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Soil conditioners improve the environment for grass growth in iron mining tailings of the Fundão dam failure

Condicionadores de solo melhoram o ambiente para o crescimento de gramínea em rejeitos de mineração de ferro

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ABSTRACT

Areas impacted by the deposition of iron mining tailings present physical and chemical characteristics that can hinder root growth, and applying soil conditioners can help alleviate these limitations. The objective was to evaluate the effect of soil conditioners in improving the environment for the growth of grass in soil affected by iron mining tailing. Four different experiments were conducted testing conditioner proportions (0, 5, 10, 25, and 50% v/v), in a completely randomized design with four replications, using *Cynodon* spp. The conditioners were sand, vermiculite, sawdust, and organic compost. Bulk density, macro- and microporosity, total pore volume (VTP), pH, organic matter content (OM), cation exchange capacity (CEC), and dry mass of the aboveground, root, and total plant were evaluated. There were improvements in porosity and a reduction in density with the application of vermiculite, sawdust, and organic compost; however, sand decreased the VTP. The pH was reduced with sawdust and increased with compost. Sawdust and compost increased OM. CEC increased with vermiculite and compost. The sand and vermiculite conditioners promoted the greatest growth of *Cynodon* spp., with emphasis on vermiculite, which provided the greatest increases in plant biomass production. The soil conditioners, overall, proved effective in improving porosity conditions, reducing density, increasing OM, and promoting plant growth, this makes this technology efficient for application in tailings. Due to its notable effect on increasing biomass and improving the environment for grass growth, vermiculite can be recommended for rehabilitation environments impacted by iron mining tailings or for post-mining revegetation.

Index terms: Technosol; vermiculite; soil rehabilitation; environmental impact.

RESUMO

Áreas impactadas pela deposição de rejeito de mineração de ferro possuem características físicas e químicas que podem dificultar o crescimento das raízes, e a aplicação de condicionadores pode ajudar a aliviar essas limitações. O objetivo foi avaliar o efeito de condicionadores de solo na melhoria do ambiente para o crescimento de gramínea em solo afetado por rejeitos de mineração de ferro. Foram realizados quatro experimentos testando proporções de condicionador (0, 5, 10, 25 e 50% v/v), em delineamento inteiramente casualizado com quatro repetições, utilizando *Cynodon* spp. Os condicionadores foram areia, vermiculita, serragem e composto orgânico. Foram avaliados densidade aparente, macro- e microporosidade, volume total de poros (VTP), pH, matéria orgânica (OM), capacidade de troca de cátions (CEC) e massa seca da parte aérea, raízes e total. Houve melhorias na porosidade e redução na densidade com a aplicação de vermiculita, serragem e composto; no entanto, a areia diminuiu o VTP. O pH foi reduzido com serragem e aumentou com composto. A serragem e o composto aumentaram a OM. A CEC aumentou com vermiculita e composto. Os condicionadores de solo, de modo geral, mostraram-se eficazes na melhoria das condições de porosidade, redução da densidade, aumento de OM e promoção do crescimento das plantas, o que torna esta tecnologia eficiente para aplicação em rejeitos. Devido ao seu notável efeito no aumento da biomassa e na melhoria do ambiente para o crescimento de gramínea, a vermiculita pode ser recomendada para ambientes de reabilitação impactados por rejeitos de mineração de ferro ou revegetação pós-mineração.

Termos para indexação: Tecnosolo; vermiculita; reabilitação de solo; impacto ambiental.

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Introduction

Mining activities bring about various socio-environmental changes with direct and/or indirect impacts, both in areas near mining facilities and in surrounding regions. Recently, in Brazil, there have been two major ruptures of iron ore mining tailings dam, sparking discussions about the risks posed by this mining model, as it generates large quantities of liquid waste stored in tailings containment dams (Vergilio et al., 2020; Santamarina, Torres-Cruz, & Bachus, 2019).

In November 2015, there was a rupture of the Fundão dam, located in the Alegria Mine complex in Mariana (MG, Brazil). This incident released over 50 million cubic meters of iron ore tailings into the Doce River basin, directly impacting water bodies and riparian zones along a stretch of over 600 km, reaching the Atlantic Ocean. More than 36 municipalities were affected, making it one of the largest mining-related environmental disasters in the world (Escobar, 2015; Hatje et al., 2017; Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis - IBAMA, 2016; Omachi et al., 2018; Segura et al., 2016). In January 2019, just over three years after the tragic incident, the BI dam at the Córrego do Feijão Mine in Brumadinho (MG, Brazil) also ruptured. This event released approximately 12 million cubic meters of iron ore mining tailings into the environment, but with significant and immediate consequences due to the substantial loss of human lives (Vergilio et al., 2020).

A significant portion of the tailings from the Fundão dam breach was carried by watercourses throughout the basin and deposited on the soils near the banks of the Doce River and its tributaries. This resulted in alterations to the natural attributes of these soils. The thick layers of tailings deposited along the riverbanks created a new environment, a mixture of soil and tailings, referred to as technosol due to its technogenic nature (presence of artificial, technical material deposited in the soil originating from human activities, IUSS Working Group WRB. 2022). This technosol exhibits physical, chemical, and biological conditions distinct from the local soil (Borges et al., 2023; Hatje et al., 2017; Páez et al., 2024; Silva et al., 2021), a higher pH, low cation exchange capacity (CEC), low organic matter content, silty-sandy texture, and is generally unstructured or poorly structured. The predominant minerals in this environment include quartz and hematite (Almeida et al., 2018; Andrade et al., 2018; Da Silva, A., et al., 2022a; Silva et al., 2021). These characteristics can limit plant growth due to low nutrient availability, unfavorable biochemical conditions, as well as not providing good physical-hydraulic behavior. This results in compromised groundwater recharge, sedimentation, and eutrophication of water resources, among other environmental problems (Almeida et al., 2018; Batista et al., 2022; Scotti et al., 2020; Segura et al., 2016).

The recovery of areas affected by mining tailings involves various techniques, but those based on revegetation are considered the most cost-effective and efficient alternatives for the stabilization and regeneration of these environments. The use of cultivated fast-growing species, such as grasses, has been considered for revegetation processes due to their rapid growth and substantial biomass production (Vamerali, Bandiera, & Mosca 2010; Zago, das Dores, & Watts, 2019; Zanchi et al., 2021). However, plant growth in tailings requires morphological, physiological, and biochemical adaptations to overcome the limitations imposed by the physicochemical characteristics of this material (Chu et al., 2018; Da Silva, R. et al., 2022; Matos et al., 2020). These physical limitations imposed by the tailings are associated with a decrease in macroporosity due to the high density of this material, resulting in physical resistance to roots. This leads to swelling of the tissues in the root meristem, reducing aeration and water infiltration. Consequently, this can lead to increased surface runoff and erosive processes (Baudson et al., 2024; Borges et al., 2023; Páez et al., 2024; Silva et al., 2021; Zanchi et al., 2022). Additionally, it may result in difficulties for the root growth of plants in such an environment (Matos et al., 2020). Changes in management practices, such as soil fertilization, application of organic matter, and planting species with a robust root system, are among the alternatives to minimize the effects of tailings impact on the soil (Cruz et al., 2020; Scotti et al., 2020; Zago, das Dores, & Watts 2019).

Applying soil conditioners such as vermiculite, sawdust, and organic compounds, in combination with fast-growing plants, can facilitate soil revegetation by improving its physical, chemical, and biological properties. The beneficial effects include increased porosity, water infiltration, and retention, promoting rooting, and reducing physical limitations to plant growth. Additionally, there is an increase in nutrient availability, a return of biological activities in the soil, stimulation of decomposition, an increase in organic matter, and the encouragement of root symbioses (Prado et al., 2019; Scotti et al., 2020). Esteves et al. (2020) observed that the application of vermicompost to iron mining tailings favored increases in the aboveground and root biomass, as well as enhancements in the length, volume, surface area, and root diameter, and in the absorption of macro and micronutrients for *Zea mays*, *Pennisetum glaucum*, and *Sorghum bicolor*. The use of organic compost also promoted the development of grasses (*Chrysopogon zizanioides*, *Cymbopogon citratus*, and *Cymbopogon winterianus*) cultivated in the tailings (Zago, das Dores, & Watts, 2019), leading to gains in biomass and essential oil production.

Given the edaphic conditions of areas affected by tailings, the use of soil conditioners can enhance the root growth environment, optimizing the revegetation process in affected areas. In this context, the objective of this research was to evaluate the use of different inorganic and organic soil conditioners (sand, vermiculite, sawdust, and organic compost) as a management technique to improve the environment for the promote the growth of grass (*Cynodon* spp.) in a technosol formed by the deposition of iron mining tailings. We hypothesize that soil conditioners, regardless of whether they are organic or inorganic, promote greater growth of grasses in the technosol by stimulating an improvement in the root environment through increased porosity, organic matter content, and CEC of the soil.

Material and Methods

Technosol sampling

The term “technosol” adopted to define the mixture of local soil with the tailings deposited in areas affected by the Fundão dam breach, was collected on the banks of the Gualaxo do Norte River, in the municipality of Mariana, MG, Brazil (20°17’55,8”S; 43°12’19,8”W). The sampling methodology and description of the chemical and physical attributes of this technosol can be found in Borges et al. (2023) (Table 1). In summary, approximately 500 kg of technosol was collected at a depth of 0 – 20 cm and transported to the Soil Biology, Microbiology, and Microbial Processes Laboratory of the Soil Science Department at the Federal University of Lavras (DCS/UFLA). In the laboratory, the material was air-dried and sieved (2.00 mm).

Experimental design and conditions

The same experimental matrix was applied in four independent experiments using soil conditioners: sand, vermiculite, sawdust, and organic compost. The choice of inorganic and organic matrix conditioners was to evaluate the feasibility of using cheap and easily accessible local products; the sand was sought to change the density and porosity; vermiculite the density and CEC; sawdust the density and carbon content; and the organic compound would be the density, carbon content, and CEC. Every one of the conditioners was considered an independent experiment, which followed the same completely randomized experimental design, with five treatments and four replications, totaling twenty pots with a capacity of three liters each by experiment. The treatments were distinguished by different proportions of conditioners concerning the volume of technosol, namely 0, 5, 10, 25, and 50% v/v (in proportion volume to volume). The volume of the mixture of technosol and conditioner used to compose the experimental units was two dm^3, placed in three-liter volumetric capacity pots containing plastic bags to seal the bottom of the pots The sand used was a mixture of 50% coarse sand (2 - 0.2 mm) and 50% fine sand (0.2 - 0.05 mm). The vermiculite used was a commercial product (“Vermiculita Expandida Fina – Multi Jardim). The sawdust used was from *Pinus*. The organic compost used was a commercial product (“Vida Verde”).

The model plant used was *Cynodon* spp., specifically the Tifton 85 cultivar. This plant was chosen because it is commonly found in areas along the banks of the rivers of the Rio Doce Basin, mainly riverside livestock farming areas. Stolons of 10 cm were used for planting, and after planting, aerial parts of the plants were cut every 30 days. The cuts were made due to the intense growth of the grass in greenhouse conditions. The first cut aimed to homogenize the stand concerning the size of the plants, followed by four production cuts, totaling five cuts during the experiment, this material was dried and quantified as the dry mass production of the aerial part of the plant. The experimental period lasted for 150 days.

The irrigation for the experiments was defined to maintain the substrate at 60% of its field capacity, determined through daily weighing of the pots. Fertilization followed the recommendations of Malavolta (1981) for potted cultivation. Most fertilizers were applied through a nutrient solution, with 100 mL of each solution per pot. Only the nutrients P and Ca were supplied in solid form during the preparation of the technosol in the pots, using 1 g of triple superphosphate per pot. Two nutrient solutions were applied: the first (S1) for the supply of N, K, and S, was applied in three split applications, according to the development of the plants: the first application was made at the time of the homogenization cut (first cut), followed by two monthly applications after the first. The second solution (S2) for the supply of Mg and the micronutrients B, Cu, and Zn, was applied together with the first application of S1. The fertilizer sources used for nutrient solution fertilization and their respective concentrations in the solutions were: S1 - NH_4NO_3 (13.2 g L^{-1}), KCl (5.7 g L^{-1}), $(NH_4)_2SO_4$ (3.3 g L^{-1}); e 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 $ZnSO_4$ (438.8 mg 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 $ZnSO_4$ (438.8 mg L^{-1}). Due to the considered sufficient available concentration of Mn and Fe in the technosol according to chemical analysis, both were not applied.

Table 1: Physical and chemical characterization of the technosol used in the experimental test.

pH	OM	Density	Sand	Silt	Clay	P-rem	H+Al	CEC	Ca	Mg	Al	**K**	**P**	**S**
H_2O	dag kg^{-1}	g cm^{-3}	---------dag kg^{-1}---------			mg L^{-1}	--------------------cmol$_c$ dm^{-3}----------------------					----------mg dm^{-3}-----------		
7.50	0.34	1.95	48.00	42.00	10.00	45.40	0.70	2.26	1.43	0.00	0.00	51.55	45.28	3.80
					B	Fe	Mn	Cu	Zn	Ba	Cd	**Cr**	**Pb**	**Ni**
Quality reference values for soil					----------------------mg dm^{-3}----------------------					-----------------------mg kg^{-1}----------------------				
					0.05	107.80	104.90	3.70	1.10	21.3	0.15	10.25	4.70	4.03
COPAM QRV (mg kg^{-1})					-	-	-	49.00	46.5	93.00	< 0.4	75.00	19.50	21.50
CONAMA PV (mg kg^{-1})					-	-	-	60.00	300.00	150.00	1.30	75.00	72.00	30.00
CONAMA AIV (mg kg^{-1})					-	-	-	200.00	450.00	300.00	3.00	150.00	180.00	70.00

OM: organic matter; P-rem: remaining phosphorus; H + Al: potential acidity; CEC: cation exchange capacity; COPAM (Environmental Policy Board of the State of Minas Gerais - Brazil); CONAMA (National Environmental Council of Brazil); QRV (quality reference value); PV (prevention value); AIV (agricultural investigation value).

Variables analyzed

For the analysis of shoot dry mass weight production (SDW), the plants were cut at the soil surface of the technosol. Subsequently, the plants were washed with distilled water and stored in paper bags for drying in an oven at 70 ºC for 72 hours or until reaching a constant mass. Four collections of aboveground parts were made during the experiment, corresponding to each production cut. These cuts were necessary because the grass has a high tillering rate, and thus allowed the experiment to be carried out for a longer period of study. The roots were separated from the technosol, washed, and underwent the same drying procedure for determining root dry mass (RDW). The total dry mass (TDW) was determined by summing the SDW and RDW.

Samples of the deformed technosol were collected to determine pH in water, potential cation exchange capacity at pH 7.00 (CEC_T), and organic matter content (Teixeira et al., 2017). Undeformed samples were collected using an Uhland sampler, driving the sampling cylinder into the technosol at a depth of 5 cm. Bulk density, total pore volume, and macro- and microporosity [macropores with a diameter greater than 0.05 mm (which lose water at tensions lower than 6 kPa), micropores, those with a diameter between 0.05 and 0.0002 mm (which are emptied at tensions between 6 and 1500 kPa)], were determined according to Teixeira et al. (2017).

Statistical analysis

Each of the experiments was statistically evaluated individually, but to facilitate understanding, they were presented in the same figure in individual graphs. The data were subjected to Jarque-Bera tests (Jarque & Bera, 1980) and Generalized ESD (Rosner, 1983) to assess the homogeneity of variances, normality of residuals, and the presence of outliers, respectively. Subsequently, an analysis of variance (ANOVA) was performed, and the varying proportions of technosol and conditioner were evaluated through regression analysis. The SPEED Stat software (Carvalho et al., 2020) was employed for these analyses.

Results and Discussion

Physical attributes of technosol

The addition of vermiculite, sawdust, and organic compost reduced the density of the technosol (Figure 1), while sand did not cause any significant changes. The reduction in bulk density was up to 19.2%, 33.5%, and 27.5% in the experiments with vermiculite, sawdust, and organic compost, respectively, at a dosage of 50% v/v of conditioner (Figure 1). Regarding the

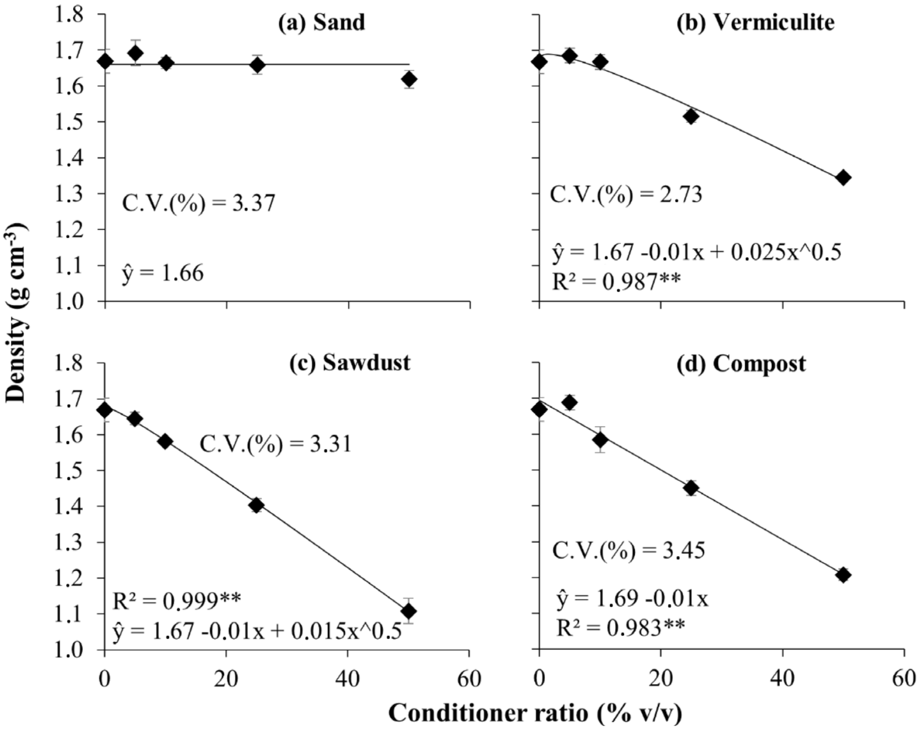

Figure 1: Soil Density (g cm^{-3}) of the technosol under conditioning with increasing doses (0, 5, 10, 25, and 50% v/v) of sand (a), vermiculite (b), sawdust (c), and organic compost (d) after 150 days of *Cynodon* spp. cultivation. Bars represent the standard error of the means. Models followed by * or ** are significant at the 5 and 1% levels of error probability, respectively, by the F-test and have non-significant regression deviation.

porosity of the technosol, there was an increase in microporosity due to the vermiculite, sawdust, and organic compost conditioners (Figure 2). This increase was up to 23.8%, 18.5%, and 8.8%, respectively. In the case of vermiculite, the highest predicted value of microporosity is 41.6%, corresponding to a dosage of 44% v/v. However, sand reduced microporosity by up to 20.9% (Figure 2).

Macroporosity increased with the addition of conditioners, except for vermiculite, which did not alter this variable (Figure 3). The increase in macroporosity occurred at the highest conditioner dose, with increases of 35.1%, 54.1%, and 30.9% in experiments with sand, sawdust, and organic compost, respectively (Figure 3). However, at doses below 25% v/v of conditioner, there was a reduction in macroporosity. Reductions in macroporosity of 9.4% occurred at a dose of 14.7% v/v of sand, 5.5% at a dose of 7.5% v/v of sawdust, and 8.2% at a dose of 6.7% v/v of organic compost. The highest doses of vermiculite, sawdust, and organic compost caused increases of 20.5%, 27.2%, and 14.3%, respectively, in total porosity (Figure 4). However, the application of sand reduced total porosity by 10.8% at a dose of 50%.

The technosol exhibits a more silt-sandy texture (sand, silt, and clay proportions of 48.00, 42.00, and 10.00 dag kg^{-1}, respectively), high bulk density (1.95 g cm^{-3}), and low total porosity (< 45%) (Table 1 Figure 4). Notably, despite having a high proportion of sand, the technosol presents higher values of fine sand, with values of 189 to 279 g kg^{-1} (Páez et al., 2024), and this fine sand behaves in the soil in a more similar way to the silt. With these high levels of silt and fine sand and the reduced clay content, there is a direct influence on the increase in soil bulk density and the decrease in porosity (Páez et al., 2024). These characteristics can pose an obstacle to root growth in depth, which hinders the rehabilitation of impacted areas (Andrade et al., 2018; Matos et al., 2020; Zanchi et al., 2022). The use of conditioners that improve this porosity, such as the application of vermiculite and sawdust, resulting in increased root growth (Figure 9), could be recommended as an effective technology for the recovery of these degraded areas and assisting in the re-vegetation of technosols in the field.

Applying of organic compost also influenced the increase in porosity and the reduction of density (Figures 1 and 4). However, it did not affect the root dry weight (RDW) and total dry weight (TDW) but increased the shoot dry weight (SDW) (Figures 8, 9, and 10). This indicates a positive effect of this soil improvement with organic compost application, which, in the long run, may also result in increases in root growth and establishment. Páez et al. (2024) highlight that the high resistance of technosols is their main physical limitation, and to overcome this effect it is necessary to combine different management practices to improve their physical properties and full multifunctionality, including the use of cover plants, conservationist cultivation, use of organic compost, phytoremediation, reforestation, and rotation.

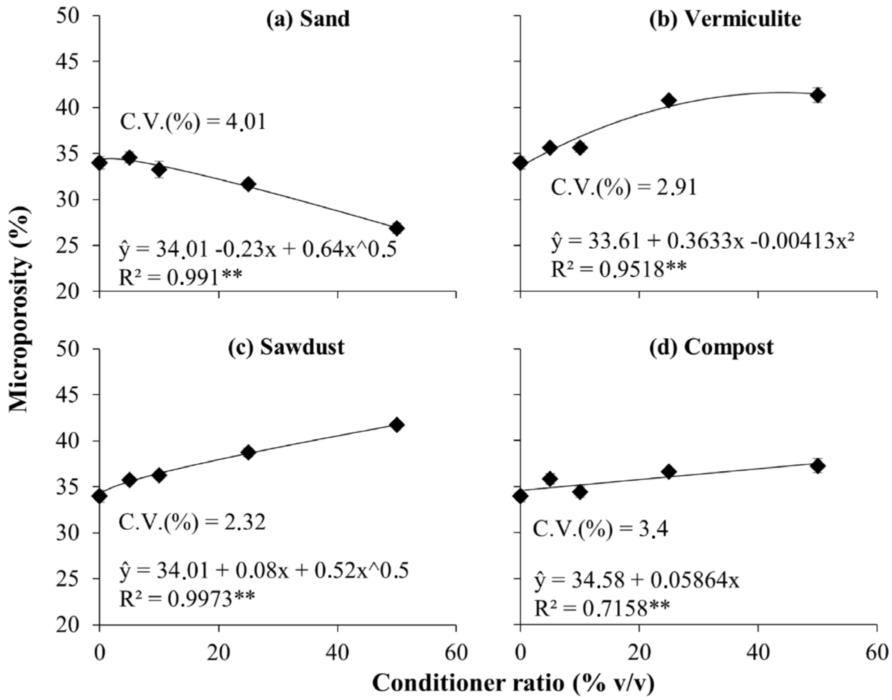

Figure 2: Microporosity (%) of the technosol under conditioning with increasing doses (0, 5, 10, 25, and 50% v/v) of sand (a), vermiculite (b), sawdust (c), and organic compost (d) after 150 days of *Cynodon* spp. cultivation. Bars represent the standard error of the means. Models followed by * or ** are significant at the 5 and 1% levels of error probability, respectively, by the F-test and have non-significant regression deviation.

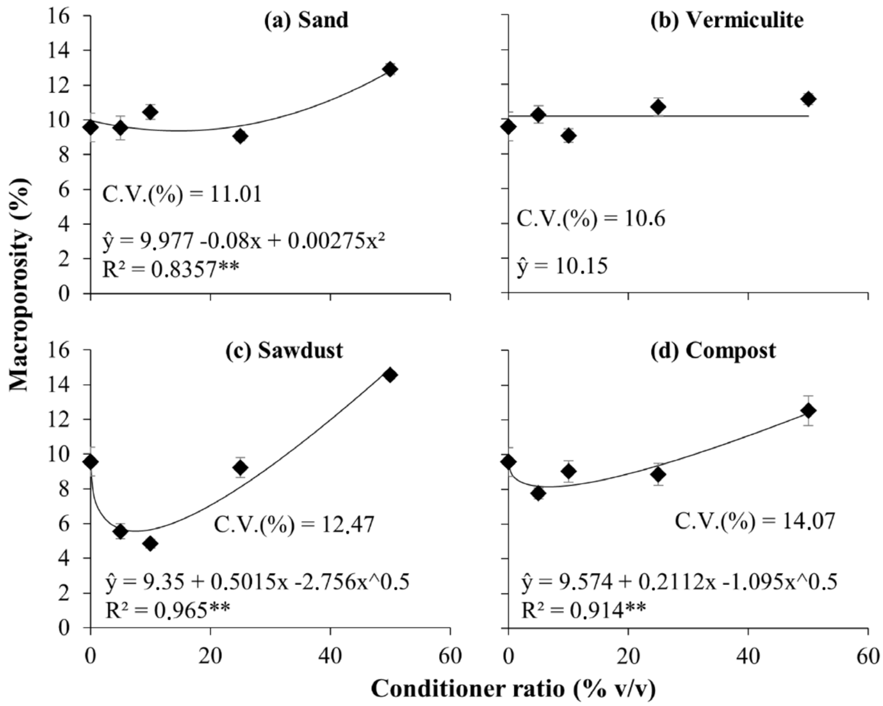

Figure 3: Macroporosity (%) of the technosol under conditioning with increasing doses (0, 5, 10, 25, and 50% v/v) of sand (a), vermiculite (b), sawdust (c), and organic compost (d) after 150 days of *Cynodon* spp. cultivation. Bars represent the standard error of the means. Models followed by * or ** are significant at the 5 and 1% levels of error probability, respectively, by the F-test and have non-significant regression deviation.

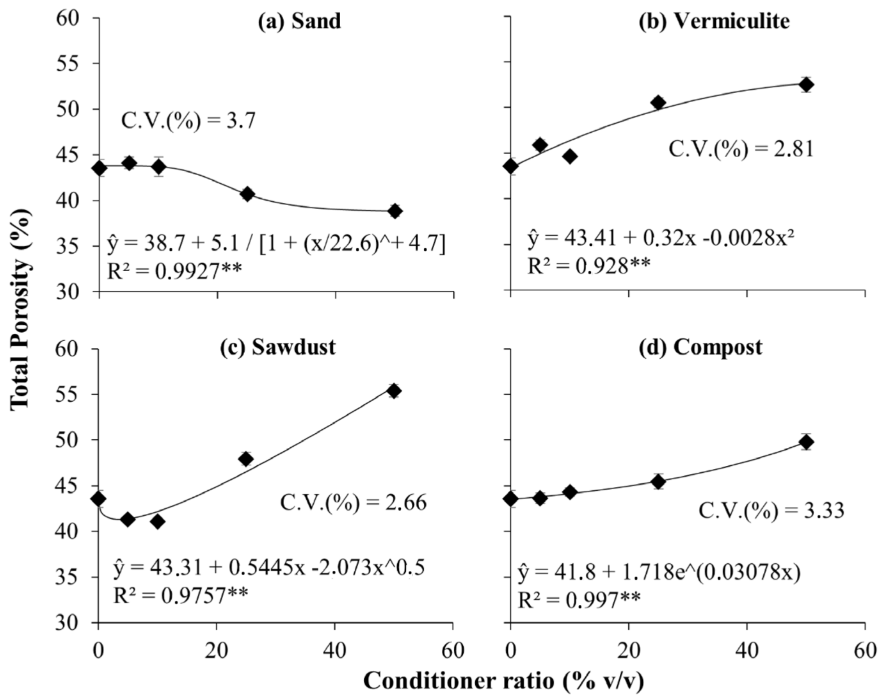

Figure 4: Total porosity (%) of the technosol under conditioning with increasing doses (0, 5, 10, 25, and 50% v/v) of sand (a), vermiculite (b), sawdust (c), and organic compost (d) after 150 days of *Cynodon* spp. cultivation. Bars represent the standard error of the means. Models followed by * or ** are significant at the 5 and 1% levels of error probability, respectively, by the F-test and have non-significant regression deviation.

The reduction in density and consequent improvement in pore distribution generated by the application of conditioners such as vermiculite, sawdust, and organic compost (Figures 1 and 4) highlights them as excellent materials that can be used in the recovery of these areas. High bulk density and low total porosity not only impact root growth but also limit water-holding capacity. Restrictions on water-holding capacity and infiltration in technosols not only affect the revegetation process but also impact erosive processes in this material (Almeida et al., 2018; Andrade et al., 2018; Borges et al., 2023). Evaluating iron mining tailings deposited along riverbanks in the Gualaxo do Norte River basin, Baudson et al. (2024) showed that this tailing is highly susceptible to water erosion processes, mainly surface phenomena, which involve detachment and transport of particles, contributing significantly to erosion processes and favoring environmental degradation in the basin. Rehabilitation measures that aim to improve the multifunctionality of the soil and that result in better aggregation can help reduce erosion processes in the technosol. Therefore, the increase in water infiltration capacity, retention, and the reduction of surface erosion are positive effects in the rehabilitation of these areas, assisting in the restoration of crucial ecosystem services.

pH, CEC, and SOM of technosol

The application of sawdust and organic compost altered the pH value, while the sand and vermiculite conditioners did not affect the pH (Figure 5). Sawdust caused a reduction in pH by up to 15% at the highest dosage (Figure 5). However, the highest pH value predicted by the model for the application of this conditioner was 7.51, corresponding to a dosage of 14.8% v/v of sawdust, resulting in a 3% increase compared to the technosol without conditioning. Organic compost led to an increase in pH of up to 12.4%, corresponding to the application of organic compost at a dose of 35.6% v/v. The organic matter content increased by up to 2178% and 793% in experiments with sawdust and organic compost, respectively, at the highest dosages (Figure 6). Among the mineral conditioners, only vermiculite showed a response in this variable, with an increment of up to 56% at the highest conditioner dose (Figure 6). Except for sand, the conditioners increased the CEC by up to 354%, 28%, and 499% in experiments with vermiculite, sawdust, and organic compost, respectively (Figure 7).

Organic conditioners alter the pH of the technosol (Figure 5). The likely reason why these conditioners affect the pH may be related to the release of electrons into the soil solution and the aeration conditions provided by their addition, as observed in porosity (Figures 3 and4). Sawdust and organic compost conditioners increased porosity; however, sawdust provides nearly double the increase in macroporosity and total porosity variables compared to organic compost, especially at higher conditioner proportions. In an environment with lower porosity, reduced oxygen concentration slows down the decomposition of this material. Since the mixture of sawdust in the technosol provides higher porosity, the carbon from this conditioner will be in a more aerobic condition, favoring the oxidation process and potentially causing a reduction in substrate pH.

The availability of nutrients for plants is related to the complex interaction between the physical and chemical characteristics of the soil. The clay content is proportional to the sorption capacity in the soil, owing to its higher specific surface area and ability to generate surface charges on this particle size. With these charges, many elements can be adsorbed, thus preventing losses through leaching, and remaining available for exchanges with the soil solution. However, highly weathered tropical soils with a more oxidized clay fraction exhibit a lower density of surface charges (Kämpf, Marques, & Curi, 2012; Schaefer & Fabris; 2008). Under these conditions, organic matter becomes the main source of charges and the generator of sorption capacity in the soils. In the case of technosols, an increase in organic matter content becomes an indicator of progress in the recovery process of the areas. This improvement enhances biological activity, charge generation, and nutrient availability, allowing for greater plant growth and development.

Despite increases in organic matter content being observed in the application of sawdust and organic compost, it was in the application of the latter and vermiculite that increases in CEC were observed (Figure 7). Vermiculite has the property of improving porosity and increasing soil CEC, as it has a mineral composition with a high surface charge content, especially when in clay size. On the other hand, organic compost is more decomposed than sawdust, favoring the expression of a higher density of surface charges. This increase in charges would improve nutrient retention, which can drive physico-chemical modifications in the technosol, as well as create better conditions for vegetation establishment (Borges et al., 2023; Da Silva, R. et al., 2022).

Plant growth

The shoot dry mass (SDW) was increased by the application of the sand, vermiculite, and organic compost conditioners by up to 19%, 33%, and 19%, respectively, at the highest dosage (Figure 8). On the other hand, the addition of sawdust caused reductions of up to 47% in SDW at the estimated dose of 30.44% v/v (Figure 8). The production of roots dry mass (RDW) was enhanced by the application of conditioners, except for organic compost, which did not affect this variable (Figure 9). Sand and vermiculite increased root dry mass production by up to 54% and 52%, respectively, at estimated dosages of 30% v/v for sand and 40% v/v for vermiculite (Figure 9). In the sawdust experiment, RDW increased by 70% at the highest dosage of this conditioner (Figure 9). The total dry mass (TDW) was not influenced by the application of organic compost and was reduced by up to 26% with the application of sawdust at an estimated dosage of 27% v/v (Figure 10). On the other hand, increases of up to 18.3% and 38.5% were observed with the application of sand and vermiculite, respectively, at the highest dosage (Figure 10).

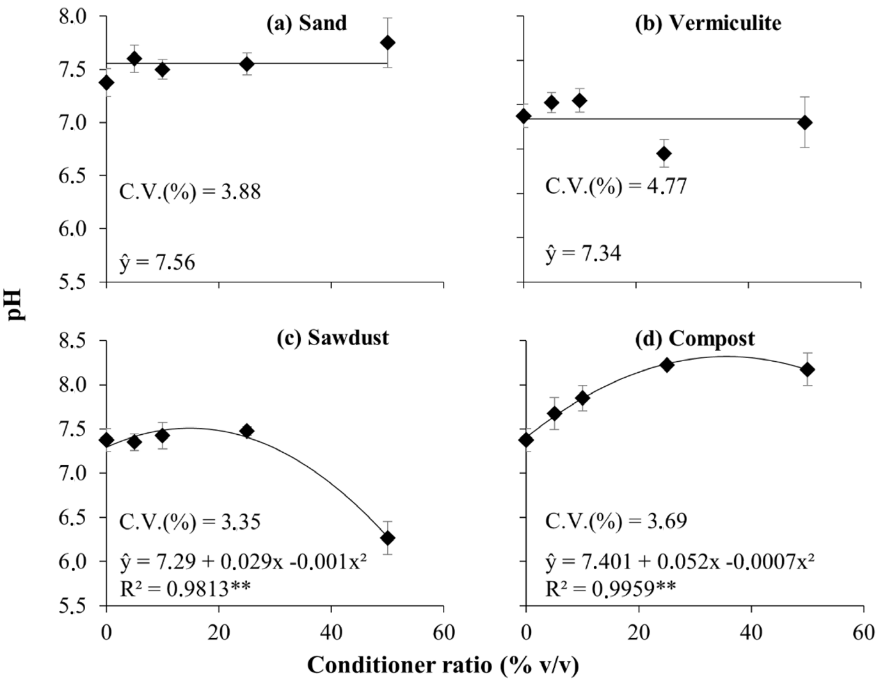

Figure 5: pH of the technosol under conditioning with increasing doses (0, 5, 10, 25, and 50% v/v) of sand (a), vermiculite (b), sawdust (c), and organic compost (d) after 150 days of *Cynodon* spp. cultivation. Bars represent the standard error of the means. Models followed by * or ** are significant at the 5 and 1% levels of error probability, respectively, by the F-test and have non-significant regression deviation.

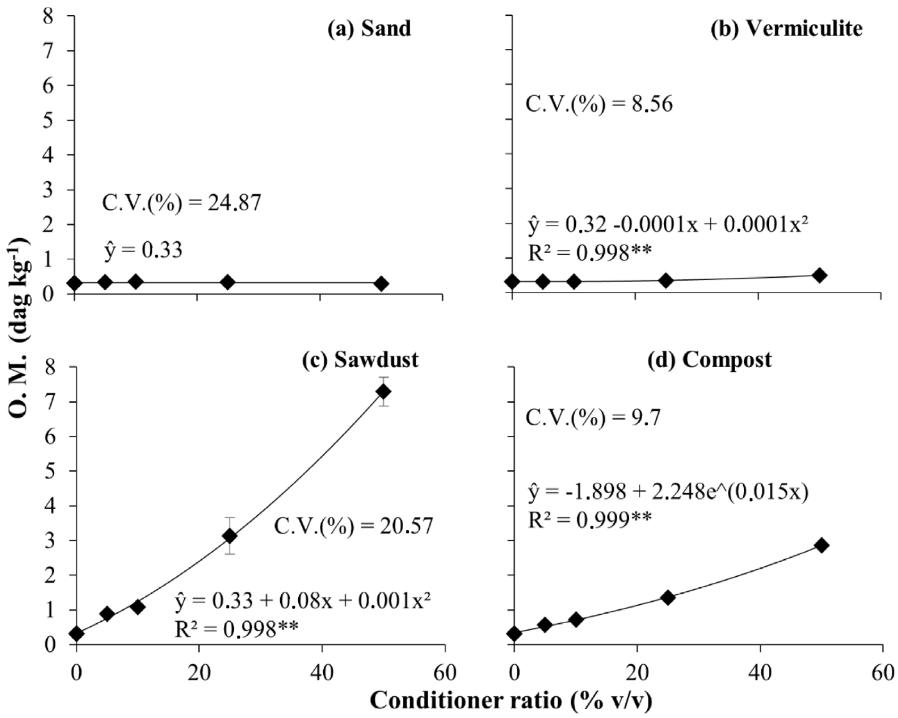

Figure 6: Organic matter content (O.M.) of the technosol under conditioning with increasing doses (0, 5, 10, 25, and 50% v/v) of sand (a), vermiculite (b), sawdust (c), and organic compost (d) after 150 days of *Cynodon* spp. cultivation. Bars represent the standard error of the means. Models followed by * or ** are significant at the 5 and 1% levels of error probability, respectively, by the F-test and have non-significant regression deviation.

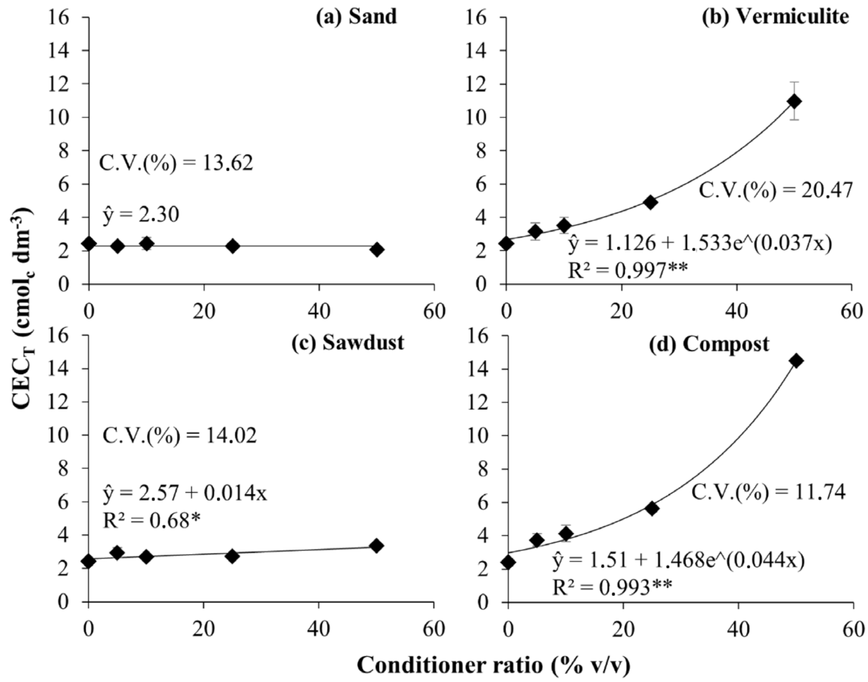

Figure 7: Potential cation exchange capacity at pH 7.0 (CEC_T) of the technosol under conditioning with increasing doses (0, 5, 10, 25, and 50% v/v) of sand (a), vermiculite (b), sawdust (c), and organic compost (d) after 150 days of *Cynodon* spp. cultivation. Bars represent the standard error of the means. Models followed by * or ** are significant at the 5 and 1% levels of error probability, respectively, by the F-test and have non-significant regression deviation.

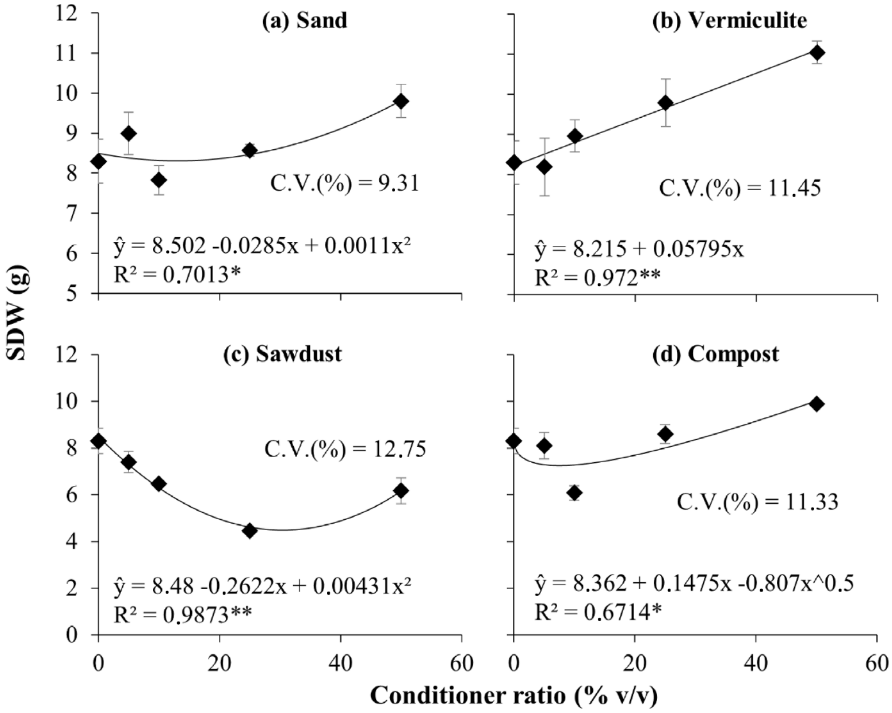

Figure 8: Shoot dry mass (SDW) of *Cynodon* spp., after 150 days of cultivation in iron mining waste soil under conditioning with increasing doses (0, 5, 10, 25, and 50% v/v) of sand (a), vermiculite (b), sawdust (c), and organic compound (d). Bars represent the standard error of the means. Models followed by * or ** are significant at the 5 and 1% levels of error probability, respectively, by the F-test and have non-significant regression deviation.

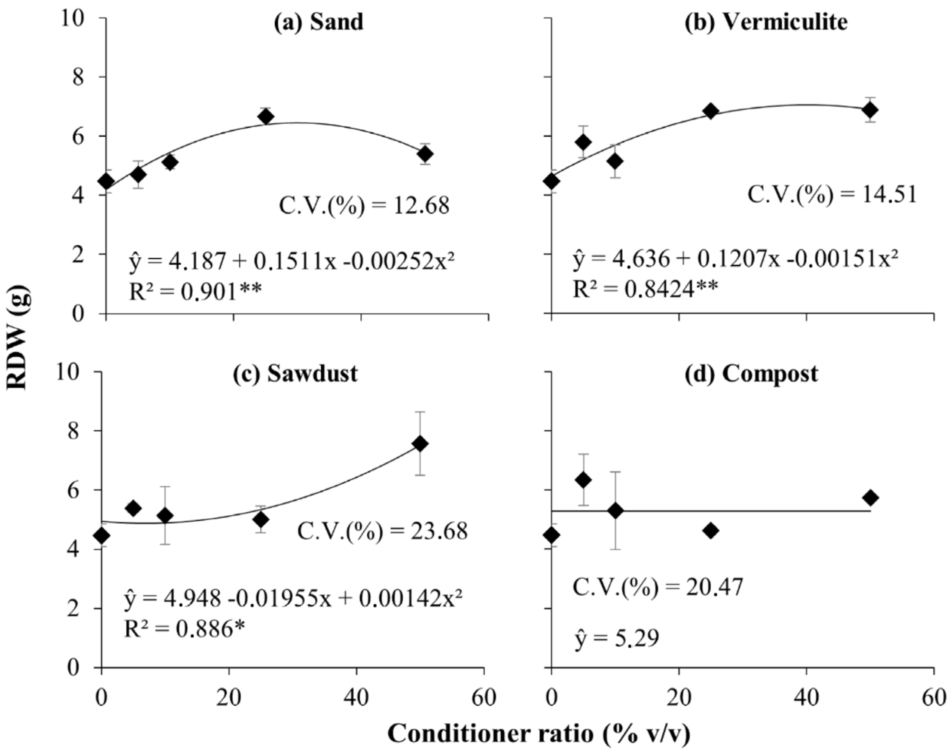

Figure 9: Root dry mass (RDW) of *Cynodon* spp., after 150 days of cultivation in iron mining waste soil under conditioning with increasing doses (0, 5, 10, 25, and 50% v/v) of sand (a), vermiculite (b), sawdust (c), and organic compound (d). Bars represent the standard error of the means. Models followed by * or ** are significant at the 5 and 1% levels of error probability, respectively, by the F-test and have non-significant regression deviation.

Although all soil conditioners alter the attributes of the technosol to some extent, only those of a mineral nature (sand and vermiculite) promoted the growth of *Cynodon* spp. (Figures 9, 10, and 11). The application of sand and vermiculite also influences the physical behavior of the technosol and the retention and availability of nutrients. Applying sand increased macroporosity (Figure 4), and vermiculite increased microporosity, total porosity, and cation exchange capacity (Figures 3, 5, and 8). Still, both did not modify pH (Figure 6) nor added carbon in the system (Figure 7). Applying organic compost and sawdust increased organic matter and changed the pH. Zanchi et al. (2022) highlighted in their study, conducted under controlled greenhouse conditions, that the low porosity of tailings can represent one of the main obstacles to developing plants in technosols. They suggest that revegetation of these environments can mitigate the adverse effects of low porosity, especially using plants with fasciculate root systems, such as grasses, particularly those that have demonstrated good growth in these specific soil types (Da Silva, R. et al., 2022; Zanchi et al., 2022). The ability of grasses to grow in technosols may explain the relatively low response of *Cynodon* spp. to the addition of doses of different types of conditioners. It is interesting to note that, in some cases, Tifton even showed more significant growth in conditioners with a more physical matrix. This can be attributed to the fact that these conditioners essentially functioned as a hydroponic substrate, facilitating the availability of the chemical nutrients provided through the nutrient solution in our experiment.

However, Páez et al. (2024) highlight the importance of jointly implementing several management practices to improve the physical properties and multifunctionality of technosols, aiming to mitigate the high resistance to penetration, which is the main physical limitation of these soils formed after the deposition of iron mining tailing from the Fundão dam. The combined use of conditioners with different modes of action can be an effective strategy, including combining various conditioners of physical and chemical action. Although nutrient scarcity is cited as another barrier to plant growth in technosols (Andrade et al., 2018; Borges et al., 2023), this limitation was remedied in our study through chemical fertilization, which may have favored plant growth mainly in sand and vermiculite conditioners, which only acted as a vehicle for plant growth. However, the joint use of different conditioners needs to be evaluated, especially for their enhancement of plant growth by improving both the physical and chemical environment of the technosol, perhaps even as a way of reducing or replacing chemical fertilization.

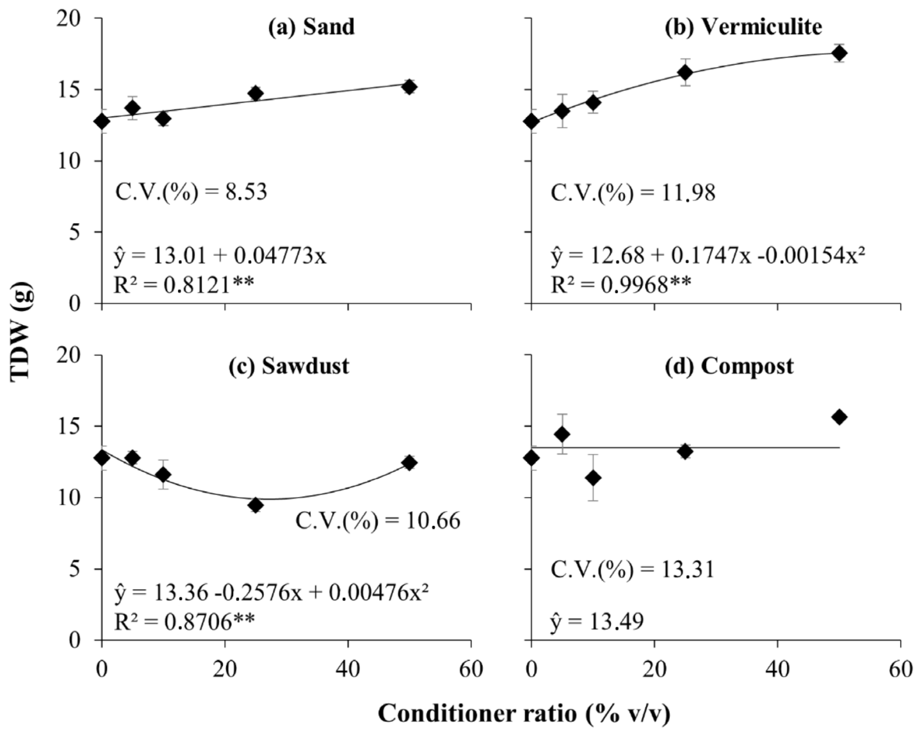

Figure 10: Total dry mass (TDW) of *Cynodon* spp., after 150 days of cultivation in iron mining waste soil under conditioning with increasing doses (0, 5, 10, 25, and 50% v/v) of sand (a), vermiculite (b), sawdust (c), and organic compound (d). Bars represent the standard error of the means. Models followed by * or ** are significant at the 5 and 1% levels of error probability, respectively, by the F-test and have non-significant regression deviation.

Application of sand and vermiculite led to increases in SDW, RDW, and TDW (Figures 8, 9, and 10). Vermiculite was the conditioner that provided the highest increases in plant biomass production. The application of organic compost increased SDW but did not influence RDW and, consequently, TDW. The application of sawdust increased RDW at the highest dosage but reduced SDW and TDW (Figures 8, 9, and 10). The primary function of conditioners is to enhance plant growth, whether in roots or aboveground. Even if it does not result in productivity, the increase in the proportion of roots can be a survival strategy for plants in tailings, as observed by Esteves et al. (2020). They highlighted that the main role of vermicompost in iron ore tailings was to promote the growth of thick and very thick roots in plants cultivated in tailings, serving as a survival strategy for species facing the physical limitations of tailings.

In this study, it becomes evident that the technosol was not limited to the growth of *Cynodon* spp., even without the application of conditioners. Part of this response can be attributed to the fertilization applied to the plants, as nutrient availability is one of the most restrictive factors for plant development in technosols (Andrade et al., 2018; Borges et al., 2023; Esteves et al., 2020). However, this is also due to the characteristics of the species itself. Some studies demonstrate that other plants such as Brachiaria, Crotalaria, and Vetiver, for example, can be used in the management of soil recovery affected by this iron ore tailings (Da Silva, R. et al., 2022; Zago, das Dores, & Watts 2019; Zanchi et al., 2021). These and other species that produce a substantial amount of biomass are essential in the initial stages of carbon incorporation into affected soils, activation, and promotion of microbial growth, and improvement of their physical and chemical attributes (Batista et al., 2022; Zanchi et al., 2021). However, it is important to highlight that our observations are carried out in experiments under controlled greenhouse conditions, which provide optimal conditions for plant growth, this fact may mask various limitations related to the physical-hydraulic behavior of the technosol. To recommend a strategy for using conditioners in this technosol, a test under field conditions is important, to assess what the application of these conditioners would be like and their effect on revegetation and progress in the recovery of the area impacted by iron mining tailing. Therefore, further research with field trials is necessary for the validation and recommendation of the employed management methods. Additionally, monitoring the conditioning of technosol under different water conditions is a relevant topic for simulations in controlled environments and can contribute to a better understanding of conditioning methods with greater implementation potential.

Conclusions

The sand and vermiculite conditioners stimulate *Cynodon* spp. growth in Technosol, enhancing root growth conditions. Organic compost, sawdust, and vermiculite improve porosity, reduce density, increase organic matter, and adjust pH and CEC. Vermiculite notably boosts plant biomass and enhances soil quality and can recommended for rehabilitating iron ore tailings-impacted areas or post-mining re-vegetation. However, growth promotion by conditioners may not justify their economic use under field conditions. Technosol fertilization alone yields satisfactory plant growth, potentially obviating the need for conditioners.

Author Contribution

Conceptual idea: Borges, P.H.C.; Carneiro, M.A.C.; Siqueira, J.O.; Methodology design: Borges, P.H.C.; Carneiro, M.A.C.; Data collection: Borges, P.H.C.; Silva, A.O.; dos Santos, J.V.; Data analysis and interpretation: Borges, P.H.C.; Silva, A.O.; de Carvalho, A.M.X.; and Writing and editing: Borges, P.H.C.; Silva, A.O.; de Carvalho, A.M.X.; dos Santos, J.V.; Carneiro, M.A.C.; Siqueira, J.O..

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