Marble quarry waste, when transformed into a powder, can be exported to different international markets for use as a soil fertilizer or pH-mitigating soil amendment, and is suitable for use with vegetable production [14]. Colombia is a developing country for ornamental stone exploration, boasting several varieties of marble, from bright grays mined in the Magdalena River Basin to the distinctive palm-veined gray of Antioquia [14,15]. There are also destinations such as Tolima, with its gray and green marble; Santander, with black marble; San Gil, with snail patterns; Huila, with whites and pinks; the Atlantic Coast, with browns; and Villa de Leiva in Boyacá, with travertine, holding a great deal of promise around sustainability aimed at using marble waste as an agricultural soil amendment [14].

Marble is used in different sizes as an aggregate for civil construction. Following cutting and shaping, waste such as blocks, pieces, dust, and mud remains [16]. During the production phase, MD is generated as blocks are cut, shaped, and polished. This dust can then be mobilized into the environment in the form of atmospheric particulate matter and can be concentrated as suspended solids in water bodies [14,17]. In this context, residual marble is also available for stabilizing expansive soil intended for agricultural use [18]. This study is justified as manuscripts examining the use of MD as a soil amendment are largely absent from the published literature. Our results highlight the potential to use MD as a soil amendment, not only for Colombia, where marble rock is abundant, but for other countries in the world. Soil acidity has been shown to be regulated by fine marble residues in studies by Tozsin et al. [11] and Fernández-Caliani et al. [12]. Furthermore, when used as a fertilizer and mineral (quartz and plagioclase) source for agricultural soil, marble waste demonstrates environmentally friendly effectiveness, as it is rich in Ca ($CaCO_3$) and can correct soils with high acidity [19]. Consequently, marble dust can raise soil pH, accelerating plant development and creating natural carbon dioxide for fertilizers [19,20].

In far-off agricultural sites where sulfide mining residues are abundant, such as in acid mine drainage, the application of marble leftovers has been shown to lessen sulfate ions' potency, counterbalancing the acidity [21,22]. Marble dust wastes can improve soil alkalinity, reduce environmental harm, and enhance agricultural productivity, contributing to global food security [23]. This study investigates the effectiveness of using marble waste from the El Porvenir Agricultural and Biotechnology Center (SENA) and Gallo Crudo Quarry in Colombia as a soil acidity neutralizer in greenhouse-grown maize (Zea mays). This pioneering study in Colombia highlights the need for technologies capable of turning an industrial waste product, in this case mineral residues from marble, into a valuable commodity for the sustainability of the agricultural maize cultivation sector. In addition, this study contextualizes a literature review based on Scopus and Web of Science, which has not yet produced results or evidence of the use of MD in Colombia. This lack of information highlights the urgent need to establish technical guidelines promoting sustainable mineral waste management as agricultural inputs. This innovation seeks to promote the integration of new technologies for sustainable development in Colombia's mining and agricultural sectors, as well as encourage the use of MD globally.

2. Materials and Methods

2.1. Study Area

The active Gallo Crudo Quarry, operated by Granitos y Mármoles, extracts limestone and marble using traditional methods (Figure 1). In the Gallo Crudo Quarry, 900 m^3 of marble are extracted annually, processing only 720 m^3 of solid marble and generating 180 m^3 of powdered waste that remains unused and without adequate disposal. This situation highlights the ornamental stone industry's lack of sustainable waste management. The quarry uses diamond cutting wire, hammers, and hydraulic jacks to extract and cut stone blocks. Excess material is loaded with a loader into dump trucks with a 25 m^3 capacity [9,24].

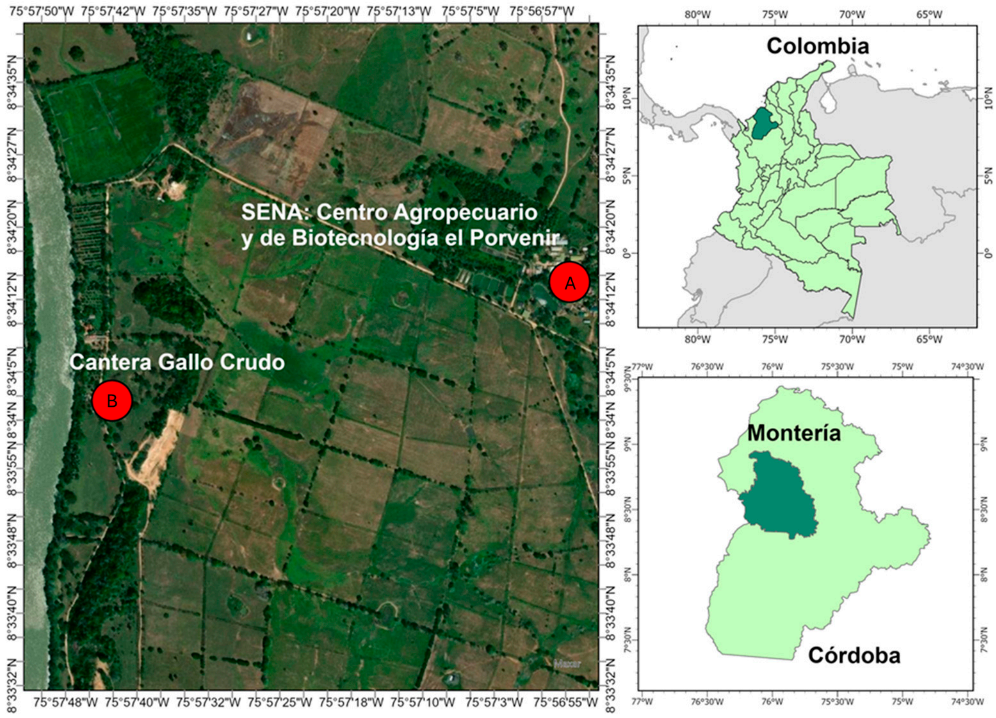

Figure 1. (**A**) El Porvenir Agricultural and Biotechnology Center—SENA; (**B**) Gallo Crudo Quarry.

The experiment was conducted at the El Porvenir Agricultural and Biotechnology Center—SENA (Figure 1, point A) and the Gallo Crudo Quarry (Figure 1, point B) between June and September 2023.

2.2. Sampling of Soil, Marble Dust, and Seeds

In June 2023, 16 soil samples were taken at the Montería, Córdoba, Colombia, experimental site (SENA) (Figure 2A,B) to assess soil fertility attributes. Following the Colombian Technical Standard—NTC 3656 guidelines [25,26], 0–20 cm samples underwent homogenization, air-drying, sieving through a 4 mm mesh, and division into quarters. Approximately 500 g of collected soil was sampled for fertility testing, and 240 kg of native soil was gathered for use in the greenhouse studies. The soil's characteristics are discussed in Section 3.3.

Figure 2. (**A**) Marble exploration front; (**B**) marble sample.

MD samples were obtained from the Gallo Crudo Quarry (Figure 2A), located 50 km away from the experimental site. MD was sampled manually and directly from the by-product piles, totaling 10 kg of sample (Figure 2B). Subsequently, the samples were homogenized, sieved through a <0.6 mm mesh, divided, and then prepared for chemical and mineralogical characterization. Maize seeds (Variety Semillas del Valle (SV) 1035–Yellow) for cultivation were purchased at a local store.

2.3. Analytical Procedures

The mineralogical composition of the MD was determined using X-ray diffraction (XRD) analysis. A Philips X-ray Diffractometer X Pert MPD (Panalytical, Almelo, Netherlands) was operated at 40 kV and 40 mA. Mineral identification was performed using Match! software, version 3.16 Build 288 Crystal Impact, Bonn, Germany. After manual grinding, the chemical analyses of the MD and soil were carried out in triplicate. X-ray fluorescence (XRF) was used with a MagiX spectrometer (Panalytical, Almelo, the Netherlands) after the MD sample was digested by total melting. The Loss-on-Ignition (LOI) analysis at 1000 °C was performed in a muffle furnace Thermolyne FB1410M (Thermo Scientific, Waltham, MA, USA) with the gravimetric technique using a Pioneer Precision Balance 0.001/0.01 g with external calibration (Ohaus, Mexico City, Mexico). These analyses were conducted at the Agronomy Laboratory at the University of Passo Fundo, Brazil. Soil fertility was determined before applying treatments and after maize harvest. The parameter of pH in soil water (1:1) was determined with a pH Meter Basic AB315 Benchtop Laboratory pH/mV Meter equipped with a pH electrode Stand (Fisherbrand™, Madrid, Spain); organic carbon (%) by the Walkey Black method for titration by NTC 5403: 2013 [27]; available sulfur (mg kg^{-1}) by extraction with monocalcium phosphate with a HI88703 table turbidity meter (Hanna Instrument, Limena, Italy); phosphorus (mg kg^{-1}) by the Bray II method with an automated spectrophotometer, model SmartChem 200 Easy Block, Smart Digestor model Block Smart (Westco Scientific Instruments, Brookfield, USA); Ca, Mg, and exchangeable acidity (cmol kg^{-1}) by the titration method with 1M potassium chloride solution; exchangeable potassium (cmol kg^{-1}) with 1M ammonium acetate solution pH 7; and texture by dispersion with sodium hexametaphosphate. The Soil Analysis Laboratory of SENA's El Porvenir Agricultural and Biotechnology Center conducted these analyses. Most tropical soils exhibit low fertility, being acidic with deficiencies in phosphorus and potassium [28]. The treatments were based on the experimental soil's pH (4.72), the MD's CaO concentration (90.27%), and regional fertilization practices [26]. Figure 3 shows the treatments applied: T0 (without MD) and three doses of MD (T1: 1.1 Mg of MD ha^{-1}; T2: 2.2 Mg of MD ha^{-1}; and T3: 3.3 Mg of MD ha^{-1}), based on the standard recommendation for maize [26]. The experiment was carried out using a randomized block design with four treatments, each replicated three times. Each experimental unit consisted of two pots.

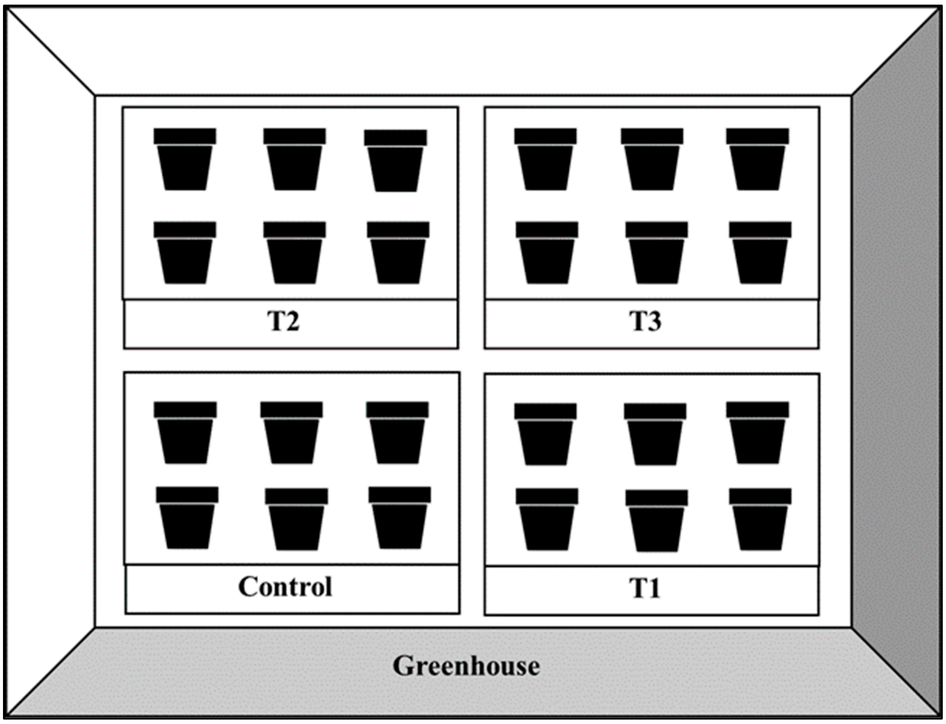

Figure 3. Greenhouse experiments.

In greenhouse experiments, pots are usually small (approximately 12 kg of soil), limiting plant development to 70 days [29,30]. In this experiment, five maize seeds were planted in each pot with 10 kg of treated soil to ensure the germination of at least three plants per pot. In the case that more than three seeds sprouted, plants were thinned and only three plants were grown, per pot, for 70 days. Each pot received 100 mL of water every two days. After 30 days, the height of the plants was measured every 8 days. At 70 days, the soils samples were collected from all treatments following the methodology of Ramos et al. [29], collecting approximately 500 g of soil from each treatment for fertility analysis.

The data were reported as the average ± standard error from the three replicates. ANOVA with Tukey's HSD post hoc test was used to examine statistically significant differences among the means of distinct treatments [8]. Significant relationships were found in all cases with a 95.0% confidence level based on p-values less than 0.05 [8,31]. GraphPad Prism version 10 software (GraphPad Software, Boston, MA, USA) was used for statistical analyses [31].

3. Results and Discussion

In tropical soils, applying lime raises soil pH to enhance fertilizer efficiency [32,33]. However, there are alternative soil amendments, such as MD, which have the potential to be used in place of lime. Developing a market for this waste material would turn it into a commodity, greatly alleviating the potential for environmental damage, as these wastes are currently simply left on site or dumped nearby [34]. According to Vargas et al. [34], these residues occupy increasingly larger mining waste dump areas, causing ecological problems. These unregulated dump sites are an increasingly challenging issue for the Department of Córdoba, and specifically for the City of Montería, located in a center for rock production and extraction.

In this context, agricultural activities present real possibilities for recycling and integrating these byproducts produced by the mining sector, as long as they have ameliorative and fertilizer characteristics for soil or water resources and are not contaminated (for example, containing heavy metals) [35,36].

3.1. Mineralogy of MD

Marble is a metamorphic rock that, in addition to its esthetic beauty, contains a chemical and mineralogical complexity that makes it valuable in various applications, from construction to sculpture and agriculture [37,38]. Commercially, marble is widely used as a covering in the interiors of large buildings, banks, palaces, offices, shopping centers, religious facilities, hotels, and luxury residences. Generally, marble, limestone, and other exotic materials are preferred for these purposes [39].

The XRD analysis (Figure 4) revealed the MD's mineral composition, highlighting a predominance of calcite ($CaCO_3$). This finding is typical of marble rock, which is formed mainly from the metamorphization of limestone [24,38].

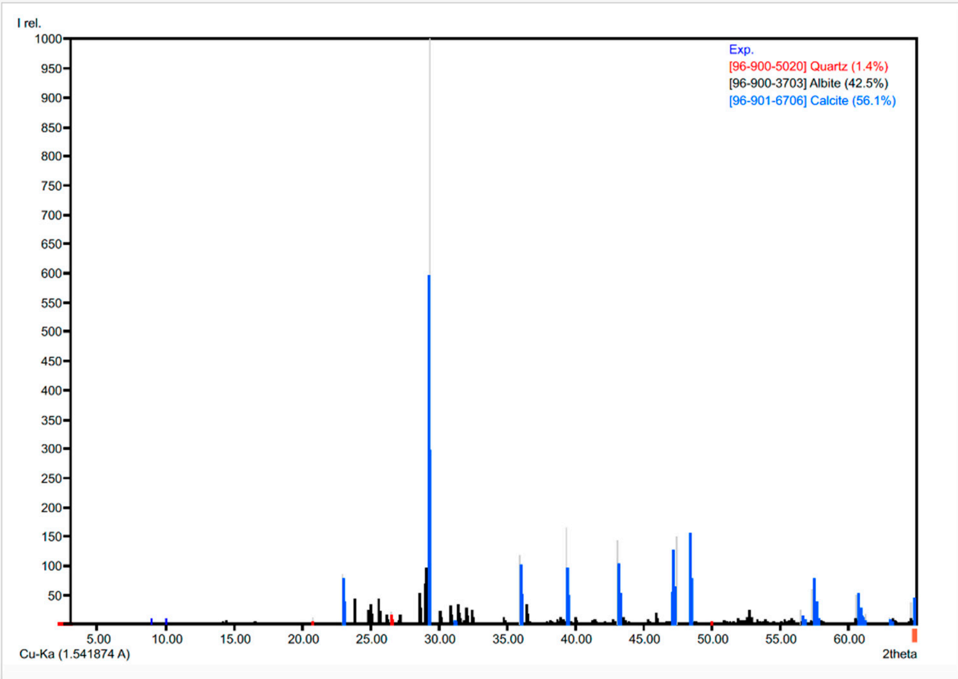

Figure 4. X-ray diffractogram of the MD used in the presented experiment.

According to Alderton [40], the secondary components of marble include chlorite, epidote, mica, garnet, limonite, pyrite, quartz, and serpentine. The predominance of calcite also suggests that MD can be an effective source of $CaCO_3$, a component relevant in agricultural practices to raise soil pH [41]. The presence of other minerals, such as quartz and plagioclase, can influence the ability of marble dust to remineralize the soil, which is a critical aspect to be considered in future research [29].

3.2. Chemical Composition of MD

The MD used in the experiment contains mainly calcium (Ca), iron (Fe), silicon (Si), and aluminum (Al), the contents of which (in oxide forms) are presented in Table 1. This result was obtained via XRD analysis (Figure 4), which shows mineral calcite ($CaCO_3$) predominance.

Calcium and Mg from MD enhanced the soil and boosted secondary macronutrient production (Table 1). Calcium plays a role in multiple plant functions, as per Gilliham et al. [42]. Magnesium is essential for chlorophyll production, photosynthesis, metabolism, respiration, and other biochemical processes [43,44]. Aluminum in marble dust poses no threat as it precipitates above a pH of 5, making it inaccessible to the soil and plants [45]. This significant discovery allows the application of by-products in sustainable agriculture without risking Al toxicity in crops [45,46]. Silicon is important in promoting crop growth and generating resistance to pests [46].

Table 1. Chemical composition by weight percentage of oxides in PM.

Oxides	(%)
CaO	54.55
Fe_2O_3	4.55
SiO_2	3.21
Al_2O_3	1.35
MgO	0.27
K_2O	0.15
LOI at 1000 °C	35.92
Total	100

Studies have shown that lime neutralizes acidity and eliminates calcium deficiency in the soil [47,48]. Therefore, mixtures containing marble and soil can release Ca and Mg into the soil while raising its pH, contributing to the development of maize and improving soil fertility attributes.

3.3. Agronomic Performance of MD

The initial soil (soil 0) was classified as sandy loam, composed of 79.37% sand, 6.14% clay, and 14.49% silt, with a pH of 4.72 and contents of C (0.34%), S (1.46 mg kg^{-1}), P (15.13 mg kg^{-1}), Ca (1.3 cmol + kg^{-1}), Mg (0.37 cmol + kg^{-1}), K (0.18 cmol + kg^{-1}), Al + H (0.2 cmol + kg^{-1}), and CEC (2.75 cmol + kg^{-1}). Figure 5 shows that soil fertility attributes such as pH and the concentration of potential acidity (Al + H), S, P, C, Mg, and CEC varied significantly ($p < 0.05$) following the 70-day maize growth period compared to the control treatment.

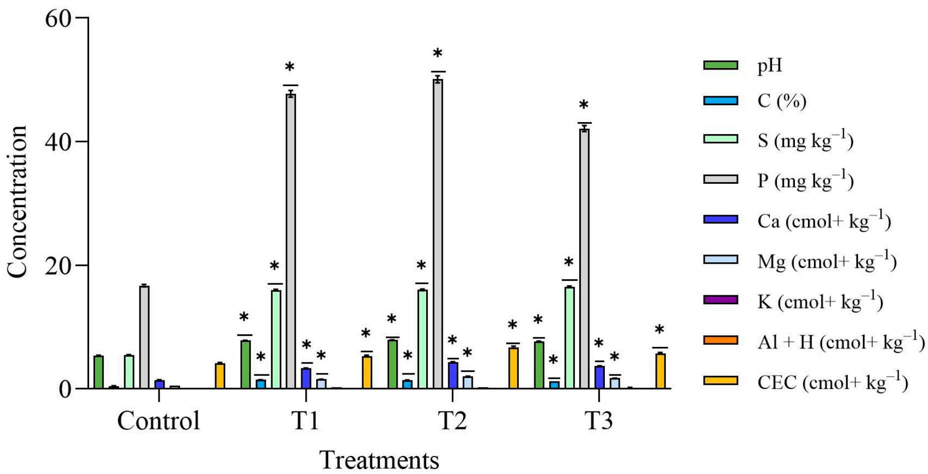

Figure 5. Nutrients are available in soils with different marble dust treatments. Notes: C: percentages (%), S and P concentrations measured in mg kg^{-1}, and Ca, Mg, K, Al + H, and cation exchange capacity in cmol + kg^{-1}, (* $p < 0.05$). Standard errors of three replications are represented by vertical bars (I).

Liming consists of applying and incorporating limestone into the cultivable layer of the soil, which is the area with the highest concentration of roots, to raise soil pH, neutralize Al (which is toxic to plants), and increase levels of Ca and Mg. This stimulates microbial activity, improves symbiotic nitrogen fixation by legumes, and increases the availability of most plant nutrients [47,48].

In soils from tropical regions, Al activity is high, and its solubility decreases with increasing soil pH, minimizing activity at pH values close to the range of 5.5–6.0. At pH values greater than 8.0, Al returns to a soluble state. As a result, liming, in addition to raising soil levels of Ca and Mg, aims to raise soil pH, reduce Al solubility, and reduce the risk of toxicity to plants [29].

The results obtained from this study are corroborated by those obtained by Raymundo et al. [49] when they compared the capacity to neutralize soil acidity between marble and limestone residues for maize cultivation in greenhouses. This study demonstrates MD's effectiveness in increasing Ca and Mg concentrations and eliminating Al toxicity, even at doses both lower and higher than those recommended for limestone (2.2 Mg of MD ha^{-1}).

The minimal environmental toxicity of MD's dissolution (1.35% Al_2O_3) is evident from Table 1. In alkaline soils, aluminum often precipitates as secondary aluminosilicates or oxides/hydroxides [29]. Figure 5 shows a statistically significant rise in soil pH ($p < 0.05$). Among the treatments, T2 exhibited the greatest pH increase from the initial 4.72, receiving 2.2 Mg ha^{-1} of MD, while the control had no MD addition. According to Osorio [26], after using MD, the pH levels in treatments T1, T2, and T3 reached 7.81, 7.91, and 7.67, respectively, classifying them as high. Prado et al. [50] observed similar pH fluctuations. According to Ghimire et al. [51], 12 Mg of limestone ha^{-1} is needed to increase soil pH to 6.0. This suggests that MD is an effective alternative for soil acidity correction.

Luchese et al. [52] reported that rock dust raises soil pH. Soil acidity hinders crop productivity in Colombia and globally. To cultivate these soils, the addition of pH-enhancing materials is essential [51]. Due to its dynamic nature, determining the ideal pH for various annual crops within the soil–plant system is complex. According to Ghimire et al. [51] and Dalmora et al. [53], most crops thrive in soils with a pH of approximately 6.0.

The application of MD reduced the Al + H content from a deficient level of <0.2 cmol + kg^{-1} to 0.0 cmol + kg^{-1} at all doses (Figure 5). Therefore, this behavior can be attributed to the application of the MD. The high acidity of most tropical soils, due to high weathering, leads to a high Al activity in the soil solution and a deficiency of Ca, Mg, and phosphorus [51,53].

The data in Figure 5 show that all MD doses tested increased the Mg concentration from the deficient level in the experimental soil (0.37 cmol + kg^{-1}) and low level in the control (0.57 cmol + kg^{-1}) to a sufficient level (1.56, 2.04, and 1.72 cmol + kg^{-1}) in treatments T1, T2 and T3, respectively, according to Osorio [26], who considers that soils with Mg contents between 1.5 and 2, 5 cmol + kg^{-1} are satisfactory.

The presence of albite minerals in MD is the primary reason for the nutrient release, yet the Ca and Mg amounts in the soil remained lower than those introduced. This finding aligns with the study by Raymundo et al. [49], which investigated the use of MD residues as a soil acidity corrector in Brazil, demonstrating its effectiveness in increasing Ca and Mg concentrations and soil pH. Similarly, Tozsin et al. [54] evaluated marble waste in Turkey, highlighting its significant impact on soil neutralization and hazelnut yield.

In this study, the experimental soil (0.18 cmol + kg^{-1}) and control treatments (0.18 cmol + kg^{-1}), as well as T2 (0.24 cmol + kg^{-1}) and T3 (0.22 cmol + kg^{-1}), had sufficient available K concentrations (0.15–0.30 cmol + kg^{-1}). However, T1 (0.3 cmol + kg^{-1}) had a higher available K concentration than that reported by Ramos et al. [55], who obtained a maximum value of 0.25 cmol + kg^{-1}. Potassium, following phosphorus, is the most consumed nutrient of crops, as Nowaki et al. reported [56]. The K concentrations in the experimental soil (0.18 cmol + kg^{-1}) and control treatments (0.18 cmol + kg^{-1}) were sufficient (0.15–0.30 cmol + kg^{-1}), while T2 (0.24 cmol + kg^{-1}) and T3 (0.22 cmol + kg^{-1}) had slightly higher concentrations. T1 (0.3 cmol + kg^{-1}) exhibited a high available K concentration, a significant and uncommon result in the existing literature. In a six-month cultivation study, Bakken et al. [57] showed that K availability to ryegrass was insignificant, regardless of the applied dose of crushed rock. Santos et al. [58] found that green rock-derived soils with a K content of 77 g kg^{-1} released less K than soils treated with up to 50 Mg of ground basalt ha^{-1}, as reported by Rodrigues et al. [59]. In this study, the addition of MD promoted increased soil K availability (T1–T3).

In São Luís do Maranhão, Brazil, Santos [60] found AG 1051 hybrid maize to perform comparably with potassium sulfate, wood ash, and MD as an organic farming system's alternative potassium source. Santos [60] found that wood ash and MD could substitute potassium. As per Santos [60], MD increases plant availability of K and offers a cost-effective and sustainable farming solution for farmers.

The potential for fixing applied phosphorus from fertilizers is high in tropical soils, while the available phosphorus levels are low. Phosphorus and nitrogen are the most limiting nutrients for crop production, according to Ghimire et al. [51] and Dalmora et al. [53]. In T2, the soil solution had the highest phosphorus availability (50.09 mg kg^{-1}), achieved at a pH of 7.91 (Figure 5). According to Theodoro et al. [61], rocks supply vital nutrients to crops. In this study's 70-day maize cultivation experiment, the MD from treatments T1–T3 showed significant reactivity in the soil.

On the other hand, carbon's role in plant growth is related to photosynthesis, water supply, and the constituents of most nutritional compounds [62]. Figure 5 shows that the C levels in the experimental (0.34%) and control (0.48%) soils increased after the treatments, reaching up to 1.46%, 1.4%, and 1.26% with doses corresponding to T1, T2, and T3, respectively. It was observed that sulfur showed the same behavior as carbon. Sulfur is an essential component of plant proteins [62]. These findings are relevant to agriculture, as the literature presents limited results regarding soil pH and acidity improvements. This research opens the door to using MD beyond correcting soil acidity, showing that this material can meet the needs of plants by making the macronutrients K and P available to plants. This statement aligns with Cardozo et al. [63], who demonstrated that MD contains essential constituents, efficiently making potassium available to plants. Furthermore, Sublett et al. [64] confirm that MD increases the nutrients in lettuce plants, highlighting its environmental sustainability.

Application of MD increased CEC from very low to low levels across all three treatments (Figure 5). However, the CEC increases obtained in the soils did not reach the range of 10–20 cmol + kg^{-1}, which is the minimum considered sufficient by Osorio [26]. The doses tested provided a linear increase in CEC. This increase in CEC was observed due to the non-exchangeable acidity correction corresponding to T1: 41%, T2: 53%, and T3: 45%. This can be attributed to the possible clayey components of the soil, which are of low activity (possibly kaolinite and Fe and Al sesquioxides), low organic carbon content (Figure 5), and high sand content.

Figure 5 shows that the experimental soil was poor in nutrients, presenting very low CEC and deficiencies in K, Ca, and Mg, possibly due to the high degree of weathering [65]. Heavy rains, winds, and soil compaction significantly accelerate the loss of nutrients, resulting in soil impoverishment [66]. This leads to a decrease in the levels of essential nutrients, such as Ca, Mg, and K. The previous results confirm the positive effect that the application of MD generates in tropical soils.

3.4. Maize Growth

In this experiment, all three maize plants grown in each pot survived for the duration of the study. Figure 6 shows size responses regarding height (H) at 38, 45, 53, 60, 68, and 76 days after planting. During all evaluations, the highest heights were observed in treatment T2. Maize plants from all treatments that received doses of MD were significantly (p < 0.05) more prominent than those from the control treatment that did not receive fertilization. The height growth of plants was linearly related to age across all treatments (Figures 6 and 7).

Treatments T2 and T3, located in the back of Figure 7, showed the development of ears in the corn plants, as seen in the zoom-in the upper left and right boxes, respectively. Tozsin et al. [54] obtained a similar result, stating that increases in hazelnut yield and efficiency due to pH neutralization due to MD applications were significant. These results demonstrated that the yield of hazelnut trees in untreated soil was 1120.3 kg ha^{-1} and gradually increased to 1605.5 kg ha^{-1} in soil treated with MD at a dose of twice the amount of lime required for agricultural application. Still, there were no significant differences between application rates. This indicates that applying MD in proportions equal to agricultural lime requirements could be sufficient for optimal performance.

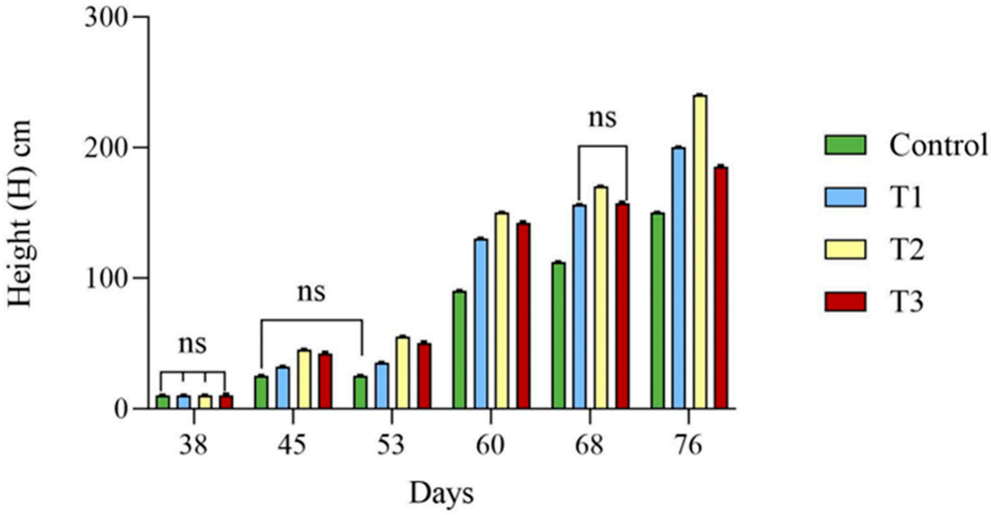

Figure 6. Effects of treatments on the height of maize plants. Note: vertical bars (I) represent the standard error of three replications.

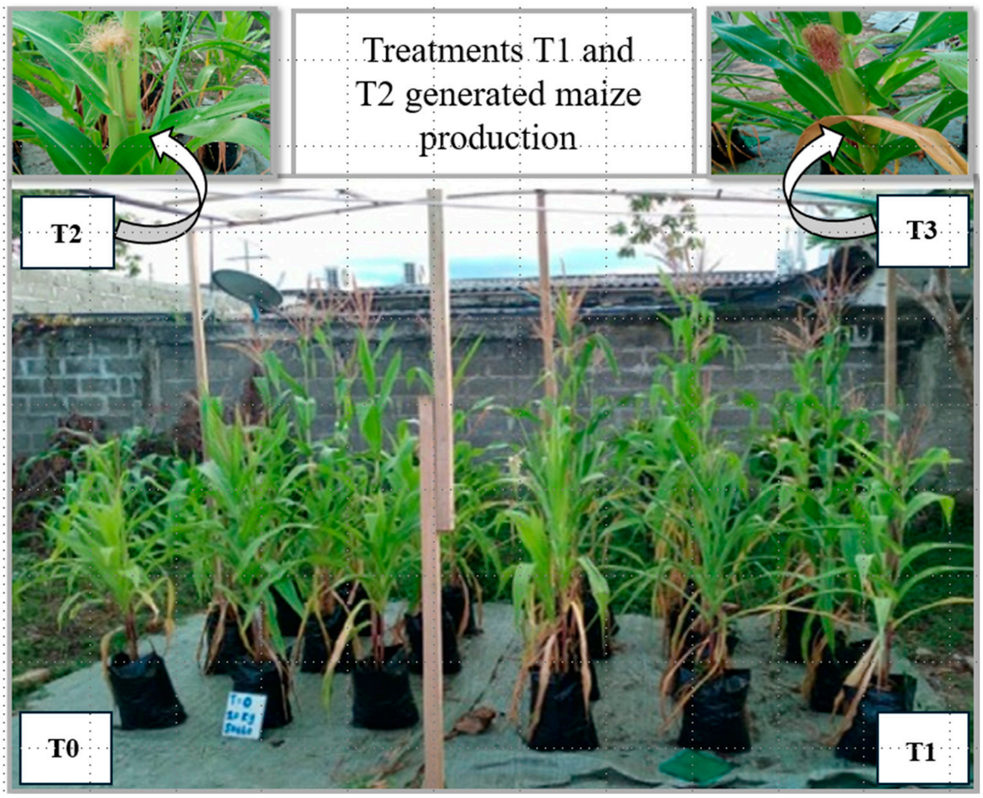

Figure 7. Comparison of the size of maize plants in different treatments.

According to the results obtained, the proposed technology presents technical feasibility as it presents improvements in the yields of the evaluated crop, mainly in the T2 treatment (2.2 Mg of MD ha^{-1}). It can also be economically viable, as it generates savings for maize producers by reducing conventional liming materials. Among them is limestone, which costs $USD 992 per Mg. As MD is currently a waste product with no value, the only cost currently associated with it is in transport. Once MD is recognized as a commodity with value, a market will arise to dictate its cost. The theoretical dose recommended for application from this study corresponds to 2.2 Mg of MD ha^{-1}. This represents current savings of $USD 992 per hectare, when MD is substituted for limestone. Consider that in Colombia, there is a total of 18,226,629 ha (16% of the country's area) suitable for commercial cultivation of hot-climate maize, and approximately 400,000 ha are currently planted, corresponding to 1% of the potential area [53]. The potential domestic market is evident.

This research contributes to sustainability in the agricultural and mining sector and examines a soil amendment which holds the potential to reduce Colombia's external dependence on agricultural production factors. This technology can effectively replace several chemical inputs, reducing soil and water pollution. Furthermore, by avoiding the intensive use of pesticides, damage to soil microfauna, and the loss of organic carbon are also minimized, positively impacting the atmosphere [53].

The technology suggested in this research matches agroecology's ecological and social principles to create sustainable agricultural and food systems. The text aims to foster interactions between plants, animals, humans, and the environment for socially equitable and sustainable food systems. According to Moro et al. [8], agroecology sets the global standard for sustainable agriculture and food systems policy. Agroecological transitions enable the achievement of various sustainability goals concurrently across various levels and contexts.

4. Conclusions

This study assessed the soil-enhancing and maize growth-promoting effects of MD. The mineralogical and chemical composition of the MD was determined using XRD and XRF. The MD analyzed for this study contained calcite, quartz, plagioclase, albite, and anorthite minerals. This study demonstrated that MD positively influenced the development of maize grown in treatments T1–T3 with doses of 1.1, 2.2, and 3.3 Mg of MD ha^{-1}.

After treatments with MD from T1 to T3, plant growth improved: there was a decrease in the Al + 3 content and a higher content of C, S, P, Ca, Mg, and increased CEC in the soil. In treatments T1–T3, the reduction in Al + H led to the release of Ca and Mg from the MD. MD doses applied to treatments T1–T3 improved plant growth, mitigated Al toxicity, increased the soil's CEC, and enriched the soil with C, S, P, Ca, and Mg.

This study indicates that MD can partly substitute for soluble fertilizers and entirely replace limestone materials, leading to cost savings for rural farmers. It is free from chemical processing. By implementing the studied MD technology, sustainable correction of soil acidity and remineralization is achieved, minimizing the need for soluble fertilizers, thereby contributing to goal no. 12 of the Sustainable Development Goals (SDGs) of the UN Environmental Programme. This work is a definitive resource on the topic and applies to local, national, and global replication.

It is advisable to perform field experiments to verify the applicability of MD in agriculture on a larger scale. This method establishes the necessary leaf and grain area for nutritional assessments based on generating enough grains or phytomass. Soil, leaf tissue, dry foliage mass, and productivity should be measured for evaluation.

Author Contributions: Conceptualization, J.O.C.P. and K.E.M.S.; methodology, C.G.R.; software, A.N.; validation, C.C.O.d.A.S., J.O.C.P. and C.G.R.; formal analysis, B.W.B.; investigation, A.N.; resources, A.N.; data curation, G.T.C.; writing—original draft preparation, H.H.P.; writing—review and editing, S.H.T. and G.M.; visualization, L.D.M. and G.M.; supervision, C.G.R. and A.N.; project administration, C.G.R. and G.M.; funding acquisition, A.L.M.-R., G.M. and L.D.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data contained within the article are presented as variable values and graphical representations.

Acknowledgments: The authors acknowledge to the University of Passo Fundo, Brazil, for performing the mineralogical and chemical analyses of the marble dust. Thanks to the Gallo Crudo Quarry for the supply of marble dust. We also thank the Center for Studies and Research on Urban

Mobility (NEPMOUR+S/ATITUS), Fundação Meridional, and the National Council for Scientific and Technological Development (CNPq), Brazil.

Conflicts of Interest: The authors declare no conflicts of interest.

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