Journal of Agriculture and Food Research 10 (2022) 100443

Contents lists available at ScienceDirect

Journal of Agriculture and Food Research

journal homepage: www.sciencedirect.com/journal/journal-of-agriculture-and-food-research

Potential of basalt dust to improve soil fertility and crop nutrition

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ARTICLE INFO

Keywords:
Remineralizer
Rock dust
Rock
Igneous rock
Agriculture

ABSTRACT

The search for higher yields, lower production costs, and increased sustainability in agriculture implies optimizing crop nutritional management. In this sense, basalt dust has shown potential to improve soil fertility and crop nutrition. Thus, the goal was to evaluate the potential use of basalt dust in a controlled environment. First, an experiment was carried out on soils with contrasting textures (sandy and medium) under a random design, with four replications. These soils were incubated with basalt dust doses for 90 days, and later analyzed for chemical properties. Then, after soil incubation, four experiments were carried out in a pot system, where maize and bean plants were grown, with four replications. Plant shoots were evaluated for dry weight and macro- and micronutrient accumulations. The results of the incubation test showed that basalt dust increased available phosphorus, potassium, calcium, and magnesium levels in the soil about twenty, ten, fifteen, and thirteen times higher than those without the basalt dust, respectively. Maize and bean plants grown in soils enriched with basalt dust showed macro and micronutrient accumulations, up to five times higher than plants without the use of basalt dust. These results showed the usefulness of basalt dust in aiding nutritional management in agriculture.

1. Introduction

Brazil has occupied a prominent position in the global mining scenario both in terms of production and reserves. This role is related to its great geological potential and diversity and to significant and continued investments in infrastructure and technology [1]. However, mineral fertilizers used in Brazilian agriculture are mostly imported, leaving the country as one of the largest consumers of fertilizers in the world [2]. In 2020, around 36.2 million tons of fertilizers were consumed in Brazil, with about 80% imported [3]. These heavy imports are explained by low natural fertility of Brazilian soils; therefore, for high yields to be achieved, large amounts of fertilizers are required. Agricultural fertilizers make up around 40% of the production costs, in addition to high values for their transport [4–6].

The silica rock dust application has been used in farms as an alternative to traditional fertilizers [1,2]. The use of silica rock dust improves soil fertility and can increase crop productivity [7]. Silica rock dust is, in most cases, waste from rock mining, which is commonly discarded. The residue may have several minerals that, when properly applied, can improve soil fertility and plant growth. Accordingly, such byproduct has been strategic for Brazil, as an important source for cost reduction in agricultural production, especially for reuse of basalt dust [1].

Basalt dust stands out among several silicate rock powders. Basalts are igneous rocks of mafic composition, hence rich in magnesium (Mg) and iron (Fe) silicates of basic pH. These rocks are also sources of phosphorus (P), potassium (K), calcium (Ca), and several micronutrients essential for plant nutrition [2]. Therefore, the use of basaltic rock dust in agriculture allows for soil fertility improvement, releasing nutrients and inducing soil pH correction as well. The nutrients are released slowly and continuously, providing satisfactory results for up to five years, without application at each planting [6,7]. Furthermore, the excess of this residue does not offer a risk of contamination to soils as it only provides the nutrients required by plants [1].

One of the main reasons to use basaltic rock dust in agriculture is due to its potential reducing chemical fertilizers. Studies have reported production cost savings of up to 50% by the use basaltic dust [8]. Most Brazilian regions have basaltic rock reserves rich in P, Ca, and Mg [7]. Furthermore, recent studies have evaluated the application of basalt

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https://doi.org/10.1016/j.jafr.2022.100443
Received 4 September 2022; Received in revised form 21 October 2022; Accepted 4 November 2022
Available online 5 November 2022

dust in agriculture and demonstrated a series of effects, such as cost reduction and potential use of residues in agriculture [2,8,9].

Brazilian farming plays a key role in global food security. However, it is highly dependent on imported soluble fertilizers, which are scarce resources with volatile prices, hindering sustainability. The work presents as a hypothesis basalt dust is an alternative to improving soil fertility and providing an increase in crop nutrition. In view of the above, this study aimed to evaluate the chemical properties of soils incubated with basaltic rock dust, and to list the effects on maize and beans cultivations.

2. Material and methods

2.1. Soil sampling and analysis

The experiment was carried out in a greenhouse at the Instituto Federal de Mato Grosso do Sul (IFMS). Pots with 5 L soil capacity were used and filled with a Typic Quartzipsamment (TQ) and Oxisol (OX) collected in the 0 to 20 cm deep layer in the municipality of Nova Andradina, State of Mato Grosso do Sul, Brazil (Table S1). Before installation, the soil samples were air-dried and passed through a 4-mm-mesh sieve.

2.2. Basalt dust analysis

Basalt dust samples were collected from a mine near the city of Itaporã, Mato Grosso do Sul State, Brazil from Pedreira Esteio Mineração Tozzi Junqueira (Fig. S1). The residue belongs to the Paraná Vulcan-sedimentary and Bauru sedimentary basins, with an age between 122 and 128 million years. Basalt dust subsamples (500 g) were used to determine the total chemical composition of major elements in the form of oxides, called quantitative geochemical and mineralogical characterization (Table S2). Potentially toxic elements of the basalt dust used were at low concentrations (arsenic - As, <15 mg kg^{-1}; cadmium - Cd, <10 mg kg^{-1}; lead - Pb, <200 mg kg^{-1}; mercury - Hg, <0.1 mg kg^{-1}), according to Brazilian legislation [10]. The residue has an abrasion pH of 8.90 and mineralogy with typical basalt composition, with the most reactive minerals being plagioclase labradorite (50.9%), pyroxene augite (25.2%), and apatite (1.6%). making a total of 77.7% of its total mass (Table S3). Grain-size analysis showed that 100.00% (±0.1) by mass of the sample passes through a 2.00-mm-mesh sieve and 82.80% (±0.9) by mass of the sample passes through a 0.840-mm-mesh sieve and 59.3% (±0.7) passing through a 0.300-mm-mesh sieve.

2.3. Incubation (Assembly, finishing, and analysis)

For incubation test, experimental unit consisted of a 5.5-kg polyethylene pot, filled with 5 kg ADFS and basalt dust doses. A completely randomized design was adopted, with five treatments (basalt dust doses) and eight replications, totaling 40 experimental units for each soil. The experiment was arranged in a factorial scheme (5x2). Both soils received the following basalt dust rates: 0, 2, 4, 6, and 8 t ha^{-1}. Samples were incubated for 90 days, correcting weight by adding deionized water weekly, always aiming to maintain humidity at about 70% of field capacity. After incubation, soil samples (200 g) were collected from each pot, being dried and passed through a 2-mm-mesh sieve, identified and stored for further chemical analysis.

2.4. Growth analysis of maize and common bean

After the incubation test, maize (*Zea mays* - Feroz VIP hybrid) and common bean (*Phaseolus vulgares* - cv Perola) plants were grown in the same experimental units. The genotypes used are adapted to the region and indicated for high-technology crops, both for summer and off-season seasons. The growth analysis was carried out in a randomized block design, with five treatments (basalt dust rates) and four replications, totaling 20 experimental units for each crop and soil.

To each pot were added 125.0 mg dm^{-3} nitrogen (N), 25.0 mg dm^{-3} phosphorus (P), and 75.0 mg dm^{-3} potassium (K), besides the basalt dust rates already mixed with the soil for the incubation test. A solution containing the following micronutrients: 0.5 mg dm^{-3} boron (B), 2.0 mg kg^{-1} copper (Cu), 3.0 mg kg^{-1} manganese (Mn), and 4.0 mg kg^{-1} zinc (Zn), as recommended by Sousa and Lobato [11]. This recommendation considers the expected productivity in Cerrado soils (used in the experiment). No conditioner or soil acidity corrective material was applied.

Plants were monitored and irrigated daily with deionized water throughout the experiment to maintain soil moisture at about 70% of water holding capacity. After plant cultivation, soil samples (200 g) were collected from each pot, dried and passed through a 2-mm-mesh sieve, identified and stored for chemical analysis.

The experiment was concluded at 55 days after emergence. Then, plant height (cm) was measured by a measuring tape, and stem diameter (mm) at 10 cm from the soil surface with pachymeter. After measuring height and diameter, plant shoot was cut at soil level, removed, washed under tap water, placed in paper bags, and then in a forced-air circulation oven, where remained at 60°C for 72 h. After drying, all plant material was weighed for dry matter mass determination, ground in a Willey-type mill, equipped with a 40-mesh sieve, homogenized and, later, packed in polyethylene bags, properly identified and stored for further chemical analysis.

Plant shoot samples of maize and beans (0.5 g dry weight) were subjected to wet digestion with nitric acid (HNO_3) and perchloric acid ($HClO_4$). Nitrogen concentration was determined by steam distillation in the sulfuric digestion extract. All analyzes were performed in triplicate. Shoot concentration of K, Ca, Mg, Cu, Fe, Mn, and Zn were determined by atomic absorption spectrophotometry, P by colorimetry, and S by turbidimetry [12].

2.5. Soil chemical analysis after plant cultivation

Soil samples collected after the incubation and plant cultivation were subjected to chemical analysis, following the protocols of Raij [13]. The pH was potentiometrically determined in ADFS suspensions with 0.01 mol L^{-1} $CaCl_2$ solution at a 1: 2.5 ratio. Organic matter determined after oxidation with $K_2Cr_2O_7$ in the presence of H_2SO_4 and titration of excess dichromate with Fe $(NH_4)_2(SO_4)2.6H_2O$ 0.4 mol L^{-1} solution. Exchangeable aluminum (Al^{+3}), exchangeable calcium (Ca^{+2}), and exchangeable magnesium (Mg^{+2}) were extracted by KCl solution (1.0 M) and quantified by AAS. Exchangeable potassium (K^+) and P were extracted by Mehlich-1, with K^+ determined by flame photometry and P by colorimetry. Potential acidity (H + Al) was estimated by the pH SMP method. After obtaining the results, sum of bases (SB), cation exchange capacity (CEC) at pH 7.0, and base saturation (V%) were calculated.

2.6. Statistical analysis

Data were subjected to ANOVA and then analyzed statistically significant at 5% level of probability of error. The assumptions of the model were evaluated by the Shapiro-Wilk test and homoscedasticity of variance by Hartley test. The interactions between the formulations and rates of basalt dust, when significant were analyzed by regression test at 5% significance. Models were chosen based on regression coefficient significance, using *t*-test for coefficient of determination (R^2).

3. Results

3.1. Soil chemical analysis after incubation

After soil incubation with basalt dust, TQ and OX showed significant changes in their chemical attributes. Both soils showed linear increases in P, K, Ca, Mg, SB, and V% (Fig. 1). After incubated with the highest

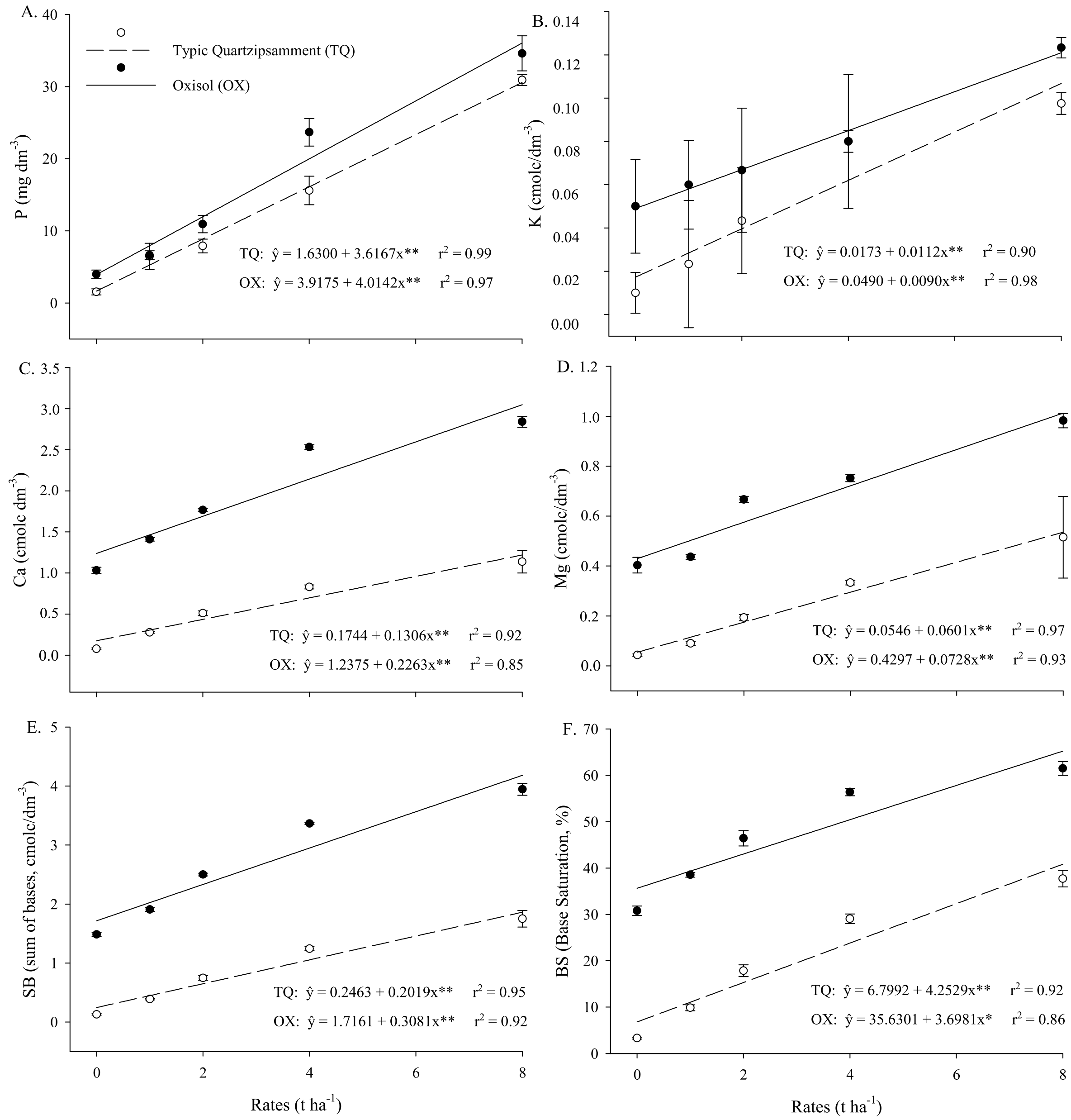

Fig. 1. Chemical attributes obtained in Typic Quartzipsamment (TQ ○) and Oxisol (OX ●) after 90 days of incubation with basalt powder.

basalt dust rate, TQ showed levels of P, K, Ca, and Mg about twenty, ten, fifteen, and thirteen times higher than those without the basalt dust, respectively. In the same way, OX samples incubated with the highest rate showed a P level in soil about ten times higher than control samples; and K, Ca, and Mg levels in soil about three times higher. In both soils, the use of the highest basalt dose increased the SB and V% values by 200% compared to samples without basalt residue incubation. The lowest basalt dust rate has already shown significant increases in P, K, Ca, and Mg contents, and hence in SB and V%.

Typic Quartzipsamment soils samples incubated with the highest basalt dust rate had a 25% increase in pH compared to control samples (Table S4). The elevation in pH of samples incubated with the highest basalt dust rate induced Al neutralization and H + Al values 24% lower than samples without basalt dust. Oxisol samples incubated with the highest basalt dust rate had a 15% increase in pH when compared to the control samples. The highest dose also induced a 26% reduction in H + Al contents and Al neutralization in OX (Table S4).

3.2. Basalt dust effect on maize plants

Maize plants had quadratic increases in shoot dry mass in both soils (Fig. 2A), height, and stem diameter (Table S5). Maize plants grown in TQ and OX showed shoot dry mass 200% greater than that of plants grown without basalt dust (Fig. 2A). Effects of basalt dust treatments on maize plants reflected the results found in soil of the incubation test (Fig. 1). At the highest residue rate, maize plants grown in TQ showed shoot dry mass accumulation (33.26 g) similar to that of plants grown in OX (34.27 g).

Regarding micronutrient accumulations, a quadratic result was observed in maize plants grown in both soils (Fig. 2). In TQ soil, plants receiving the highest basalt dust rate showed B, Cu, Fe, Mn, and Zn accumulations of six, fifteen, nine, four, and eight times greater than those of plants not receiving the residue, respectively. For plants grown in OX, the highest rate promoted increases in B and Cu accumulations seven times higher than those of control plants. Moreover, the highest dose also provided Fe, Mn, and Zn accumulations eight, six, and twenty-

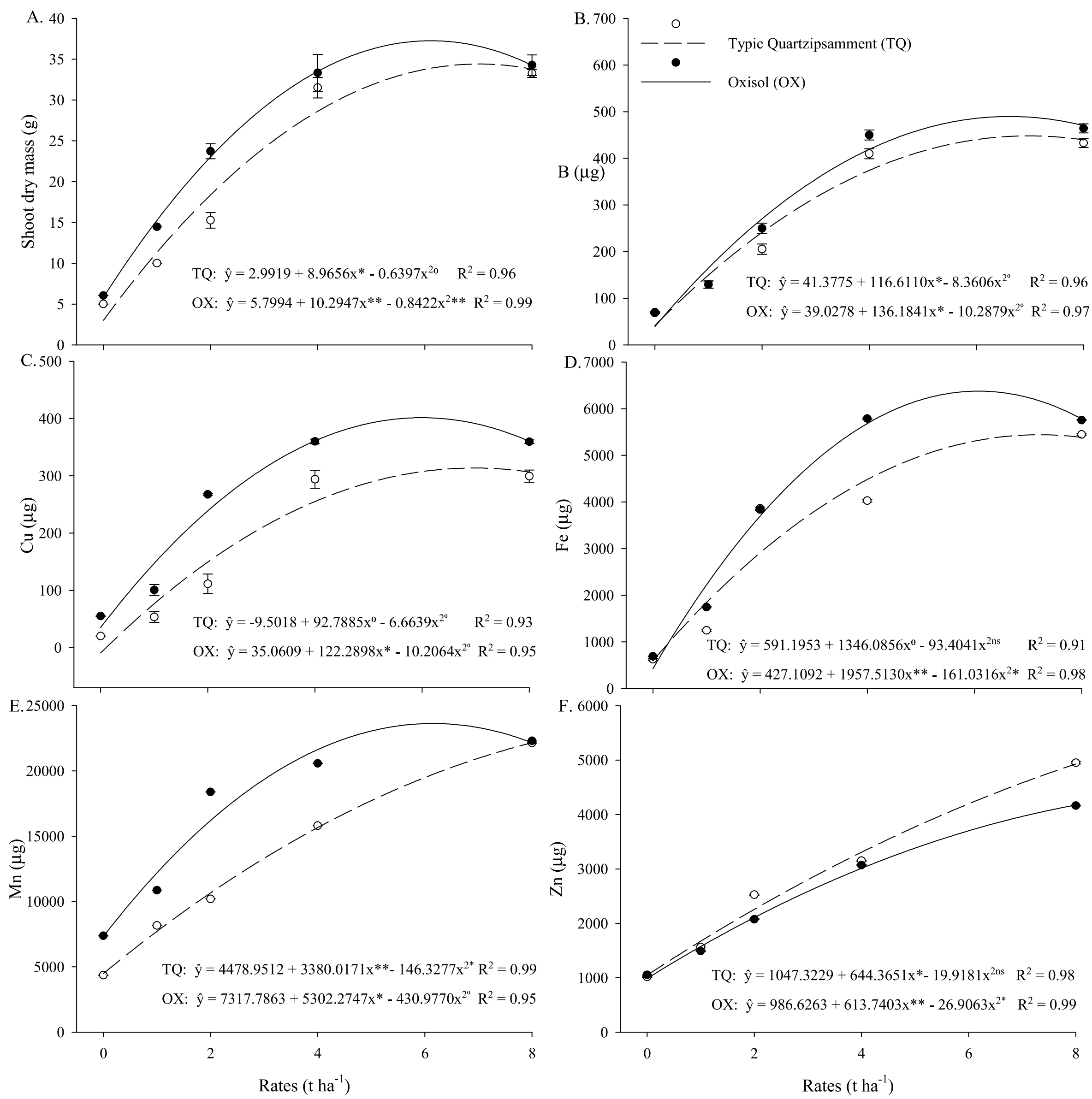

Fig. 2. Shoot dry matter (A) and shoot accumulation of boron (B, B); cupper (Cu, C); iron (Fe, D); manganese (Mn, E); and zinc (Zn, F) in maize plants cultivated up to 55 days after emergence of maize plants (V6 stage) in Typic Quartzipsamment (TQ ○) and Oxisol (OX ●) grown in soil containing different concentrations of basalt powder for 55 days.

one times greater than those of control plants, respectively (Fig. 2).

The macronutrient accumulations in maize shoot showed a quadratic increase (Fig. 3). When compared to the control, plants grown in TQ with the highest basalt dust rate had N and P accumulations five times higher, K and S eight times higher, Ca twelve times higher, and Mg twenty-three times higher. In maize plants grown with the highest basalt dust rate in OX, nitrogen accumulation was seven times greater than that of plants that received only mineral fertilization, as well as P, K, and Ca accumulations six times greater, Mg twenty-four times greater, and S seven times greater (Fig. 3).

In both soils, residual effect of basalt dust after corn cultivation promoted increases in P, Ca, and Mg contents, as well as in CEC, SB, and V% (Tables S6 and S7). After maize cultivation in TQ, the samples receiving the highest basalt dust rate showed P, K, Ca, and Mg levels in soil about 40% higher than those of control. In OX, the samples receiving the highest basalt dust rate had P, K, Ca, and Mg levels in soil about 30% higher than those of samples not receiving the residue.

3.3. Basalt dust effect on bean plants

Beans plants showed a quadratic increase in shoot dry mass (Fig. 3A), height, and stem diameter (Fig. S1) for both soils evaluated. The beans plants grown in TQ and OX showed shoot dry masses about 300% higher than control plants (Fig. 3A). Notably, beans grown with the highest basalt dust rate in TQ showed a shoot dry mass accumulation (36.27 g) similar to that in OX with the highest residue rate (36.45 g).

Micronutrient accumulation in bean shoots showed a quadratic increase as a function of basalt dust rates (Fig. 3). The highest basalt dust rate in TQ promoted B, Mn, and Zn accumulations five times higher than those in the control, as well as Cu and Fe accumulations two and three times greater, respectively. In OX, the highest basalt dust dose promoted B and Zn accumulations four times greater than those in the control. Moreover, plants grown with the highest dose showed twice as much Cu accumulation, and three times as high Fe and Mn accumulations than in control plants (Fig. 3).

In both soils, shoot macronutrient accumulation in bean plants

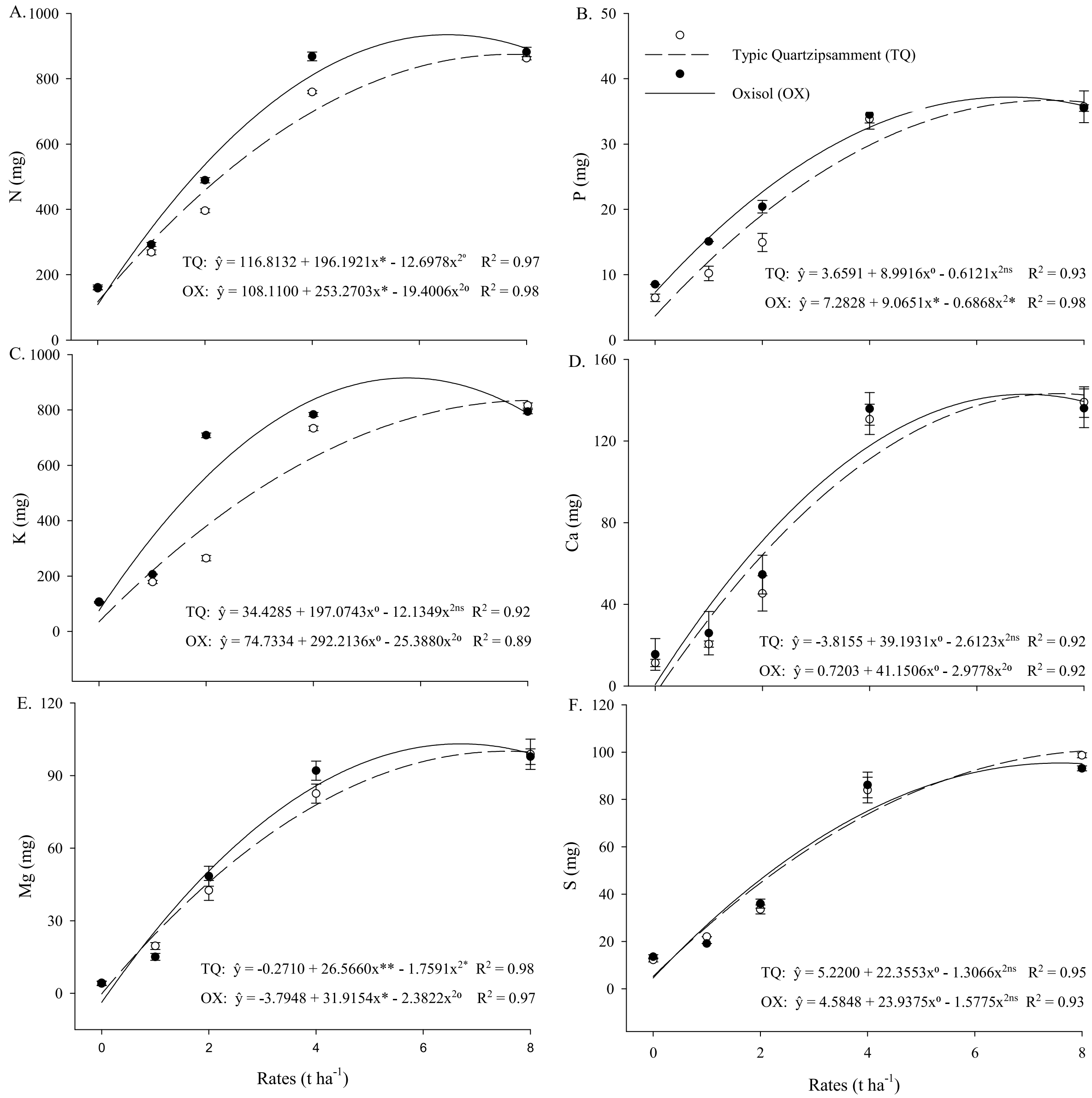

Fig. 3. Shoot accumulation of nitrogen (N, A); phosphorus (P, B); potassium (K, C); calcium (Ca, D); magnesium (Mg, E); and sulfur (S, F) in maize plants cultivated up to 55 days after emergence of maize plants (V6 stage) in Typic Quartzipsamment (TQ ○) and Oxisol (OX ●) grown in soil containing different concentrations of basalt powder for 55 days.

increased as a function of increasing basalt dust rates (Fig. 4). Similar to growth data (Fig. 3), basalt dust rates increased macronutrient uptakes by beans. Plants grown in TQ with the highest rate showed N and P accumulations two and six times higher than control plants, respectively. Accumulations of K, Ca, Mg and S in plants receiving the highest basalt dust dose were six times higher than in control plants. Plants grown in OX with the highest basalt dust rate had N and P accumulations three times higher than in control plants. Also, plants grown with the highest basalt dust dose showed K and S accumulations four times higher, and Ca and Mg accumulations five times higher than control plants (Fig. 4). In both soils, after bean cultivation, results indicate that residual effect of basalt dust provided increases about of 150% in P, Ca, and Mg levels in soil, as well as increases in CEC, SB, and V% (Tables S8 and S9) (see Fig. 5).

4. Discussion

The use of basalt dust rate provided suitable chemical properties in soil for crop cultivation in both soils. Generally, the nutrients supplied by basalt dust above all determined by its mineralogy [2,8]. Potassium occurs in a wide range of silicate minerals and is a primary focus of many studies with silicate minerals [2,4,6,14]. However, in the present work, there was an increase in the levels of K in soil, as well as in the levels of Ca, Mg and P. Recent studies also reported significant increases in P, K, Ca, and Mg levels in the soil as a function of the increase in basalt dust doses [15,16].

Phosphorus levels in both soils was the nutrient with the most significant increase. Basalt dust changed P levels class in both soils to high levels (>25 mg dm^{-3}) [11]. Such an effect can be attributed to basalt mineralogical composition, both apatite presence and P availability from silicon (Si) release [15,17]. Silicate anion can be made available by basalt dust application, competing with phosphate anion for the same absorption site, increasing P availability [9,18]. Worldwide, agriculture relies on expensive inorganic P fertilizer inputs for maximum crop production [19]. This strategy is not considered economically or ecologically sustainable in the long term, because P fertilizer is a

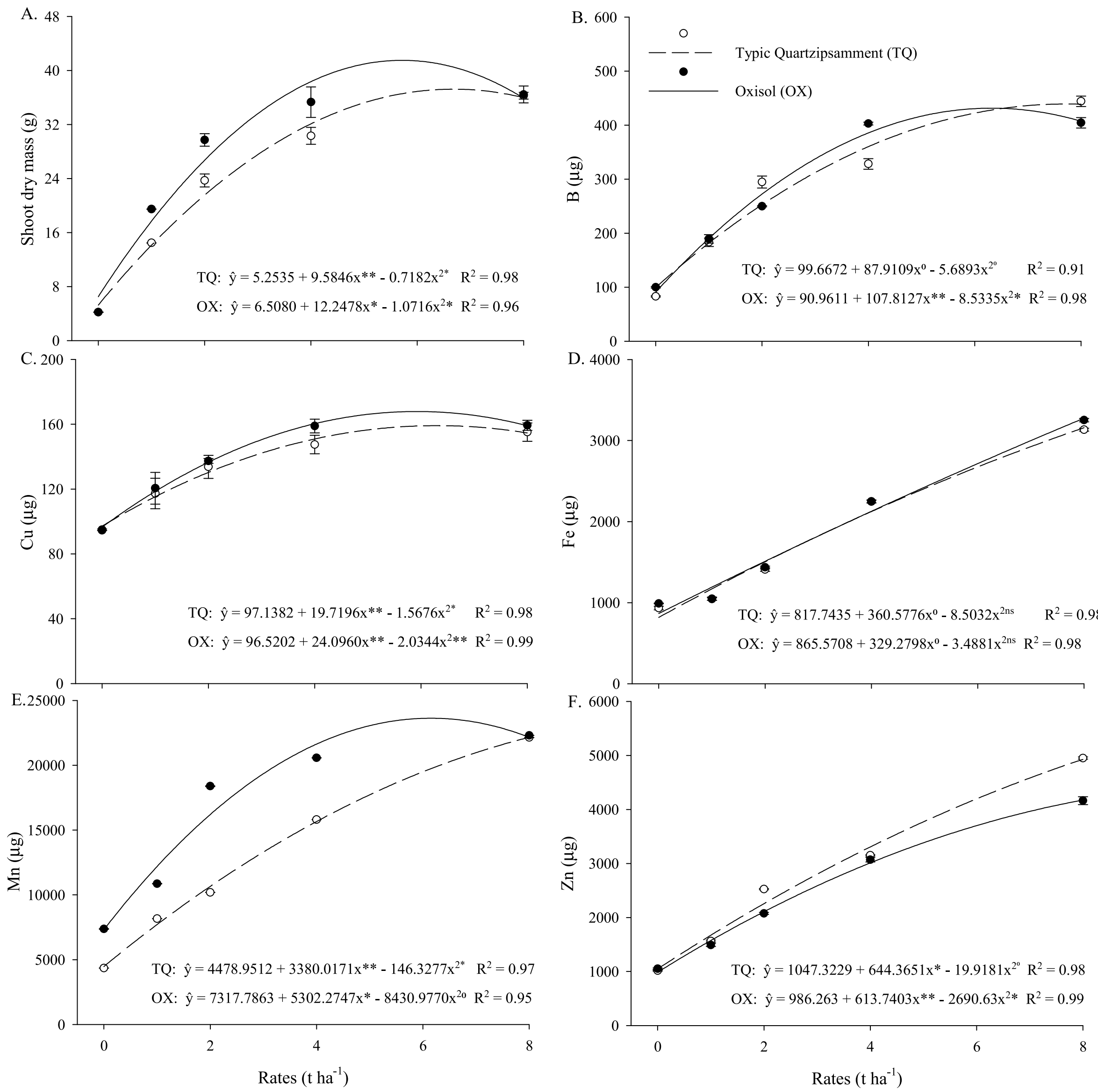

Fig. 4. Shoot dry matter (A) and shoot accumulation of boron (B, B); cupper (Cu, C); iron (Fe, D); manganese (Mn, E); and zinc (Zn, F) in bean plants cultivated up to 55 days after emergence of bean plants (F1 stage) in Typic Quartzipsamment (TQ ○) and Oxisol (OX ●) grown in soil containing different concentrations of basalt powder for 55 days.

non-renewable resource and contributes to the eutrophication of the environment [20,21]. The results presented here indicate that the use of basalt dust increases the availability of this nutrient in the soil. Thus, strategies focused on managing with basalt dust can mitigate the future shortage of P.

Several reports showed increased soil pH by basalt dust [2,8,9]. The pH increase due to basalt application were promoted by the reaction of Ca and Mg carbonates with hydrogen in the soil, releasing water and carbon dioxide. It is noteworthy that the increase in pH values using basalt dust induced Al neutralization in both soils. Aluminum toxicity affects agricultural production on a worldwide scale, particularly in tropical regions [22]. In this sense, the potential of using basalt to help correct soil pH and Al neutralization is highlighted.

The beneficial effects of basalt dust incubation in both soils allowed an increase in the initial growth of bean and maize plants. Basalt dust improved maize nutritional management, increasing initial growth and nutrient uptake. The slow and continuous solubility of basalt dust favors its residual effect; therefore, it acts as a supplementary fertilizer, reducing demand for mineral fertilizers over the years [2,9]. Despite the high productive potential of maize (12 t grains ha^{-1}) in Brazilian farms, much lower yields have been related. Low corn yields occur due to unsuitable liming and fertilization, reducing macronutrient uptake [14]. Thus, basalt dust can be used as an alternative to help nutritional management in maize.

Some studies have shown that reductions in the availability of cationic micronutrients as soil pH increases is common. However, soil pH increases as a function of basalt dust in our study had no effect on micronutrient uptakes by maize plants. Our results show that soil pH and plant micronutrient uptake increased concomitantly, allowing an adequate development of maize plants in both soils. Maize crops have great economic importance in Brazil. A growing demand for this cereal has generated the need to map areas with production potential. For economic reasons, such increase in national maize production in recent years has been achieved by off-season cropping or as a second crop. Maize cultivation as a secondary crop to soybeans started to be widely used in the 2011/12 season; until then, it was mostly grown as main crop. Given this context, products that may have a residual effect for the next crop began to be evaluated [23]. Thus, the use of basalt powder

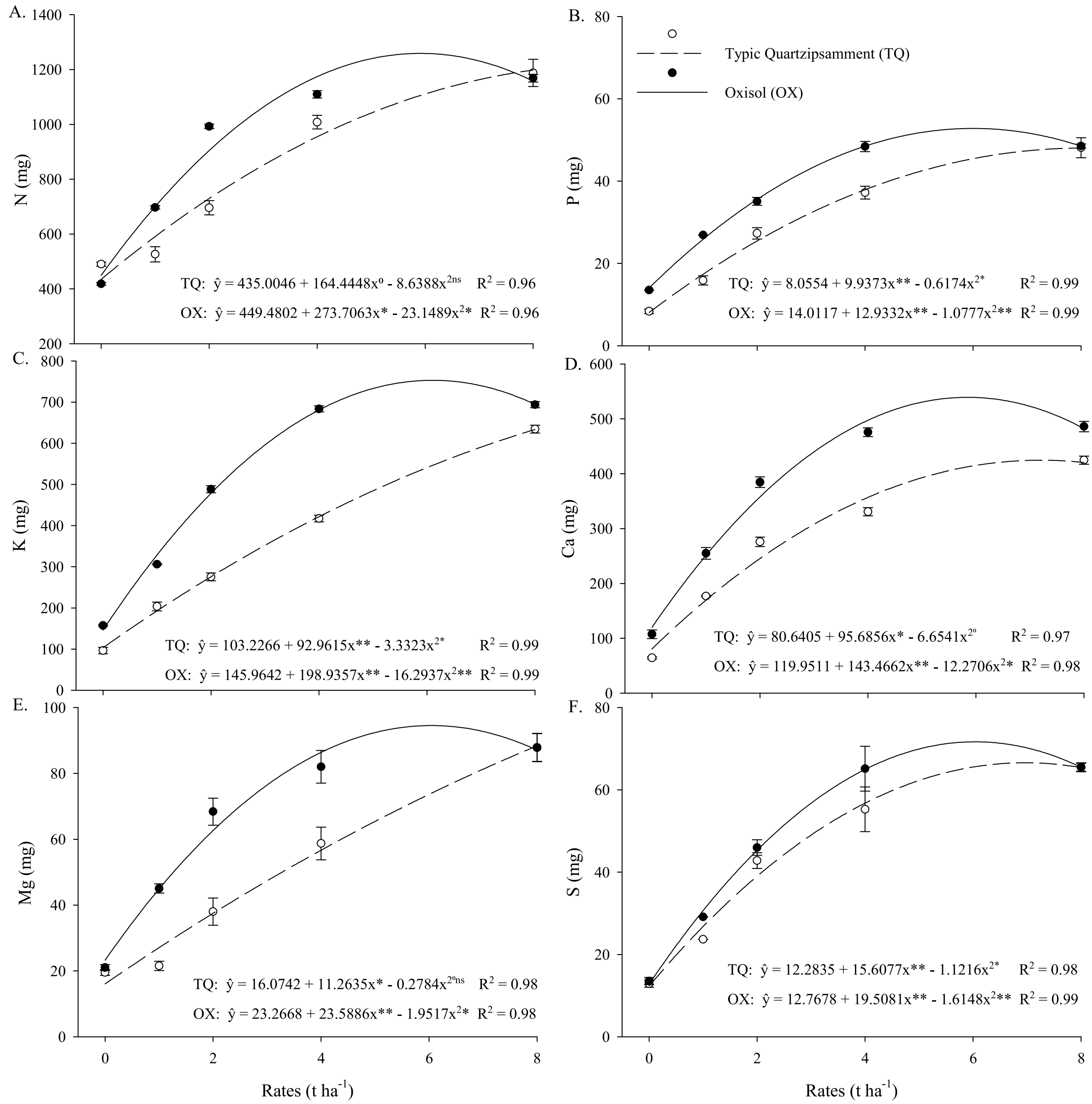

Fig. 5. Shoot accumulation of nitrogen (N, A); phosphorus (P, B); potassium (K, C); calcium (Ca, D); magnesium (Mg, E); and sulfur (S, F) in maize plants cultivated up to 55 days after emergence of bean plants (F1 stage) in Typic Quartzipsamment (TQ ○) and Oxisol (OX ●) grown in soil containing different concentrations of basalt powder for 55 days.

helps in the crops management of corn and beans, and can be used in the nutritional management.

The use of basalt dust promoted benefits for common bean cultivation. In Brazil, common beans have shown low mean yields (>1000 kg ha^{-1}) due to several reasons, from climatic effects and crop health to economic problems of farmers. In this sense, fertilization is a decisive factor in changing this situation [24]. In both soils, macronutrient accumulations in bean shoots occurred as a function of basalt dust dose increments. The low exploitation of the root growth and short cycle of bean plants requires a concern with nutritional management [25] Therefore, nutritional management should be properly performed. Accordingly, basalt dust proved capable of optimizing the nutritional status of beans by stimulating nutrient uptake. The increase of nutrient accumulations in beans enhances crop yield potential, which has been often overlooked in the nutritional management of production systems [24]. Micronutrient uptake by common beans improves the biological N fixation [25]. Thus, the use of basalt dust allows an increasevnutrients uptake, thus stimulating the initial growth of beans.

Currently, the Brazilian production of beans is intended for domestic consumption and is of great importance as food and income generation, mainly for family farming. However, these plants have been increasingly grown to reform sugarcane fields or as an option in crop rotation systems [24]. Our results highlight basalt dust potential for bean cropping systems. Such a statement derives from the maintenance of improved chemical properties in the soil, after bean cultivation with basalt dust. Among these chemical attributes, we highlight the increased P, Ca, and Mg contents, as well as acidity and Al neutralization reductions in both soils. Such effect may be potentiated when associated with other practices such as crop rotation, green manure, and no-tillage. Our findings reinforce the potential of basalt dust to improve soil chemical properties, even after growing bean plants. Additionally, future studies should be carried out by mixing basalt dust and organic residuals such as sludge, aiming at modifications in the structure of the rock powder and largest release of nutrients in smaller time interval.

5. Conclusion

Basalt dust improved soil chemical properties after both soil incubation and crop cultivation. It also increased macro- and micronutrient accumulations in maize and bean plants. The several benefits from basalt dust were due to its parent rock, which provides part of the macro and micronutrients required for plant development and soil pH rebalancing. These results showed the usefulness of basalt dust in aiding nutritional management in agriculture.

Authorship contribution statement

L. T. Conceição: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. G. N. Silva: Conceptualization, Formal analysis, Funding acquisition, Software, Writing –review & editing. H. M. S. Holsback: Formal analysis, Investigation, Visualization, Writing – review & editing. C. F. Oliveira: Formal analysis, Methodology, Writing – review & editing. N. C. Marcante: Conceptualization, Supervision, Writing – review & editing. É. S. Martins: Conceptualization, Writing – review & editing. F. L. S. Santos[2]: Conceptualization, Writing – review & editing. E. F. Santos: Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Software, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jafr.2022.100443.

References

[1] D.F.M. Burbano, S.H. Theodoro, A.M.X. de Carvalho, C.G. Ramos, Crushed volcanic rock as soil remineralizer: a strategy to overcome the global fertilizer crisis, Nat. Resour. Res. 31 (2022) 2197–2210, https://doi.org/10.1007/s11053-022-10107-x.
[2] P. Swoboda, T.F. Döring, M. Hamer, Remineralizing soils? The agricultural usage of silicate rock powders: a review, Sci. Total Environ. 807 (2022), https://doi.org/10.1016/j.scitotenv.2021.150976.
[3] Ama Brasil, Brazilian Fertilizer Mixers Association, Production and Import of Fertilizers, 2022. http://amabrasil.agr.br/web/portfolio-item/producao-e-importacao-de-fertilizantes/. (Accessed 6 April 2022). accessed.
[4] D.R. Guelfi-Silva, G. Marchi, C.R. Spehar, L.R.G. Guilherme, T.A. Rein, D.A. Soares, F.W. Ávila, Characterization and nutrient release from silicate rocks and influence on chemical changes in soil, Rev. Bras. Ciência do Solo 36 (2012) 951–962, https://doi.org/10.1590/s0100-06832012000300025.
[5] D.R. Guelfi-Silva, G. Marchi, C.R. Spehar, L.R.G. Guilherme, V. Faquin, Agronomic efficiency of potassium fertilization in lettuce fertilized: with alternative nutrient sources, Rev. Cienc. Agron. 44 (2013) 267–277, https://doi.org/10.1590/S1806-66902013000200008.
[6] D.R. Guelfi-Silva, R.S. Carlos, M. Giuliano, de A.S. Danilo, L.C. Eduardo, S.M. der de, Yield, nutrient uptake and potassium use efficiency in rice fertilized with crushed rocks, Afr. J. Agric. Res. 9 (2014) 455–464, https://doi.org/10.5897/ajar2013.7638.
[7] C.G. Ramos, X. Querol, M.L.S. Oliveira, K. Pires, R.M. Kautzmann, L.F.O. Silva, A preliminary evaluation of volcanic rock powder for application in agriculture as soil a remineralizer, Sci. Total Environ. 512–513 (2015) 371–380, https://doi.org/10.1016/j.scitotenv.2014.12.070.
[8] V.F. Melo, S.C.P. Uchôa, F. de O. Dias, G.F. Barbosa, Doses de basalto moído nas propriedades químicas de um Latossolo Amarelo distrófico da savana de Roraima, Acta Amazonica 42 (2012) 471–476, https://doi.org/10.1590/S0044-59672012000400004.
[9] V.L. Augusto, A.P. LaÃ©rcio, A.B. Marcelo, S. Fã¡bio, P. da S.G. Ana, C.D.C. Janete, Agronomic feasibility of using basalt powder as soil nutrient remineralizer, Afr. J. Agric. Res. 17 (2021) 487–497, https://doi.org/10.5897/ajar2020.15234.
[10] BRASIL, Instrução Normativa 5 - Regras dos remineralizadores e substratos de plantas, 2022 n.d.), https://www.gov.br/agricultura/pt-br/assuntos/insumos-agropecuarios/insumos-agricolas/fertilizantes/legislacao/in-5-de-10-3-16-remineralizadores-e-substratos-para-plantas.pdf. accessed 9 January.
[11] E. Lobato, D.M.G. Sousa, Cerrado: correção do solo e adubação, 2014.
[12] E. Malavolta, G.C. Vitti, S.A. Oliveira, Evaluation of the Nutritional Status of Plants: Principles and Applications, Potafos, Piracicaba, 1997.
[13] B. Raij, Soil Fertility and Nutrient Management, Internatio, Piracicaba, 2011.
[14] T.A.R. Nogueira, B.G. Miranda, A. Jalal, L.G.F. Lessa, M.C.M.T. Filho, N. C. Marcante, C.H. Abreu-Junior, A.D. Jani, G.F. Capra, A. Moreira, É. de S. Martins, Nepheline syenite and phonolite as alternative potassium sources for maize, Agronomy 11 (2021) 1–19, https://doi.org/10.3390/agronomy11071385.
[15] L.F. Pereira, W.Q.R. Junior, M.L.G. Ramos, N.Z. dos Santos, G.F. Soares, R.A. das Chagas Noqueli Casari, O. Muller, C.J. Tavares, É. de Souza Martins, U. Rascher, C. A. de Lima Guimarães, A.F. Pereira, L.M. Mertz-Henning, C.A.F. de Sousa, Physiological changes in soybean cultivated with soil remineralizer in the Cerrado under variable water regimes, Pesqui. Agropecu. Bras. 56 (2021) 1–12, https://doi.org/10.1590/S1678-3921.PAB2021.V56.01455.
[16] L.G. Plata, C.G. Ramos, M.L. Silva Oliveira, L.F. Silva Oliveira, Release kinetics of multi-nutrients from volcanic rock mining by-products: evidences for their use as a soil remineralizer, J. Clean. Prod. 279 (2021), 123668, https://doi.org/10.1016/j.jclepro.2020.123668.
[17] A. da Silva Sandim, L. Theodoro Büll, A. Reis Furim, G. da Silva Lima, J. Luis Nantes Garcia, Phosphorus availability in oxidic soils treated with lime and silicate applications (1) resumo, Disponibilidade De Fósforo Em Razão Da Aplicação De Calcário E Silicatos Em Solos Oxídicos 38 (2014) 1215–1222.
[18] A. Da Silva, J.A. Almeida, C. Schmitt, C.V.T. Do Amarante, Fertilidade do solo e desenvolvimento de feijão comum em resposta adubação com pó de basalto, Rev. Bras. Ciência Avícola 7 (2012) 548–554, https://doi.org/10.5039/agraria.v7i4a1491.
[19] P.J.A. Withers, M. Rodrigues, A. Soltangheisi, T.S. De Carvalho, R.D.S. Nunes, C. A. Rosolem, F.D. Andreote, A.D.O. Jr, E.L.M. Coutinho, P.S. Pavinato, Transitions to Sustainable Management of Phosphorus in Brazilian Agriculture, 2018, pp. 1–13, https://doi.org/10.1038/s41598-018-20887-z.
[20] E.F. Santos, P. Pongrac, A.R. Reis, P.J. White, J. Lavres, Phosphorus–zinc interactions in cotton: consequences for biomass production and nutrient-use efficiency in photosynthesis, Physiol. Plantarum 166 (2019) 996–1007, https://doi.org/10.1111/ppl.12867.
[21] E.F. Santos, P. Pongrac, A.R. Reis, F.H.S. Rabêlo, R.A. Azevedo, P.J. White, J. Lavres, Unravelling homeostasis effects of phosphorus and zinc nutrition by leaf photochemistry and metabolic adjustment in cotton plants, Sci. Rep. 11 (2021) 1–14, https://doi.org/10.1038/s41598-021-93396-1.
[22] F. Furlan, L. Borgo, F.H.S. Rabêlo, M.L. Rossi, F.S. Linhares, A.P. Martinelli, R. A. Azevedo, J. Lavres, Aluminum-induced toxicity in Urochloa brizantha genotypes: a first glance into root Al-apoplastic and -symplastic compartmentation, Al-translocation and antioxidant performance, Chemosphere 243 (2020), 125362, https://doi.org/10.1016/j.chemosphere.2019.125362.
[23] J.H.M. Viana, A.M. Coelho, A. Thomazini, M.P.F. DE Carvalho, Evaluation of the agricultural potential of the serpentinite rock as a soil remineralizer, An. Acad. Bras. Cienc. 93 (2021) 1–14, https://doi.org/10.1590/0001-3765202120201614.
[24] O.H. De Castro Pias, C.A. Welter, T. Tiecher, M.R. Cherubin, J.P.M. Flores, L. A. Alves, C. Bayer, Common bean yield responses to nitrogen fertilization in Brazilian no-till soils: a meta-analysis, Rev. Bras. Cienc. Do Solo. 46 (2022) 1–28, https://doi.org/10.36783/18069657rbcs20220022.
[25] M. Hungria, M.A. Nogueira, R.S. Araujo, Co-inoculation of soybeans and common beans with rhizobia and azospirilla: strategies to improve sustainability, Biol. Fertil. Soils 49 (2013) 791–801, https://doi.org/10.1007/s00374-012-0771-5.