Water Air Soil Pollut (2023) 234:538
https://doi.org/10.1007/s11270-023-06563-7

# Pelletization and Fertilization Improve the Root Environment in Soil Affected by Iron Mining Tailings

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Received: 13 April 2023 / Accepted: 27 July 2023 /

**Abstract** Iron mining tailings raise several concerns regarding their deposition and the decommissioning of storage dams, particularly regarding the limitations of this substrate for plant establishment, including poor substrate aggregation and limited availability of nutrients. The objective of this study was to evaluate the effect of the interaction of pelleting and fertilization on the physical and chemical conditioning of the root environment for the growth and development of plants in technosol formed by the deposition of iron mining tailings. Three experimental trials were carried out using indicator plants (*Urochloa brizantha* Hochst. ex A. Rich., *Eucalyptus grandis* W. Hill ex Maiden, and *Phaseolus vulgaris* L.), in a randomized block design, and the treatments distributed in a factorial arrangement (5×2): five levels of technosol pelleting (0, 25, 50, 75, and 100% m/m), with and without fertilization, with five replications. Fertilization promoted the growth of all plants and demonstrated that the supply of nutrients is fundamental for plant growth in this technosol, mainly by promoting root development, which in turn favored substrate porosity. Pelleting mainly increased the technosol macroporosity in all tests. However, it was only effective in providing better growth conditions and enhancing the supply of nutrients for *Eucalyptus grandis*. While pelleting improves the physical conditions of the root environment, the availability of nutrients was found to be the main limiting factor for plant growth in the technosol formed by iron mining tailings. With adequate fertilization, the plants had less difficulty developing in this substrate under vase conditions.

**Keywords** Technosol · Macroporosity · Particle agglomeration · Fundão dam · Revegetation

## 1 Introduction

The recent catastrophic events resulting from the rupture of two iron mining tailings storage dams in Minas Gerais, Brazil (the Fundão dam in 2015 and the Mina do Córrego do Feijão dam in 2019) have brought urgent attention to the discussion about tailings storage practices employed by the mining industry. These events have highlighted the need for addressing the challenges of the rehabilitation of areas impacted by

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**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s11270-023-06563-7.

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the rupture of dams, as well as concerns regarding the disposal of these materials. Despite being called tailings, they may still contain valuable minerals that can be accessed due to advancements in extraction and processing techniques. Therefore, it is essential to explore options for the recommissioning of the dams, the depositing of these tailings, and for the revegetation of areas impacted by the rupture of dams. These issues are particularly relevant in regions with a high concentration of mining activity, such as the *Quadrilátero Ferrífero (MG)*, which is the largest mining region in Brazil. Some authors have already pointed out the need to reassess the safety of existing tailings dams and to improve tailings management practices to prevent further disasters (Santamarina et al., 2019; Vergilio et al., 2020).

The rupture of the Fundão dam in Mariana, MG, in 2015 resulted in the deposition of a significant amount of tailings in the Rio Doce Basin. The layer of deposited tailings in the gutters of rivers and floodplains of watercourses reached more than 1 m, in several stretches along the impacted areas. This deposition presents a significant challenge to the recovery of these areas and prolongs the time required for the rehabilitation of the physical structure of the soil and the restoration of biodiversity (Batista et al., 2020; Couto et al., 2021; Fernandes et al., 2016). Furthermore, the dam rupture disrupted the hydro-sedimentological regime in the deposition areas, affecting the physical attributes of the sedimentary environment, and creating a crust that can waterproof the surface (Cordeiro et al., 2019; Duarte et al., 2021; Hatje et al., 2017). The continuous input of material that remains suspended during the rainy season increases the turbidity of the water in the rivers.

The mineralogical composition of the tailings is simpler than that found in the local soil. The tailings have a predominance of quartz ($SiO_2$) and hematite ($Fe_2O_3$), which are common minerals in the constitution of iron ore. On the other hand, the unaffected soils present a greater diversity in mineralogical composition, composed of quartz ($SiO_2$), hematite ($Fe_2O_3$), goethite (FeOOH), kaolinite ($Al_2Si_2O_5(OH)_4$), muscovite ($KAl_2(AlSi_3O_{10})(OH)_2$), and calcite ($CaCO_2$) (Almeida et al., 2018; Da Silva et al., 2022). This difference in mineralogical composition influences the chemical and physical characteristics of the tailing, especially those related to the aggregation, structuring, and cation exchange capacity (CEC) of this material (Almeida et al., 2018; Couto et al., 2021; Da Silva et al., 2022; Duarte et al., 2021).

According to Almeida et al. (2018), the tailings have a granulometry composed of 42% sand, 47.5% silt, and 10.5% clay, therefore having a silty texture with low CEC, greatly reducing its ability to sorb. The authors also note that the particle density of the tailings, whose value is 2.94 g $cm^{-3}$, coincides with the particle density of soils with high iron content. This higher particle density influences soil density, which can be detrimental to root growth (Andrade et al., 2018; Matos et al., 2020).

The tailings still have several biological and fertility limitations that may restrict the revegetation process of the affected areas. The low availability of nutrients, alkaline pH, low levels of organic matter, low microbial activity, and lack of structure stand out (Batista et al., 2020; Da Silva et al., 2022; Silva et al., 2016, 2021). The latter is one of the most critical in terms of management since the particle aggregation process, in analogy to pedogenetic processes, depends on a complex interaction between physical, chemical, and biological factors (Duiker et al., 2003; Kay, 1998).

Therefore, to manage the agglomeration of the technosol particles mechanically, giving it minimum physical conditioning, we use compression or molding mechanisms of individualized materials to produce pellets that promote the pelletization of the technosol. This practice can promote the physical conditioning of the technosol, providing macroporosity between agglomerates, increasing the capacity for infiltration and water drainage, and the aeration porosity, essential for root development. This practice of pelletizing the tailings would not be an alternative for the areas impacted by the deposition of tailings from the Fundão dam failure, but rather an alternative to be used in the decommissioning of other iron mining tailings dams. The State of Minas Gerais has hundreds of mining tailings dams (Guerra et al., 2023), and the destination of this material and the mischaracterization of these dams are the focus of many studies.

In addition to physical conditioning, chemical conditioning of the technosol is required since some authors have shown that technosol fertilization enables plant growth (Esteves et al., 2020a, b; Scotti et al., 2020; Zago et al., 2019). Fertilization provides an increase in the availability of nutrients, helps in the acidification of the tailing (Da Silva et al., 2022), and can contribute to increasing its sorptive capacity, increasing the available loads, which increases the production of phytomass. These characteristics make fertilization an important step for the revegetation of areas impacted by iron mining tailings.

Thus, the objective of this work was to evaluate the effect of physical conditioning, by the pelleting mechanism (mechanical agglomeration of particles), in interaction with fertilization to improve the root environment for plant growth and development in technosol affected by tailings deposition from iron mining, coming from the Fundão dam.

## 2 Material and Methods

### 2.1 Sampling of the Tailing (Technosol)

With the rupture of the iron mining tailings storage dam, a wide range of soils along the Doce River Basin were impacted by the large volume of tailings deposition. Throughout the text, we will refer to this mixture of tailings and soil as "technosol" from the affected region. The technosol samples were collected on the banks of the Gualaxo do Norte River in the Bento Rodrigues district of Mariana municipality, MG, Brazil (20°17′55.8″S; 43°12′19.8″W). This material was transported to the Soil Department of the Federal University of Lavras, where it was air-dried, sieved through a 4.75 mm mesh, and chemically and physically characterized (Teixeira et al., 2017) as follows: pH in $H_2O$ 7.6; cation exchange capacity at pH 7.0 2.4 $cmol_c\ dm^{-3}$; base saturation 62.2%; organic matter 0.3 dag $kg^{-1}$; phosphorus (P) 4.9 mg $dm^{-3}$; remaining phosphorus 48.5 mg $L^{-1}$; potassium (K) 32.5 mg $dm^{-3}$; sulfur (S) 4.2 mg $dm^{-3}$; calcium (Ca) 1.3 $cmol_c\ dm^{-3}$; magnesium (Mg) 0.1 $cmol_c\ dm^{-3}$; aluminum (Al) 0.0 $cmol_c\ dm^{-3}$; potential acidity 0.9 $cmol_c\ dm^{-3}$; iron (Fe) 101.5 mg $kg^{-1}$; manganese (Mn) 125.1 mg $kg^{-1}$; zinc (Zn) 0.7 125.1 mg $kg^{-1}$; copper (Cu) 1.2 125.1 mg $kg^{-1}$; boron (B) 0.03 125.1 mg $kg^{-1}$; nickel (Ni) 7.71 125.1 mg $kg^{-1}$; chromium (Cr) 19.71 125.1 mg $kg^{-1}$; cadmium (Cd) 0.22 125.1 mg $kg^{-1}$; lead (Pb) 7.59 125.1 mg $kg^{-1}$; barium (Ba) 51.0 125.1 mg $kg^{-1}$; sand 76.0 dag $kg^{-1}$; silt 18.0 dag $kg^{-1}$; and clay 6.0 dag $kg^{-1}$. The maximum compactness density of the technosol (Dmax) and the optimal moisture content for compaction (Uo) were determined by the standard Proctor test (ABNT, 1986), being Dmax 1.95 g $cm^{-3}$ and Uo 9.71% (m/m).

### 2.2 Experimental Design

Three plant species brachiaria (*Urochloa brizantha* Hochst. ex A. Rich.), eucalyptus (*Eucalyptus grandis* W. Hill ex Maiden), and common bean (*Phaseolus vulgaris* L.) were tested in independent experiments. The experiments were designed in randomized blocks, with five replications, and treatments distributed in a factorial scheme (5×2), the first factor being five levels of technosol pelleting (0, 25, 50, 75, and 100% m/m) and the second factor composed of two levels of fertilization (with or without fertilization).

### 2.3 Pelletizing Mechanism

The methodology used for pelletizing was adapted from Meyer (1980) and consisted of agglomerating the technosol particles using water and a rotating mechanism in a concrete mixer to mold the agglomerates (Fig. 1). For this, air-dried technosol was used and passed through a 4.75 mm sieve. Five kilograms of technosol were processed at a time in a concrete mixer operating at 30 rpm and a 45° inclination. During the process, water was added to the technosol mass through a sprayer until reaching an amount equivalent to 15% (m/m) of water. Each process lasted about 40 min. After forming the pellets, they were subjected to a curing process by air drying, and subsequently, the granulometric classification of pellet samples was performed by sieving in a set of 8.00, 4.75, and 2.00 mm mesh diameter sieves, with a bottom to retain pellets and particulate matter smaller than 2 mm in diameter. The material retained on each sieve was weighed, and the following granulometric proportions were obtained: 14.33% > 8.00 mm; 13.49% 8.00–4.75 mm; 46.00% 4.75–2.00 mm; and 26.19% < 2.00 mm (Fig. 1). The amount of technosol used to compose the experimental units was 2 kg. Depending on the proportions of technosol pelleted or not, for each treatment, this amount was placed in 3-L vases containing plastic bags to avoid the loss of water and nutrients by leaching and percolation.

**Fig. 1** Scheme of the technosol pelletizing process using water and rotation mechanism in a concrete mixer to model the agglomerates and granulometric classification by size (> 8.00 mm; 8.00–4.75 mm; 4.75–2.00 mm; and < 2.00 mm). Detailing the root system of a plant growing in pelleted technosol

## 2.4 Conduct of Experiments

The experiment was conducted in a controlled environment (greenhouse) to ensure that the results were not affected by external factors such as temperature and water availability. The substrate was maintained at 60% of its field capacity, and distilled water was used for irrigation. The fertilization of the experiments was carried out according to the recommendations for fertilizing plants in vases by Malavolta (1981). The fertilizers were applied via nutrient solution, applying 100 mL of each solution per vase. Only the P and Ca were supplied in technosol in the preparation of the substrate in the pots in solid form, applying 1 g of triple superphosphate per pot. Two nutrient solutions were applied to provide other necessary nutrients to the plants. The first solution (S1) provided N, K, and S, and was applied three times during the experiment, according to the plants' development. The first application was made in the germination of the brachiaria seeds, in the planting of the seedlings of eucalyptus, and in the emission of the first pairs of true leaves of the bean; the second and third applications were made fortnightly after the previous application. The second solution (S2) provided Mg and micronutrients B, Cu, and Zn, applied once on the first application. The fertilizer sources used and their respective concentrations in the solutions were: S1—$NH_4NO_3$ (13.2 g $L^{-1}$), KCl (5.7 g $L^{-1}$), and $(NH_4)_2SO_4$ (3.3 g $L^{-1}$); and S2—$Mg(NO_3)_2$ (6.3 g $L^{-1}$), $H_3BO_3$ (57.2 mg $L^{-1}$), $CuSO_4$ (117.6 mg $L^{-1}$), and e $ZnSO_4$ (438.8 mg $L^{-1}$). Because the available concentration of Mn and Fe in technosol was considered sufficient by chemical analysis, both were not applied.

In the experiment with brachiaria, 16 seeds were sown per pot, and a population of 8 plants per pot was maintained throughout the experiment, with recurrent thinning. The test was conducted for 100 days after plant emergence, and at the end of this period, samples were taken for plant and technosol analysis. For analysis of shoot dry mass (SDW) production, the plants were cut close to the surface of the technosol, which was stored in paper bags for drying in an oven at 70 °C for 72 h or until constant mass. The roots were separated from the technosol, washed, and the same drying procedure was followed to determine the root dry mass (RDW). In addition, the total dry mass (TDW) was determined by the sum of SDW and RDW.

In the experiment with eucalyptus, standardized seedlings of 10 cm in height were used, planting one seedling per pot. The seedlings were planted by cutting the root apex and placing them in technosol. The test was carried out for 120 days after planting the seedlings and the plant analyses were carried out, determining the stem diameter, plant height, SDW, RDW, and TDW. In the case of this experiment, SDW was fractioned in stem dry mass (St_DW) and leaf dry mass (LDW).

In the experiment with beans, 4 seeds were sown per pot, leaving only one plant per pot, after the development of the first pairs of true leaves. The test was carried out for 90 days after seedling emergence, followed by the analysis of SDW, RDW, and TDW, grain dry mass (GDW).

### 2.5 Chemical Analysis of Plant Material

The contents of elements (nutrients and metals), P, K, Ca, Mg, S, Fe, Mn, Zn, Ni, Ba, Cr, and Cu, were determined in the aerial part (PA) of the plants in the three experiments. The determination was made by microwave acid digestion and reading by plasma-coupled optical emission spectrometry (ICP-OES), according to the USEPA 3051A method (USEPA, 2007). For the procedure quality control, each batch of analyses contained a White Clover BCR® 402 reference sample and a blank sample. The analysis of the reference material had the following recoveries (%): Fe (105), Mn (116.5), Zn (97), Ni (91), and Cr (72). Such values demonstrate the quality of the analytical procedures used to determine the content of these elements in the plant material. The limits of detection (LOD) assumed were those reported by the manufacturer. Thus, the accumulation of elements in the plant was determined by the product between SDW and the content of the element.

### 2.6 Chemical and Physical Analyses of Technosol

Before separating the roots, technosol samples were collected to determine the pH in water and chemical attributes (Teixeira et al., 2017; USEPA, 2007). Concentrations of elements were determined using ICP-OES. For quality control analysis was using the standard reference material (SRM) NIST 2711a (Montana Soil II) was analyzed. The recovery percentages for elements [(ICP-OES concentration/certified concentration) × 100] were: Fe (81.4%), Mn (106.5%), Zn (112.1%), Cu (118.7%), Ba (88.1%), Cr (102.4%), and Ni (89.3%). The LOD assumed were those reported by the manufacturer.

The collection of technosol samples for physical analysis was performed using an Uhland sampler. Sampling was carried out by digging the sampling cylinder into the technosol, at a depth of 5 cm from the surface, subsequently wrapping the sample with film paper, until it was sent to the laboratory for leveling the sample in the cylinder and saturating with water to proceed with the analyses. Technosol density (Ds), total pore volume (VTPd), macro (Mac), and microporosity (Mic) were determined according to Teixeira et al. (2017). The Ds was used to calculate the degree of compaction (GC). The GC was determined by the ratio between the Ds and the maximum density (Dmax), being: $GC = (Ds/Dmax.) \times 100$.

### 2.7 Statistical Analysis

Data were submitted to the Jarque–Bera (Jarque & Bera, 1980) and Generalized ESD (Rosner, 1983) tests to evaluate the conditions of homogeneity of variances, normality of residuals, and presence of outliers, respectively. Then, analysis of variance (ANOVA) was performed, and the means of treatments without and with fertilization, when the pelleting factor was not significant ($p > 0.05$), were compared by the SNK test at 5% probability of error and the levels of pelletizing were evaluated using regression analysis. For these analyses, the SPEED Stat software (Carvalho et al., 2020) was used. Principal component analysis (PCA) was also performed on each species to investigate the general pattern of correlations of the analyzed variables between treatments using the vegan package (Oksanen et al., 2019) in the R software (R Core Team, 2019).

## 3 Results

For a better understanding of the results, it is important to consider some aspects related to the effects of fertilization on the response variables used to discriminate treatments. For example, identifying that fertilization has a significant effect on variables related to physical attributes, such as porosity or degree of compaction, does not mean there is a cause-and-effect relationship between fertilizers and these variables. However, it is understood that the plant responds to fertilization and changes technosol physical attributes due to root development.

In the Supplementary Material of this work is the summary of the analysis of variance of each experiment (Tables S1, S2, and S3) and the relationships of the variables that were not presented in graphic form, evaluated by regression analysis, when there was only an effect of the fertilization factor (Table S4).

The chemical conditioning of technosol through fertilization had a significant effect ($p < 0.05$) on most of the response variables in all three experiments. However, in the experiment with eucalyptus, fertilization did not significantly influence technosol microporosity. Similar behavior was observed in the experiment with beans about the physical attributes of technosol (Table S3).

The use of pelleting as physical conditioning of technosol had a significant effect ($p < 0.05$) on a few response variables. Of these, only macro- and microporosity, RDW, and TDW were significant differences in the three experiments. In addition, for most of the variables, in which the pelleting factor had a significant effect, there was also a significant interaction between the factors. The exceptions were total pore volume (VTPd) in the experiment with brachiaria, macro-, and microporosity, in the experiments with eucalyptus and beans, and accumulated S in the aerial part in the experiment with beans (Tables S2 and S3).

### 3.1 Technosol Physical Attributes

Fertilization indirectly provided an increase of 19.7% in the VTPd of technosol cultivated with brachiaria (Fig. 2) and 5.5% with eucalyptus (Table S4). However, in treatments with fertilization and the experiment with brachiaria, pelleting reduced the VTPd by up to 6.4% (Fig. 2). In addition, fertilization provided reductions of 12.8% and 7.2% in the degree of compaction (GC) of technosol cultivated with brachiaria and eucalyptus, respectively, regardless of pelleting (Table S4).

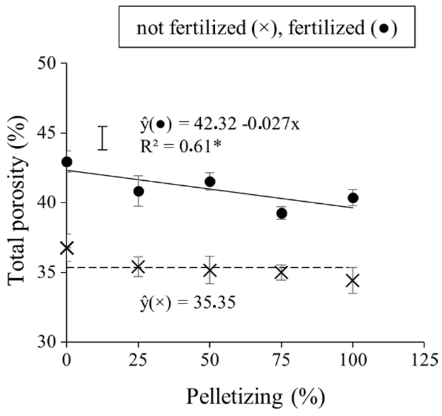


**Fig. 2** Total pore volume (VTPd) of technosol cultivated with brachiaria under pelleting and fertilization interaction ($n = 5$). Bars represent the standard error of means and isolated bars represent the margin of error defined by the confidence interval of the experiment. Models followed by * or ** are significant at the 5 and 1% error probability level, respectively, by the *F* test, and have non-significant regression deviation

Pelleting increased the macroporosity and reduced the microporosity of the technosol. In the fertilized treatments and in the experiments with brachiaria and eucalyptus, the increase in macroporosity was up to 32% and 53%, respectively. In treatments without fertilization and in experiments with brachiaria and eucalyptus, this increase was up to 85% and 75%, respectively. In the experiment with beans, regardless of fertilization, the increase in macroporosity was 89.5% (Fig. 3). Regarding microporosity and in the experiment with brachiaria, the reduction was 14.3% in the fertilized treatments and 25.8% in the treatments without fertilization, while in the experiments with eucalyptus and beans, the reduction, regardless of fertilization, was 21.5% and 23.5%, respectively (Fig. 3).

### 3.2 Technosol pH

In experiments with brachiaria and eucalyptus, fertilization reduced technosol pH by 8.4% and 14.6%, respectively (Table S4). In the experiment with beans, this reduction was 14%, among treatments without pelleting. Between pelleting levels and fertilization, the trend was a reduction in pH values with increasing levels of technosol pelleting. There was a reduction in the pH values between the levels of pelleting and without fertilization, with 7.36 being the lowest pH value observed, referring to the treatment without fertilization and with 50% of pelletized technosol (Fig. 4).

### 3.3 Plant Growth and Development

Fertilization promoted a significant increase in all variables related to plant development. SDW increased by 1057% and 630% in experiments with brachiaria and eucalyptus, respectively (Table S4 and Fig. 5). In the experiment with eucalyptus, leaf dry mass increased by 571% as a function of fertilization (Table S4).

In the experiment with common beans and as a function of fertilization, an increase of 502% in SDW was observed, considering treatments without pelleting (Figs. 5 and 6). As the pelleting levels increased, in treatments with fertilization, there was a reduction in bean SDW, resulting in up to 38.1% reduction

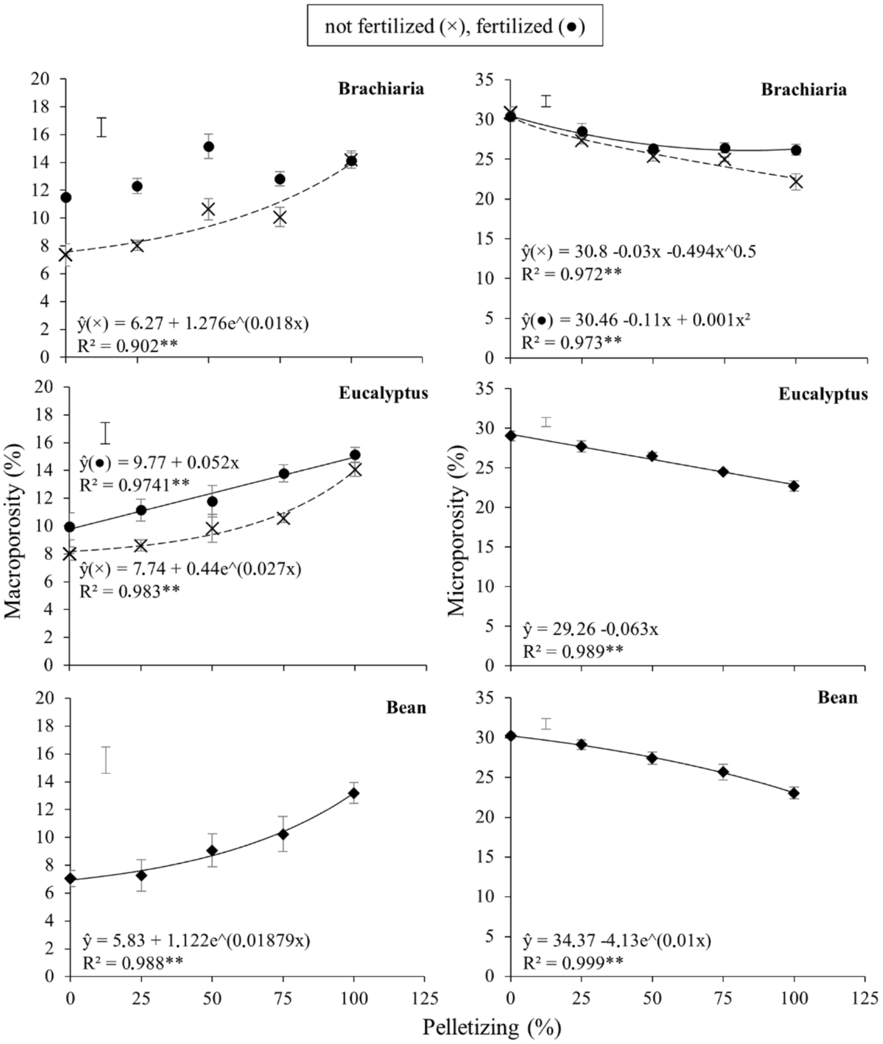


**Fig. 3** Macro- and microporosity of technosol cultivated with brachiaria, eucalyptus, and common bean under the interaction of pelleting and fertilization ($n=5$). Bars represent the standard error of means and isolated bars represent the margin of error defined by the confidence interval of the experiment. Models followed by * or ** are significant at the 5 and 1% error probability level, respectively, by the *F* test, and have non-significant regression deviation

in this variable. In treatments without fertilization, regardless of the level of pelleting, the SDW was 0.96 g. Similarly, the dry mass of grains also tended to decrease due to the increase in pelleting levels, in the treatments with fertilization in the experiment with beans; however, the adjusted model indicates the level of 17.63% of pelleting for higher grain mass, equivalent to 2.56 g, 2.48% higher than the treatment with fertilization and without pelleting. In treatments without fertilization, the value was 0.3 g for this variable, regardless of the level of pelleting (Fig. 6).

In the experiment with eucalyptus and on the variables plant height, stem diameter, and stem dry mass, there was an increase of 39.2%, 60.4%, and 546.6%, respectively, because of fertilization (Fig. 7). Pelleting did not have a significant effect on treatments without fertilization; however, it potentiates the effect of fertilization with increases of up to 29.3%, 22.7%, and 54.3%, respectively, on plant height, stem diameter, and stem dry mass. In the fertilized treatments, the highest values, predicted by the models, and their respective pelleting levels are 38.33 cm and 60.91%; 5.66 mm and 30.97%; and 3.5 g and 71.21%, for plant height, stem diameter, and stem dry mass, respectively (Fig. 7).

Like SDW, RDW and, consequently, TDW increased significantly as a function of fertilization (Fig. 8). Regarding RDW, this increase was 750.3%, 121.4%, and 436.5% in the experiments with brachiaria, eucalyptus, and beans, respectively. Pelleting, however, reduces this effect by up to 23.3% and 60.8% in experiments with brachiaria

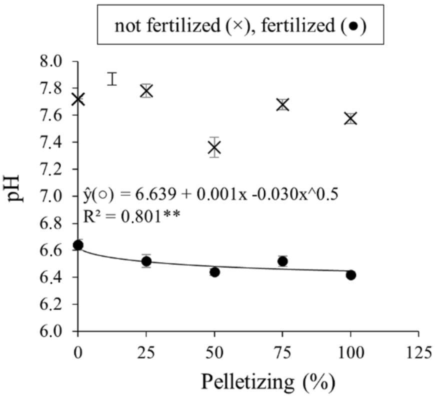


**Fig. 4** Technosol pH cultivated with common beans and under pelleting and fertilization interaction ($n=5$). Bars represent the standard error of means and isolated bars represent the margin of error defined by the confidence interval of the experiment. Models followed by * or ** are significant at the 5 and 1% error probability level, respectively, by the *F* test, and have non-significant regression deviation

and beans, respectively (Fig. 8). Similarly, this also occurred on the TDW variable, in which fertilization promoted increases of 890%, 342%, and 405% in the experiments with brachiaria, eucalyptus, and beans, respectively, while pelleting reduces this effect by up to 9.03% and 50%, in the experiments with brachiaria and beans, respectively. This reduction in the TDW variable caused by pelleting still occurs in the treatments without fertilization in the bean experiment, reaching a 63% reduction. Only in the experiment with eucalyptus was it observed that pelleting increased RDW and TDW in fertilized treatments, with increases of up to 67.7% and 46.1%, respectively (Fig. 8).

### 3.4 Accumulation of Elements in the Plants

Regarding the accumulation of elements in the shoot, fertilization promoted an increase in all elements, including those that were not supplied via fertilization, such as Fe and Mn (Table S4). In addition, the accumulated amount depended on pelleting, in the eucalyptus experiment for most nutrients, on Zn and Ba, in the brachiaria experiment, and P and S in the bean experiment (Tables S1, S2, and S4).

Pelleting caused effects with distinct trends in the accumulation of some nutrients and metals by plants. In cases where this effect was significant, it occurred on treatments with fertilization. The exception was the accumulation of Zn in the aboveground part of brachiaria, in which the increase in pelleting levels also increased the amount of accumulated Zn by up to 110% in treatments without fertilization (Fig. 9).

In treatments with fertilization, pelleting, when significant, had a positive effect on most of the variables referring to the accumulated amount of nutrients and metals in the shoot. For the accumulated amount of Ba, in the experiment with brachiaria, an increase of up to 29% in the accumulated amount is estimated, due to a pelleting level of 18.51% (Fig. 10). For the same plant and at the 100% pelleting level, the amount of accumulated Zn was 122% higher than in technosol without pelleting (Fig. 10).

The accumulated amount of all macronutrients analyzed was increased due to pelleting, in treatments with fertilization, and in the experiment with

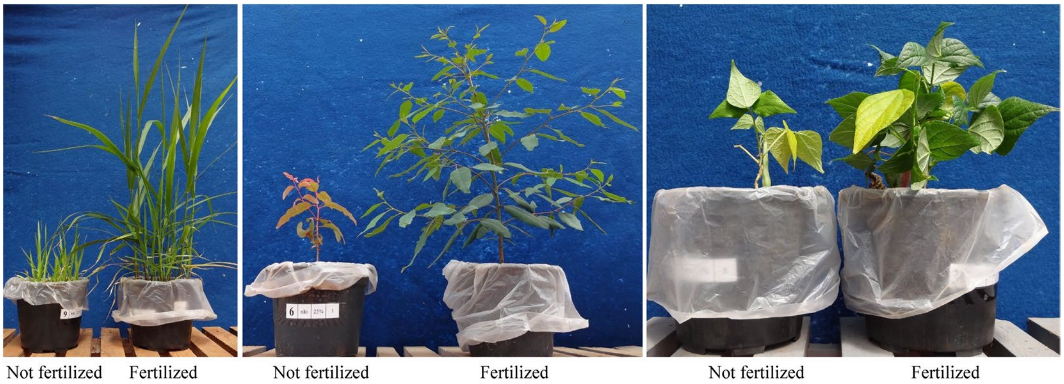


**Fig. 5** Visual aspect of brachiaria, eucalyptus, and common bean plants cultivated in technosol under pelleting and fertilization interaction

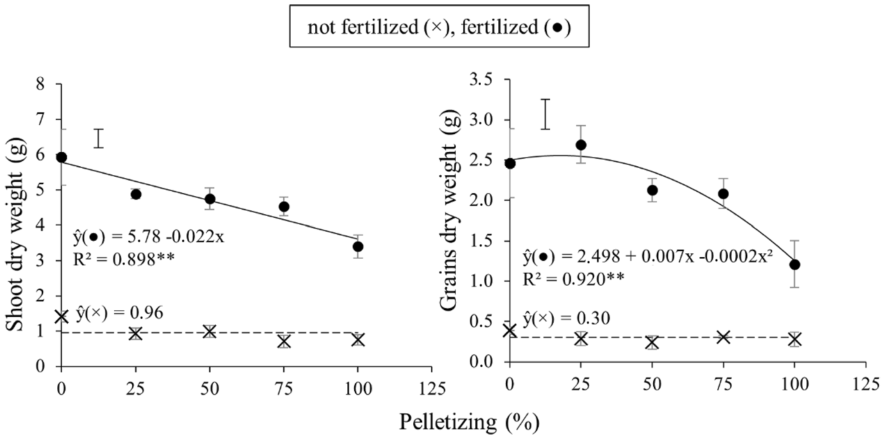


**Fig. 6** Shoot dry mass (SDW) and grain dry mass (GDW) of common bean cultivated in technosol under pelleting and fertilization interaction ($n=5$). Bars represent the standard error of means and isolated bars represent the margin of error defined by the confidence interval of the experiment. Models followed by * or ** are significant at the 5 and 1% error probability level, respectively, by the *F* test, and have non-significant regression deviation

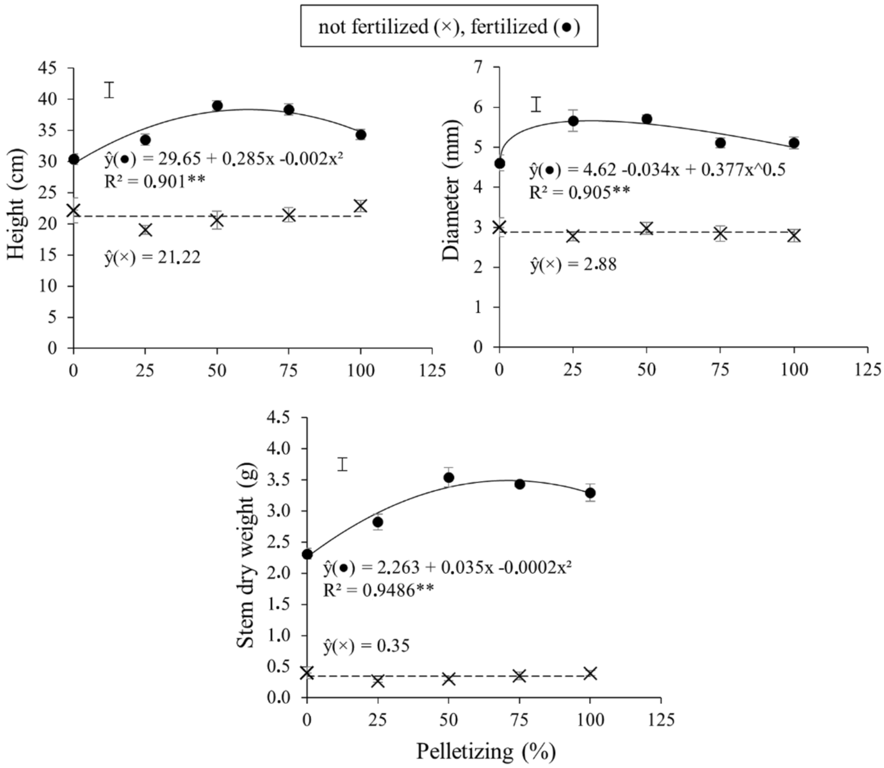


**Fig. 7** Plant height, diameter, and dry mass of eucalyptus stem grown in technosol under pelleting and fertilization interaction ($n=5$). Bars represent the standard error of means and isolated bars represent the margin of error defined by the confidence interval of the experiment. Models followed by * or ** are significant at the 5 and 1% error probability level, respectively, by the *F* test, and have non-significant regression deviation

eucalyptus. The increases and corresponding macronutrients, in parentheses, were: 52.1% (P), 16.4% (K), 56.1% (Ca), 50.1% (Mg), and 41.6% (S) (Fig. 11). Of the micronutrients, only Fe and Mn showed significant increases in the accumulated amount, depending on the pelleting in the treatments. These increases were up to 60.8% and 94.6%, respectively (Fig. 11). In the bean experiment, however, pelleting reduces the accumulated amount of macronutrients P and S by up to 61.7% and 45.4%, respectively (Fig. 12).

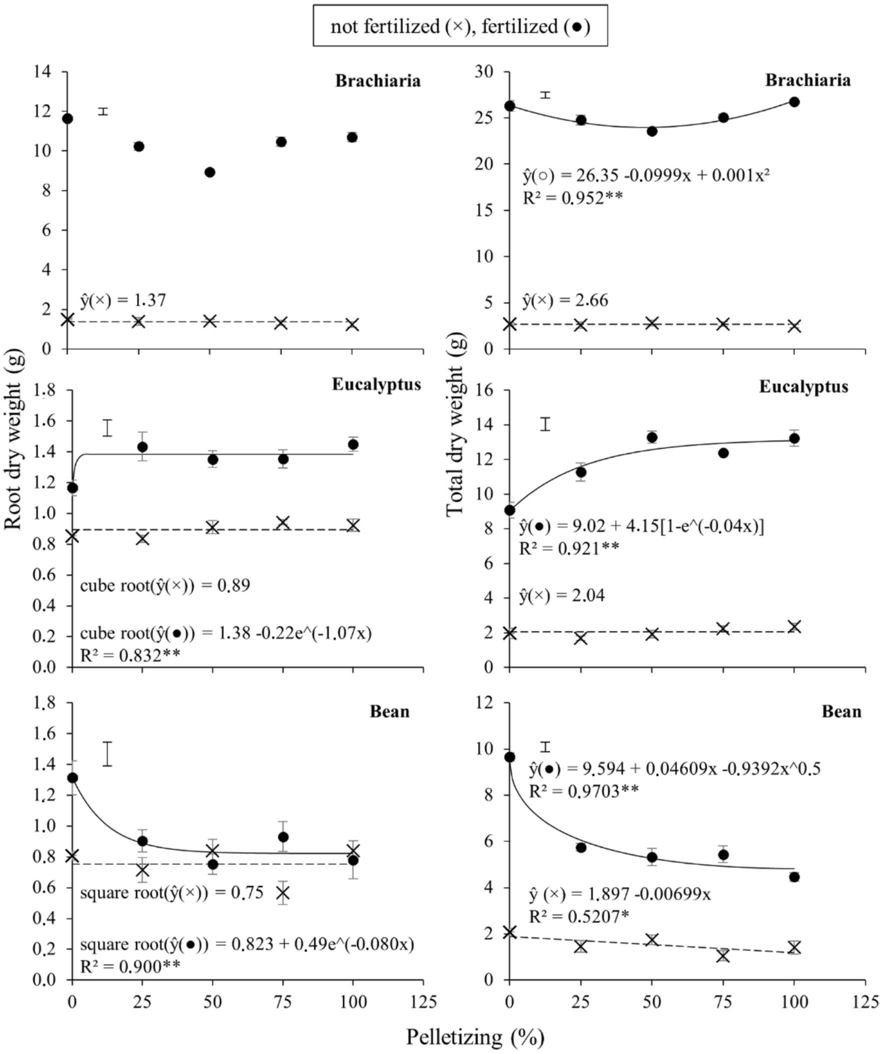


**Fig. 8** Root dry mass (RDW) and total dry mass (TDW) of brachiaria, eucalyptus, and common bean cultivated in technosol under the interaction of pelleting and fertilization ($n = 5$). Bars represent the standard error of means and isolated bars represent the margin of error defined by the confidence interval of the experiment. Models followed by * or ** are significant at the 5 and 1% error probability level, respectively, by the *F* test, and have non-significant regression deviation

### 3.5 Multivariate Analysis

PCA explained 93% of the data variation in the brachiaria experiment, 90% in the eucalyptus experiment, and 77% in the bean experiment (Fig. 13). In all experiments, there was a clear separation of treatments with and without fertilization, which indicates that this factor was responsible for the greatest magnitude of variation in the experiments. We observed that treatments without fertilization had the highest pH and GC values (Fig. 13) and that these variables correlated negatively with variables related to plant growth and development and technosol porosity. Corroborating these results, we observed that the degree of compaction correlated positively with treatments without fertilization and with the lowest levels of pelleting (Fig. 13). On the other hand, macroporosity was positively related to the fertilized treatments and the highest levels of pelleting. Total porosity was also correlated with fertilization and pelleting (Fig. 13).

## 4 Discussion

Pelleting modifies the arrangement of the technosol pores, providing greater macroporosity and lower microporosity (Fig. 3). The plants under study are completely different in the root system and physiology; therefore, they also respond in different ways to changes in pore distribution. This is evident from

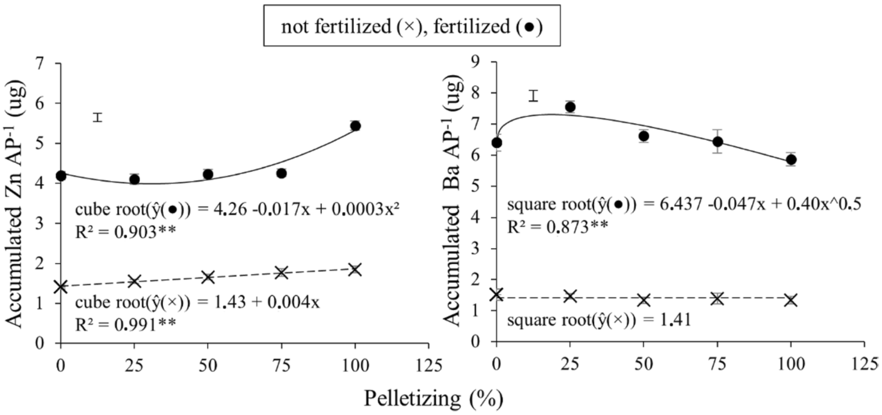


**Fig. 9** Zn and Ba content in brachiaria aerial part, cultivated in technosol under pelleting and fertilization interaction ($n=5$). Bars represent the standard error of means and isolated bars represent the margin of error defined by the confidence interval of the experiment. Models followed by * or ** are significant at the 5 and 1% error probability level, respectively, by the *F* test, and have non-significant regression deviation

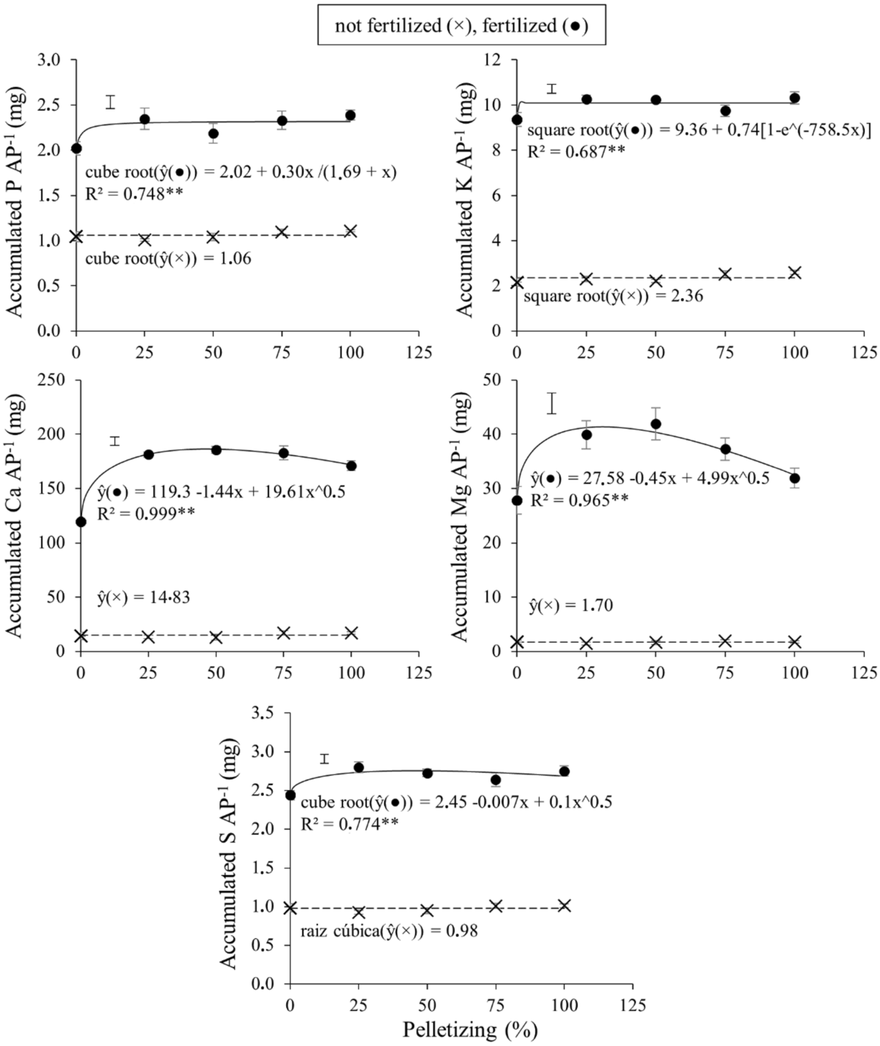
the effect of pelleting on the RDW of the plants, with a reduction in this variable in brachiaria and bean plants, the intensity of this effect being 2.61 times greater in beans than that in brachiaria, and, on the other hand, an increase in RDW in eucalyptus, compared with treatments with fertilization (Fig. 8). Since eucalyptus roots have a larger caliber, even if there is an increase in macroporosity in the technosol, and root contact is lower in this type of root system than that in bean and brachiaria. This contact is fundamental mainly to reduce the dryness of the roots and promote root growth and, consequently, the aerial part of the plants.

On the other hand, the physical attribute that most positively correlated with plant production was total porosity (Fig. 13). The PCA shows the trend that the highest values in the variables related to plant growth were influenced by the highest technosol porosity and nutrient supply, regardless of the plant used (Fig. 13). This result indicates that the improvement in porosity associated with the increase in nutrient availability is favorable for plant growth in technosol. In this way, it is evident that the induction of root system growth l is an important method to physically condition technosol.

Our experiment has the limitation of having been developed in a vase. In this experimental condition, the roots of the plants are strongly restricted to the reduced space of the vase, which can, consequently, give us different answers from an in situ evaluation. In situ experiments could present other answers, with perhaps greater effectiveness of pelleting to improve the root growth environment. However, this practice of pelletizing tailings would not be an alternative for areas impacted by the deposition of tailings from the Fundão dam failure, as it would be an expensive practice to be used in these areas. The most viable alternative for these areas is revegetation, with ecological restoration taking place with the process of returning ecosystem services. Pelleting could, however, be used in other situations, such as de-characterizing mining tailings dams. Considering the large number of dams in the State of Minas Gerais (Guerra et al., 2023), and the destination of this tailing, the rehabilitation of dam areas requires the application of many methods that may favor the rapid establishment of revegetation; therefore, pelletizing could be feasibly employed in these areas.

Fertilization promoted improvements in the root environment for the growth of the three plant species studied. Corroborating with this, Andrade et al. (2018), Esteves et al. (2020a), Esteves et al. (2020b), and Zago et al. (2019) also show that organic and/or mineral fertilization improve the growth and development of monocots and eudicots cultivated in technosol. This plant response to fertilization is related to the fact that technosol has a silty-sandy texture, low CEC, and low nutrient availability, so fertilization can be a factor for the initial survival of plants that grow on iron mining tailings. Technosol is almost

**Fig. 10** Macronutrient content (P, K, Ca, Mg, and S) in the aerial part (PA) of eucalyptus cultivated in technosol under pelleting and fertilization interaction ($n=5$). Bars represent the standard error of means and isolated bars represent the margin of error defined by the confidence interval of the experiment. Models followed by * or ** are significant at the 5 and 1% error probability level, respectively, by the *F* test, and have non-significant regression deviation



like a hydroponic system, meaning the added soluble fertilizers are available in the soil solution and easily accessible to plant roots. However, because the technosol has a low retention capacity, these same fertilizers can cause problems when they leach and/or percolate into the environment.

The granulometry of the alluvial sediments of the Rio Doce is essentially sandy, even after the accident with a high percentage of coarse sand, but with a relative increase in fine particles, mainly fine sand, silt, and clay, in the river bottom sediment (Duarte et al., 2021), whereas the fluvial sediments deposited on riverbanks are silt and sand in size. Sandy sediments are a disadvantage for the accumulation of organic carbon and decrease the CEC, while the greater presence of clay provides both the accumulation of carbon and the retention of elements (Gao et al., 2014; Liang et al., 2006). Clay particles in the soil, by generating surface charges and having smaller sizes, provide physical–chemical protection to carbon in the soil jointly to a greater capacity to retain ions by electrostatic forces of attraction than larger particles. Considering that the mineralogical composition of the tailings is predominantly quartz and iron oxides (Almeida et al., 2018; Couto et al., 2021), distributed in silt and sand size, they have little capacity to retain ions and carbon in the soil.

The effect of fertilization is due not only to the supply of nutrients to the plants but also to the acidification of technosol, in which the pH was negatively correlated with the variables that indicate plant growth and fertilization (Fig. 13). Acidification is a natural

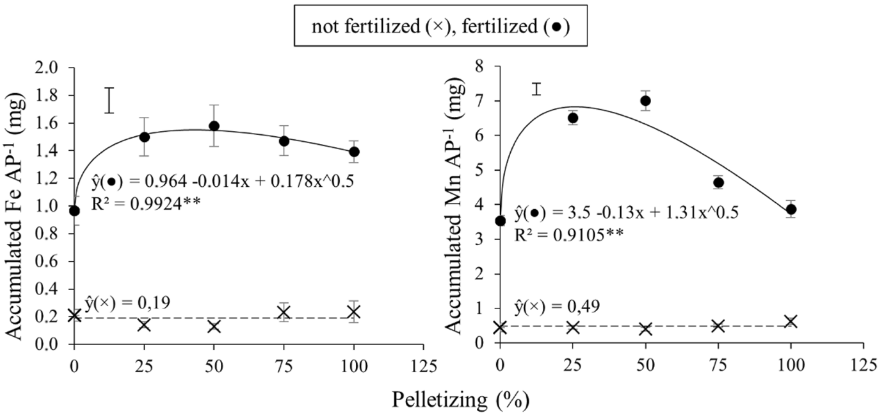


**Fig. 11** Fe and Mn content in the aerial part (PA) of eucalyptus cultivated in technosol under pelleting and fertilization interaction ($n=5$). Bars represent the standard error of means and isolated bars represent the margin of error defined by the confidence interval of the experiment. Models followed by * or ** are significant at the 5 and 1% error probability level, respectively, by the *F* test, and have non-significant regression deviation

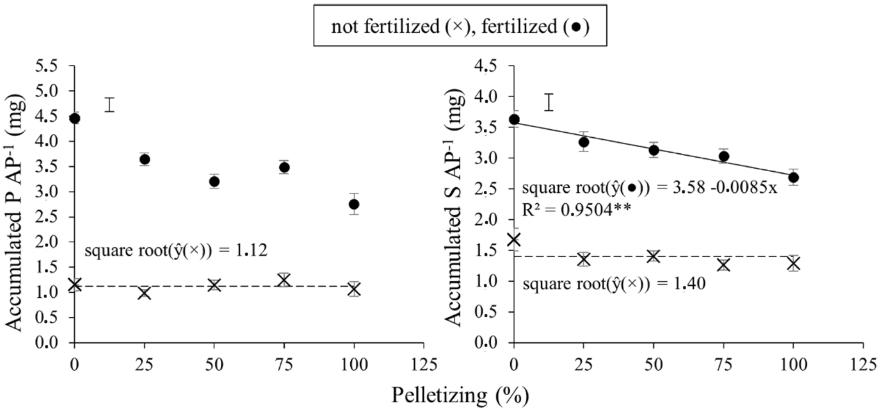


**Fig. 12** P and S content in the aerial part (PA) of common bean, cultivated in technosol under pelleting and fertilization interaction ($n=5$). Bars represent the standard error of means and isolated bars represent the margin of error defined by the confidence interval of the experiment. Models followed by * or ** are significant at the 5 and 1% error probability level, respectively, by the *F* test, and have non-significant regression deviation

soil process, related to several chemical and biochemical reactions, promoted by the action of roots, microorganisms, leaching, precipitation, and anthropic activities, among others, which can lead to deprotonation of pH-dependent loads and release of H + ions in the soil solution (Geng et al., 2020; Houben et al., 2013; Zhang et al., 2019). The interaction between pelleting and fertilization reduced the pH of the technosol in the three experiments (Fig. 4 and Table S4). However, a greater effect was noticed in the reduction of pH in the fertilized treatments, indicating the greater effect of fertilization in this aspect. The addition of ammoniacal nitrogen sources such as ammonium nitrate and sulfate, applied via nutrient solution, to supply the N and S demands, may have been responsible for this decrease in pH. These sources release $NH_4^+$ in solution, which can undergo a nitrification process and release $H^+$ ions, thus reducing the pH (Moreira & Siqueira, 2006).

The pH value of technosol in treatments without fertilization was approximately 7.7 (Table S4; Fig. 4). This high pH value can influence the availability of

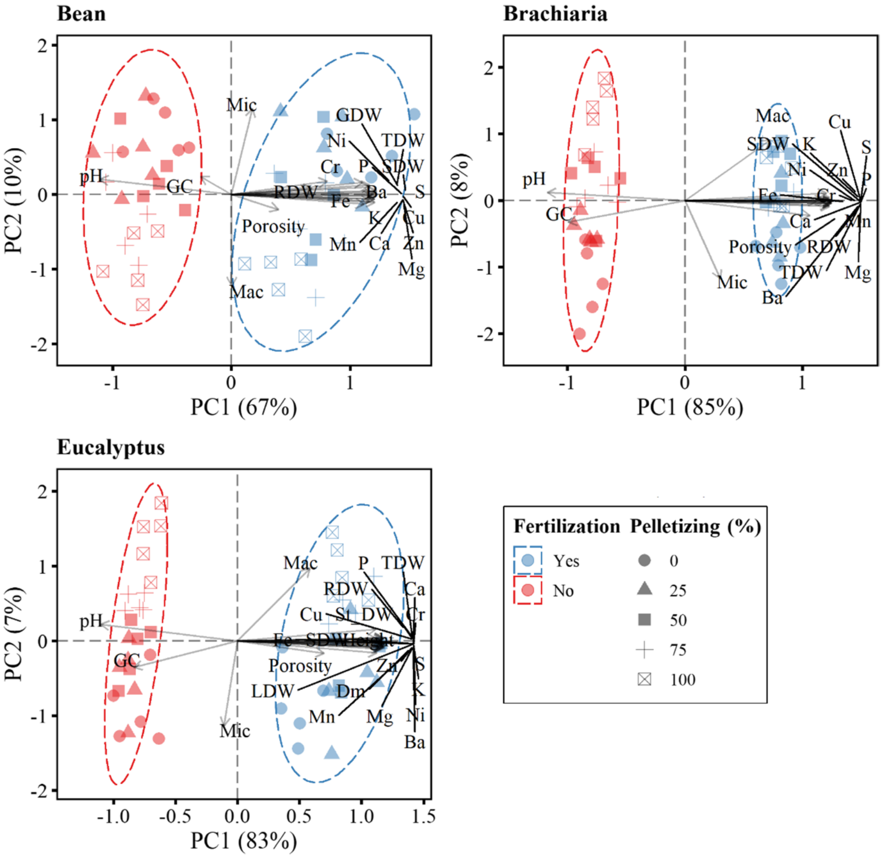


**Fig. 13** Principal component analysis (PC) involving the variables: accumulation of nutrients and metals in the shoot (P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, Zn, Ba, Cr, and Ni), dry mass of aerial part (SDW), root dry mass (RDW), total dry mass (TDW), grain dry mass (GDW), stem dry mass (St_DW), leaf dry mass (LDW), plant height (Height), stem diameter (Dm), pH, degree of compaction (GC), total pore volume (Porosity), macro (Mac), and microporosity (Mic), of plants cultivated in technosol under the interaction of pelleting and fertilization (*n* = 5)

nutrients in technosol, both due to the effect on the solubility of nutrients in solution and in the reactions that promote the availability of charges in Fe oxides, the main constituents of this substrate. In the experiments with brachiaria and eucalyptus, the pH value in the fertilized treatments and without pelleting was 7.02 and 6.61, respectively (Table S4), and with beans, 6.64 (Fig. 4). The addition of organic compounds released by plants has effects on the pH change in soils, caused by the complexation or adsorption of $H^+$ and $Al^{3+}$ ions by these compounds (Pavinato & Rosolem, 2008), in addition to the exchanges carried out by the plant during the absorption of nutrients. In addition to the acidification ratios as a function of cationic exchange in the solution, fertilization provided increases in plant growth (Figs. 5 , 8, and 13). With greater development, plants increase the exudation of organic compounds, which may have potentiated this decrease in technosol pH. Demonstrating that fertilization should be advocated in rehabilitation activities in areas impacted by iron mining tailings (Esteves et al., 2020a).

On the other hand, fertilization in technosol should be recommended with a certain moderation. This is because technosol does not have favorable characteristics for nutrient retention (Almeida et al., 2018). This limitation occurs both for the anionic forms, due to the high value of remaining phosphorus, and for the cationic forms, due to the low CEC. This fact can result in overestimated dosages of fertilizers, which can leach. This leached material may potentially contaminate watercourses, causing eutrophication. Contamination of watercourses can be aggravated by the low macroporosity and structure of the technosoil. Thus, less water infiltrates and drains into the subsoil, causing surface runoff and laminar erosion, carrying technosoil particles, organic matter, and nutrients to the riverbeds. The worsening of this phenomenon can lead to the silting up of these beds and, consequently, cause a drastic reduction in river flow. Increases in water turbidity were observed in rivers affected by tailings deposition (Hatje et al., 2017), just as there were changes in the size of river bottom sediments

(Duarte et al., 2021). This is an indication that even after the stabilization of the tailings, this material is still very likely to erode and be easily carried away. Strengthening the adoption of management practices that, in addition to protecting the technosol, provide increases in soil organic matter may be the key factor for better aggregation of these mineral particles from the technosol, avoiding this process of particle entrainment by erodible forces.

## 5 Conclusion

The physical changes caused by pelletizing provide better technosol conditions for the growth and development of eucalyptus, in addition to enhancing the effect of fertilization on this plant. However, it restricts the growth of brachiaria and beans. Although the chemical and physical attributes are not adequate, the main limiting factor for plant growth in technosol is nutrient availability. With adequate fertilization, the plants had less difficulty developing in this substrate in vase conditions, which are more restricted conditions for the root system. The soil affected by the deposition of iron mining tailings presents chemical and physical attributes that are under restrictive conditions when considering it as a medium for plant growth. However, these conditions did not prevent the plants from thriving under adequate nutritional supply. Therefore, the limiting factor for plant growth in technosol is nutrient availability. It is important to note that the experiments were conducted under controlled environmental conditions aimed at promoting good plant development. However, this fact may mask several limitations related to the physical-hydric behavior of technosol. Therefore, research with field tests is necessary for the validation and recommendation of management methods employed.

It is expected that during the process of recovering areas degraded by tailing deposition, the deposition of organic matter will increase, contributing to the increase in nutrient cycling and making more nutrients available for plants, and increasing the carbon content in the soil and the aggregation of particles. The greater the process of aggregation, influenced by cementing power of the organic matter, the more it will favor porosity and the establishment of plants, reducing erosion and increasing the retention capacity of this material. However, there is a growing concern about the risk of erosion of the tailings and the leaching of fertilizers that may be added to revegetation processes carried out at the site. Therefore, attention should always be paid to monitoring these areas.

**Acknowledgements** We thank the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), the Conselho Nacional de Desenvolvimento Científico e Tecnologia (CNPq, 150500/2023-8), and the Fundação de Amparo a Pesquisa de Minas Gerais (FAPEMIG-APQ-01661-16) for the financial support and scholarships granted to the authors.

**Data Availability** The authors declare that data supporting the findings of this study are available within the article and its supplementary information files.

**Declarations**

**Conflict of Interest** The authors declare no competing interests.

## References

Almeida, C. A., Oliveira, A. F., Pacheco, A. A., Lopes, R. P., Neves, A. A., & Queiroz, M. E. L. R. (2018). Characterization and evaluation of sorption potential of the iron mine waste after Samarco dam disaster in Doce River basin e Brazil. *Chemosphere, 209*, 411–420. https://doi.org/10.1016/j.chemosphere.2018.06.071

Andrade, G. F., Paniz, F. P., Martins, J. R. A. C., Rocha, B. A., Lobato, A. K. S., Rodrigues, J. L., Cardoso-Gustavson, P., Masuda, H. P., & Batista, B. L. (2018). Agricultural use of Samarco's spilled mud assessed by rice cultivation: A promising residue use? *Chemosphere, 193*, 892–902. https://doi.org/10.1016/j.chemosphere.2017.11.099

Associação Brasileira de Normas Técnicas – ABNT. (1986). NBR 7182: Solo. Ensaio de compactação - ABNT. 1986. NBR 3. Rio de Janeiro. 11 p.

Batista, É. R., Carneiro, J. J., Pinto, F. A., Dos Santos, J. V., & Carneiro, M. A. C. (2020). Environmental drivers of shifts on microbial traits in sites disturbed by a large-scale tailing dam collapse. *Science of The Total Environment, 738*, 139453. https://doi.org/10.1016/j.scitotenv.2020.139453

Carvalho, A. M. X., Mendes, F. Q., Mendes, F. Q., & Tavares, L. F. (2020). SPEED stat: A free, intuitive, and minimalist spreadsheet program for statistical analyses of experiments. *Crop Breending and Applied Biotechnology, 20*(3), e327420312. https://doi.org/10.1590/1984-70332020v20n3s46

Cordeiro, M. C., Garcia, G. D., Rocha, A. M., Tschoeke, D. A., Campeão, M. E., Appolinario, L. R., Soares, A. C., Leomil, L., Froes, A., Bahiense, L., Rezende, C. E., Almeida, M. G., Rangel, T. P., Oliveira, B. C. V., Almeida, D. Q. R., Thompson, M. C., Thompson, C. C., & Thompson, F. L. (2019). Insights on the freshwater microbiomes metabolic changes associated with the world's largest mining disaster. *Science of the Total Environment, 654*, 1209–1217. https://doi.org/10.1016/j.scitotenv.2018.11.112

Couto, F. R., Ferreira, A. M., Pontes, P. P., & Marques, A. R. (2021). Physical, chemical and microbiological characterization of the soils contaminated by iron ore tailing mud after Fundão Dam disaster in Brazil. *Applied Soil Ecology, 158*, 103811. https://doi.org/10.1016/j.apsoil.2020.103811

da Silva, A. P. V., Silva, A. O., Lima, F. R. D., Benedet, L., Franco, A. J., Souza, J. K., Ribeiro Júnior, A. C., Batista, E. R., Inda, A. V., Curi, N., Guilherme, L. R. G. G., & Carneiro, M. A. C. (2022). Potentially toxic elements in iron mine tailings: Effects of reducing soil pH on available concentrations of toxic elements. *Environmental Research, 215*, 114321. https://doi.org/10.1016/j.envres.2022.114321

Duarte, E. B., Neves, M. A., De Oliveira, F. B., Martins, M. E., De Oliveira, C. H. R., Burak, D. L., Orlando, M. T. D., & Rangel, C. V. G. T. (2021). Trace metals in Rio Doce sediments before and after the collapse of the Fundão iron ore tailing dam, Southeastern Brazil. *Chemosphere, 262*, 127879. https://doi.org/10.1016/j.chemosphere.2020.127879

Duiker, S. W., Rhoton, F. E., Torrent, J., Smeck, N. E., & Lal, R. (2003). Iron (hydr)oxide crystallinity effects on soil aggregation. *Soil Science Society of America Journal, 67*(2), 606–611. https://doi.org/10.2136/sssaj2003.6060

Esteves, G. F., Bressanin, L. A., De Souza, K. R. D., Da Silva, A. B., Mantovani, J. R., Marques, D. M., Magalhães, P. C., Pasqual, M., & De Souza, T. C. (2020a). Do tailings from the Mariana, MG (Brazil), disaster affect the initial development of millet, maize, and sorghum? *Environmental Science and Pollution Research, 27*, 38662–38673. https://doi.org/10.1007/s11356-020-10013-w

Esteves, G. F., Souza, K. R. D., Bressanin, L. A., Andrade, P. C. C., Veroneze Júnior, V., Reis, P. E., Silva, A. B., Mantovani, J. R., Magalhães, P. C., Pasqual, M., & Souza, T. C. (2020). Vermicompost improves maize, millet and sorghum growth in iron mine tailings. *Journal of Environmental Management, 264*, 110468. https://doi.org/10.1016/j.jenvman.2020.110468

Fernandes, G. W., Goulat, F. F., Ranieri, B. D., Coelho, M. S., Dales, K., Boesche, N., Bustamante, M., Carvalho, F. A., Carvalho, D. C., Dirzo, R., Fernandes, S., Galetti, J. R. P. M., Millian, V. E. G., Mielke, C., Ramirez, J. L., Neves, A., Rogass, C., Ribeiro, S. P., Scariot, A., & Soares-Filho, B. (2016). Deep into the mud: Ecological and socio-economic impacts of the dam breach in Mariana, Brazil. *Natureza & Conservação, 14*, 35–45. https://doi.org/10.1016/j.ncon.2016.10.003

Gao, G. L., Ding, G. D., Wu, B., Zhang, Y. Q., Qin, S. G., Zhao, Y. Y., Bao, Y. F., Liu, Y. D., Wan, L., & Deng, J. F. (2014). Fractal scaling of particle size distribution and relationships with topsoil properties affected by biological soil crusts. *PLoS One, 9*(e88559), 2014. https://doi.org/10.1371/journal.pone.0088559

Geng, H., Wang, F., Yan, C., Tian, Z., Chen, H., Zhou, B., Yuan, R., & Yao, J. (2020). Leaching behavior of metals from iron tailings under varying pH and low molecular-weight organic acids. *Journal of Hazardous Materials, 383*, 121136. https://doi.org/10.1016/j.jhazmat.2019.121136

Guerra, M. B. B., de Oliveira, C., de Carvalho, M. R., Silva, A. O., Alvarenga, I. F. S., Barbosa, M. V., Feitosa, M. M., Penido, E. S., Santos, J. V., Carneiro, M. A. C., Bundschuh, J., & Guilherme, L. R. G. (2023). Increased mobilization of geogenic arsenic by anthropogenic activities: The Brazilian experience in mining and agricultural areas. *Current Opinion in Environmental Science & Health, 33*, 100472. https://doi.org/10.1016/j.coesh.2023.100472

Hatje, V., Pedreira, R. M., Rezende, C. E., Schettini, C. A. F., Souza, G. C., Marin, D. C., & Hackspacher, P. C. (2017). The environmental impacts of one of the largest tailing dam failures worldwide. *Scientific Reports, 7*, 1–13. https://doi.org/10.1038/s41598-017-11143-x

Houben, D., Evrard, L., & Sonnet, P. (2013). Mobility, bioavailability and pH-dependent leaching of cadmium, zinc and lead in a contaminated soil amended with biochar. *Chemosphere, 92*, 1450–1457. https://doi.org/10.1016/j.chemosphere.2013.03.055

Jarque, C. M., & Bera, A. K. (1980). Efficient tests for normality, homoscedasticity and serial independence of regression residuals. *Economics Letters, 6*(255–259), 1980. https://doi.org/10.1016/0165-1765(80)90024-5

Kay, B. D. (1998). Soil structure and organic carbon: A review. In R. Lal, J. M. Kimble, R. F. Follett, & B. A. Stewart (Eds.), *Soil processes and the carbon cycle* (pp. 169–197). Boca Raton.

Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., O'neill, B., Skjemstad, J. O., Thies, J., Luizão, F. J., Petersen, J., & Neves, E. G. (2006). Black carbon increases cation exchange capacity in soils. *Soil Science Society of America Journal, 70*(1719), 1730. https://doi.org/10.2136/sssaj2005.0383

Malavolta, E. (1981). *Manual de Química Agrícola: Adubos e Adubações* (3rd ed., p. 596). Editora Agronômica Ceres: São Paulo SP.

Matos, L. P., Andrade, H. M., Marinato, C. S., Prado, I. G. O., Coelho, D. G., Montoya, S. G., Kasuya, M. C. M., & Oliveira, J. A. (2020). Limitations to use of *Cassia grandis* L. in the revegetation of the areas impacted with mining tailings from Fundão Dam. *Water, Air, & Soil Pollution, 231*, 1–9. https://doi.org/10.1007/s11270-020-04479-0

Meyer, K. (1980). *Pelletizing of iron ores* (p. 302). Springer-Verlag.

Moreira, F. M. S., & Siqueira, J. O. (2006). *Microbiologia e Bioquímica do Solo* (2nd ed., p. 729p). Lavras: Universidade Federal de Lavras.

Oksanen, J. et al. (2019). Vegan: Community Ecology Package. https://cran.r-project.org/package=vegan

Pavinato, P. S., & Rosolem, C. A. (2008). Disponibilidade de nutrientes no solo: Decomposição e liberação de compostos orgânicos de resíduos vegetais. *Revista Brasileira De Ciência Do Solo, 32*, 911–920. https://doi.org/10.1590/S0100-06832008000300001

R Core Team. (2019). R: *A language and environment for statistical computing*. R Found.

Rosner, B. (1983). Percentage points for a generalized ESD many-outlier procedure. *Technometrics, 25*, 165–172. https://doi.org/10.2307/1268549

Santamarina, J. C., Torres-Cruz, L. A., & Bachus, R. C. (2019). Why coal ash and tailings dam disasters occur. *Science, 364*(6440), 526–528.

Scotti, M. R., Gomes, A. R., Lacerda, T. L., Ávila, S. S., Silva, S. L. L., Antão, A., Santos, A. G. P., Medeiros, M. B., Alvarenga, S., Santos, C. H., & Rigobelo, E. C. (2020). Remediation of a riparian site in the Brazilian Atlantic Forest reached by contaminated tailings from the collapsed Fundão dam with native woody species. *Integrated Environmental Assessment and Management, 16*, 669–675. https://doi.org/10.1002/ieam.4272

Silva, A. C., Cavalcante, L. C. D., Fabris, J. D., Júnior, R. F., Barral, U. M., Farnezi, M. M. M., Viana, A. J. S., Ardisson, J. D., Fernandes-Outon, L. E., Lara, L. R. S., Stumpf, H. O., Barbosa, J. B. S., & Silva, L. C. (2016). Chemical, mineralogical and physical characteristics of a material accumulated on the river margin from mud flowing from the collapse of the iron ore tailings dam in Bento Rodrigues, Minas Gerais, Brazil. *Revista Espinhaço, 5*, 44–53. https://doi.org/10.5281/zenodo.3957942

Silva, A. O., Guimarães, A. A., Lopez, B. D. O., Zanchi, C. S., Vega, C. F. P., Batista, E. R., Moreira, F. M. S., Souza, F. R. C., Pinto, F. A., Santos, J. V., Carneiro, J. J., Siqueira, J. O., Kemmelmeier, K., Guilherme, L. R. G., Rufini, M., Dias Junior, M. S., Aragão, O. O. S., Borges, P. H. C., Oliveira-Longatti, S. M., & Carneiro, M. A. C. (2021). Chemical, physical, and biological attributes in soils affected by deposition of iron ore tailings from the Fundão Dam failure. *Environmental Monitoring and Assessment, 193*, 462. https://doi.org/10.1007/s10661-021-09234-4

Teixeira, P. C., Donagemma, G. K., Wenceslau, A. F., & Teixeira, G. (2017). *Manual de Métodos de Análise de Solo* (3rd ed., p. 573p). Embrapa Solos.

U.S. Environmental Protection Agency – USEPA. (2007). *Method 3051A (SW-846): Microwave assisted acid digestion of sediments, sludges, and oils, revision* (1st ed.). USEPA.

Vergilio, C. S., Lacerda, D., Oliveira, B. C. V., Sartori, E., Campos, G. M., Pereira, A. L. S., Aguiar, D. B., Souza, T. S., Almeida, M. G., Thompson, F., & Rezende, C. E. (2020). Metal concentrations and biological effects from one of the largest mining disasters in the world (Brumadinho, Minas Gerais, Brazil). *Scientific Reports, 10*, 1–12. https://doi.org/10.1038/s41598-020-62700-w

Zago, V. C. P., das Dores, N. C., & Watts, B. A. (2019). Strategy for phytomanagement in an area affected by iron ore dam rupture: A study case in Minas Gerais State Brazil. *Environmental Pollution, 249*(1029), 1037. https://doi.org/10.1016/j.envpol.2019.03.060

Zhang, P., Sun, L., Wang, H., Cui, J., & Hao, J. (2019). Surfactant-assistant atmospheric acid leaching of laterite ore for the improvement of leaching efficiency of nickel and cobalt. *Journal of Cleaner Production, 228*, 1–7. https://doi.org/10.1016/j.jclepro.2019.04.305