



# Assessing the Effects of Restoration Techniques on Technosol Physical and Chemical Properties after Kaolin Mining in the Amazon

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## Abstract

The physical and chemical properties of Technosol are crucial for forest restoration, as they can limit the development of pioneer vegetation in mined areas. In this study, we investigated how different restoration techniques affect the physical and chemical properties of the Technosol in two sites restored after kaolin mining in the eastern Amazon. Twenty months after planting seedlings, two distinct field experiments evaluated the efficiency of applying organic compounds (Topsoil - TS, Sawdust - SD, Cow manure - CM) in trenches and applying dolomitic limestone in pits of different sizes (Small pit - SP, Medium pit - MP, and Large pit - LP). The responses in the properties of the Technosol varied according to the management applied during the implementation of the restoration project. The techniques used to modify the physical and chemical properties in the study sites resulted in statistical differences between the kaolin mines in 21 of the 27 properties evaluated. The application of limestone reduced the toxicity of elements such as aluminum (Al), iron (Fe), and manganese (Mn) by more than 100% and increased the soil pH to over 5.5, while the incorporation of organic compounds restored organic matter (O.M), increased potassium (K), and contributed to moisture retention. We highlight the importance of proper management of the Technosol to mitigate the impacts of open-pit kaolin mining in the Amazon, as well as the need to implement more sustainable management policies and practices to ensure soil restoration after mining.

**Keywords** Limestone · Moisture retention · Organic compounds · Reconstructed soil · Soil texture

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## 1 Introduction

The Amazon is the largest continuous tropical forest in the world (Laurance et al. 2001), hosting more than 10% of all terrestrial biodiversity (Cardoso et al. 2017) and an estimated richness of over 15,000 tree species (ter Steege et al. 2020). Furthermore, the Amazon has a vast diversity of mineral resources, notably iron ore, aluminum, gold, manganese, nickel, and zinc (Murguía et al. 2016). In this context, mining exerts a strong influence on the regional dynamics and contributes to the economy at various scales (Martins et al. 2022), playing a key role in different sectors and production chains (Melo et al. 2018). On the other hand, this economic activity causes serious impacts on the natural landscape, such as the removal of native vegetation, destruction of soil profiles, alteration of biogeochemical cycles, and displacement of wildlife (Santos et al. 2016). Thus, forest restoration in these areas is the only viable alternative for the gradual return of ecosystem services, climate change mitigation,

and the potential reintroduction of the environment into economic use (Morán-Ordóñez et al. 2022).

In Brazil, the restoration of ecosystems degraded by mining is a mandatory activity, and the country has extensive environmental legislation that supports the mitigation of environmental liabilities caused by this activity (Gastauer et al. 2018). Among the most commonly used methods in the restoration of mined sites, active restoration through the planting of native tree species stands out, being the most widespread in tropical forests, as it more rapidly reestablishes vegetation and ecological processes (Guerra et al. 2020). However, in sites degraded by mining in the Amazon, certain ecological factors severely limit the success of forest restoration, such as: (a) high density and compaction of the reconstructed soil (defined as Technosol), (b) low fertility of Technosol (Román-Dañobeytia et al. 2015), and (c) climatic limitations caused by extreme weather events that lead to severe drought in the Amazon (Sousa et al. 2020).

Regarding the first factor, reconstructed sites exhibit physical characteristics that drastically limit the development of pioneer vegetation, such as the high compaction and density of Technosol caused by the traffic of heavy machinery used for topographic reshaping (Masto et al. 2015). Compacted post-mining sites have low porosity, resulting in limited water retention and poor nutrient absorption, which restricts plant root development (Macdonald et al. 2015). Hence, physical interventions such as subsoiling, trench construction, and planting larger pits can increase porosity and contribute to the initial development of plants (Oliveira et al. 2022, 2023).

Considering the second factor, to develop the fertility of Technosol, it is important to ensure the success of the ecological processes that will sustain pioneer vegetation (Hernandez-Santin et al. 2020). A strategic alternative to increase the fertility of Technosol is the addition of organic compounds (e.g., sawdust and composted manure) and inorganic fertilizers (e.g., limestone, N:P: K, urea, and superphosphate) (Gebhardt et al. 2017). This also has implications for improving the physical properties of Technosol, such as structure, porosity, density, and texture (Wang et al. 2020). The application of organic compounds and inorganic fertilizers is also an efficient way to ensure an immediate increase in water retention capacity and the subsequent survival of plants during the critical first months of development (Zancada et al. 2004).

Finally, regarding the third factor, recurring climatic events such as El Niño have been causing severe droughts in the Brazilian Amazon, as observed in 2005 and 2015/2016 (Ribeiro et al. 2022), which negatively impacts forest restoration projects in mining areas, making it necessary to ensure sufficient water supply for plant survival during the driest periods. Under these unfavorable climatic conditions,

plants experience intense water stress (Kramer and Boyer 1995), leading to high mortality rates in the first months after planting (Roy et al. 2020). In this sense, it is important to select native species that are resistant and adapted to the specific site conditions to increase the chances of restoration success (Rosado et al. 2023). Therefore, with water scarcity during dry periods, the use of organic compounds as mulch (e.g., cellulose fiber, coconut fiber, manure, and wood residues) can be employed to increase water retention and reduce evaporation from Technosol (Chirino et al. 2011).

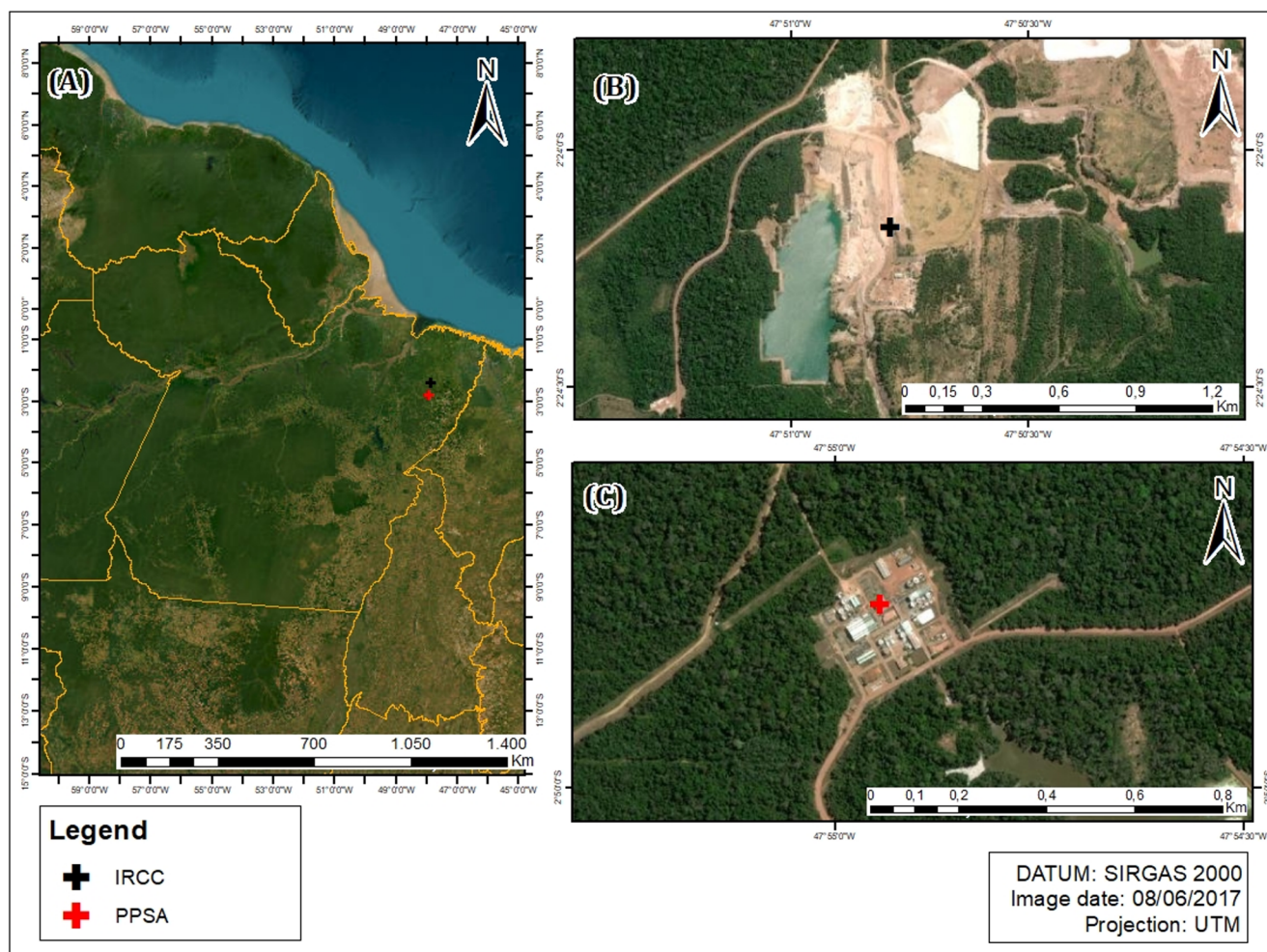
Thus, it is important to assess the conditions of the Technosol alongside the evaluation of vegetation development, as this information on the physical and chemical properties of the Technosol can shed light on the effectiveness of the techniques and procedures used in restoration and their long-term sustainability (Rashmi et al. 2024). Moreover, the physical and chemical properties of the Technosol are considered indicators of restoration success, which, in many cases, are subject to slow recovery after excessive use and severe disturbances such as mining (Trujillo-Miranda et al. 2018) and are often neglected in periodic monitoring.

Given the main issues related to the restoration of Technosol in disturbed or newly constructed sites after mining in the Amazon, it is of great practical interest to test different combinations and management arrangements for the restoration of these critical ecosystems, essential for maintaining terrestrial biodiversity and regulating the climate on a global scale. In this context, the objective of this study was to identify changes in the physical and chemical properties of Technosol associated with different management conditions (organic fertilization and trenches vs. liming and pits of different sizes) following kaolin mining in eastern Amazon. For this purpose, we hypothesize that Technosol management techniques will promote improvements in physicochemical properties, including increased organic matter, moisture, pH, and cation exchange capacity.

## 2 Materials and Methods

### 2.1 Study Area

The study was conducted in the municipality of Ipixuna, state of Pará, Brazil (Fig. 1), in two open-pit kaolin mines: Pará Pigmentos (PPSA) and Imerys Rio Capim Caulim (IRCC), both owned by the French mining company Imerys S.A. The main natural vegetation type in the region is the Tropical and Subtropical Moist Broadleaf Forest (Olson et al. 2001), and the climate classification for the region, according to Köppen, is Aw (tropical wet). The average annual precipitation in the region is 1,800 mm, the average annual temperature is 26.3 °C, and the relative humidity



**Fig. 1** Location of study areas: (A) State of Pará, eastern Amazon, Brazil, (B) Overview of the IRCC mine and (C) PPSA mine

is above 80% (Alvares et al. 2013). During the years 2019 and 2021, the period when physical and chemical analyses of the Technosol were conducted, the average precipitation and temperature were 42 mm and 27 °C, and 98 mm and 26 °C, respectively (Fig. 2). The soils in this region are classified according to the IUSS Working Group WRB (2015) as Yellow Ferralsol and Yellow Acrisol, characterized by high physical and chemical weathering.

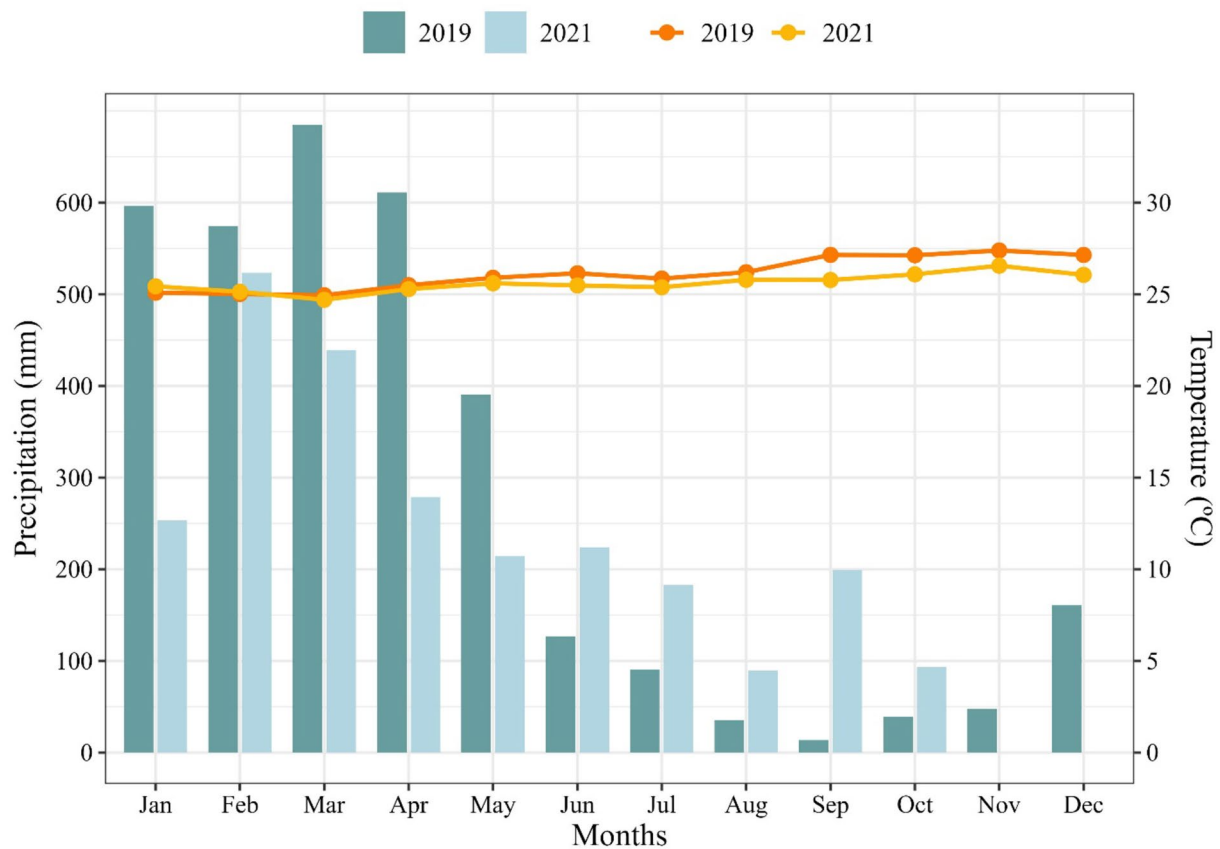
## 2.2 Site Preparation Techniques

### 2.2.1 PPSA Mine

The site was prepared for the experiment in November 2017, covering 0.35 ha of mined soil, with the planting of tree seedlings occurring at the beginning of the rainy season in January 2018. Nine trenches measuring 1 m × 20 m and 1 m deep were dug in this area. The trenches were spaced 6 m apart and filled with topsoil extracted from a depth of 1 m from adjacent areas to be excavated. After filling the

trenches with topsoil, pits measuring 0.40 m × 0.40 m × 0.40 m were dug along the length of each trench, with a distance of 1.5 m between them. Then, 400 g pit<sup>-1</sup> of single superphosphate (16% P<sub>2</sub>O<sub>5</sub>), 130 g pit<sup>-1</sup> of urea (46% nitrogen), and 130 g pit<sup>-1</sup> of potassium chloride (60% K<sub>2</sub>O) were applied, divided into two applications with an interval of 60 days. Inorganic fertilization was predetermined by the mining company to accelerate the initial growth of the planted tree species and increase the surface moisture of the Technosol. Finally, supplemental organic compost was added in three different treatments: Topsoil (TS), Sawdust (SD), and Cow manure (CM), each comprising the pits in three trenches. In SD and CM, 40 dm<sup>3</sup> per pit of the respective organic was used, which was mixed with topsoil to complete the volume. In the spaces between rows, i.e., in the 6 m space between the trenches, a 0.10 m layer of aged sawdust was added over the Technosol.

The sawdust used consisted of residues from sawmills located near the experimental site. Following the establishment of the experimental treatments, seedlings of six



**Fig. 2** Monthly precipitation and average monthly temperature in the study areas (PPSA 2019 and IRCC 2021), eastern Amazon, Brazil (Data made available by the Imerys mining company's rainfall station

located in the study area). Legend: Bars represent rainfall and lines represent the average monthly temperature

pioneer tree species (*Byrsonima spicata* (Cav.) DC., *Clitoria fairchildiana* R.A. Howard, *Croton matourensis* Aubl., *Inga edulis* Mart., *Syzygium cumini* (L.) Skeels, and *Tachigali vulgaris* L.F. Gomes da Silva & H.C. Lima) were planted at a spacing of 3 m x 3 m. These species were considered cover species, nitrogen fixers, and attractive to dispersing fauna. The seedlings had an average height of 28 cm and were distributed among the three treatments. The planting order of the species in the trenches (planting lines) was performed randomly, allowing a maximum of two individuals of the same species to be planted consecutively.

### 2.2.2 IRCC Mine

The site was prepared for the experiment in November 2019, covering 0.22 ha of mined soil, with the planting of tree seedlings occurring at the beginning of the rainy season in January 2020. In this area, topographic reformation was carried out, along with the deposition of topsoil and subsoiling in the planting rows to a depth of 0.60 m. Soil liming was performed with the application of 2 t ha<sup>-1</sup> of dolomitic limestone to the total area (Total Relative

Neutralizing Power – TRNP 83%, CaO 33%, and MgO 12%) to correct the acidity of the Technosol. Subsequently, pits of three distinct sizes were opened: Small pit (0.45 m wide x 0.72 m long x 0.33 m deep), Medium pit (0.35 m x 0.80 m x 0.60 m), and Large pit (0.80 m x 1.50 m x 0.75 m). A manual soil auger was used for the small pits, while a Caterpillar® backhoe model 416-E was used for the medium and large pits. A total of 300 g per pit of single superphosphate (18% P<sub>2</sub>O<sub>5</sub>) and 40 dm<sup>3</sup> per pit of matured sawdust were applied to all treatments.

From the establishment of the experimental treatments, seedlings were planted at a spacing of 3 m x 3 m for six pioneering tree species (*Byrsonima crassifolia* (L.) Kunth, *Clitoria fairchildiana* R.A. Howard, *Eugenia candolleana* DC., *Inga cayennensis* Sagot ex Benth., *Inga edulis* Mart., and *Tachigali vulgaris* L.F.G.Silva & H.C. Silva). These species are cover crops, nitrogen fixers, and attractive to dispersing fauna. The seedlings had an average height of 35 cm and were distributed among the three treatments: Small pit (SP), Medium pit (MP), and Large pit (LP), respectively. The order of planting the species in the pits was randomized, allowing for a maximum repetition of two individuals

of the same species consecutively. In March 2020, two months after planting, a base fertilization was conducted with 150 g per pit<sup>1</sup> of N: K (proportion of 18:18) + micro-nutrients (0.5% B, 0.5% Cu, and 0.5% Zn), applied in a circular shape at a minimum distance of 20 cm from the plant.

### 2.3 Physical Technosol Analysis

The properties of Technosol were evaluated for each treatment (0–20 cm depth in the planting hole) 20 months after planting, specifically in August 2019 for PPSA and in August 2021 for IRCC, following the same methodology and during the same period of the year. For the physical analysis of Technosol, eight undisturbed samples per treatment were collected from each mine (removing the litter layer beforehand) using a hammer-type sampler and volumetric rings measuring 50 mm x 53 mm. After collection, the samples were taken to the Soil Laboratory of Embrapa Eastern Amazon, where they were dried in a forced circulation oven at 105 °C for 48 h to obtain the dry mass. The fractions of Total sand, Silt, and Clay were determined using the sieve-pipette method after dispersion with 0.1 mol L<sup>-1</sup> NaOH (Gee and Bauder 1986). Total porosity (Tp, m<sup>3</sup> m<sup>-3</sup>) was determined based on the water content under saturated conditions. The pore size distribution was determined with an edge diameter of 0.05 mm, obtained by equilibrating the water content at -60 hPa for separating Macroporosity (Mac, m<sup>3</sup> m<sup>-3</sup>) and Microporosity (Mic, m<sup>3</sup> m<sup>-3</sup>) (IUSS Working Group WRB 2015). Bulk density (Bd, g cm<sup>-3</sup>) was determined using the volumetric ring method, and Particle density (Pd, g cm<sup>-3</sup>) was measured using the volumetric balloon method (Embrapa 2017) (*In Portuguese*). Gravimetric humidity (GU, %) was determined by the ratio of the volume of water to the total volume of the soil sample, and Volumetric humidity (VU, %) was obtained by multiplying GU by Bd (Caputo and Caputo 2015) (*In Portuguese*).

### 2.4 Chemical Technosol Analysis

For the chemical analyses of Technosol, eight samples were collected from the holes for each treatment of the PPSA mine (TS, SD, and CM) and eight samples from the holes for each treatment of the IRCC mine (SP, MP, and LP) using a Dutch auger. The disturbed samples were taken to the Soil Laboratory of Embrapa Eastern Amazon, where the pH was determined in H<sub>2</sub>O (1:2.5 v/v<sup>-1</sup>) using a potentiometer. For the extraction of Ca, Mg, Al, and H+Al, KCl (1.0 mol L<sup>-1</sup>) was used as the extractant, with Ca and Mg determined by flame atomic absorption spectrophotometry (F-AAS) and Al by a diluted NaOH solution in the presence of bromothymol blue solution as an indicator. P and K were extracted with Mehlich<sup>-1</sup> solution (HCl 0.05 mol L<sup>-1</sup> + H<sub>2</sub>SO<sub>4</sub> 0.0125 mol

L<sup>-1</sup>) and determined by colorimetry and flame photometry, respectively (IUSS Working Group WRB 2015). Organic carbon (O.C) was determined by the method provided by Walkley and Black (1934) and converted to organic matter (O.M) using the factor of 1.724. The values of Sum of bases (SB=Ca+Mg+K), Cation exchange capacity at pH 7 (CEC=SB + (H+Al), Base saturation (V = (SB/CEC) x 100), and Al saturation (m = (Al/CEC) x 100) were also calculated (Silva et al. 2009) (*In Portuguese*).

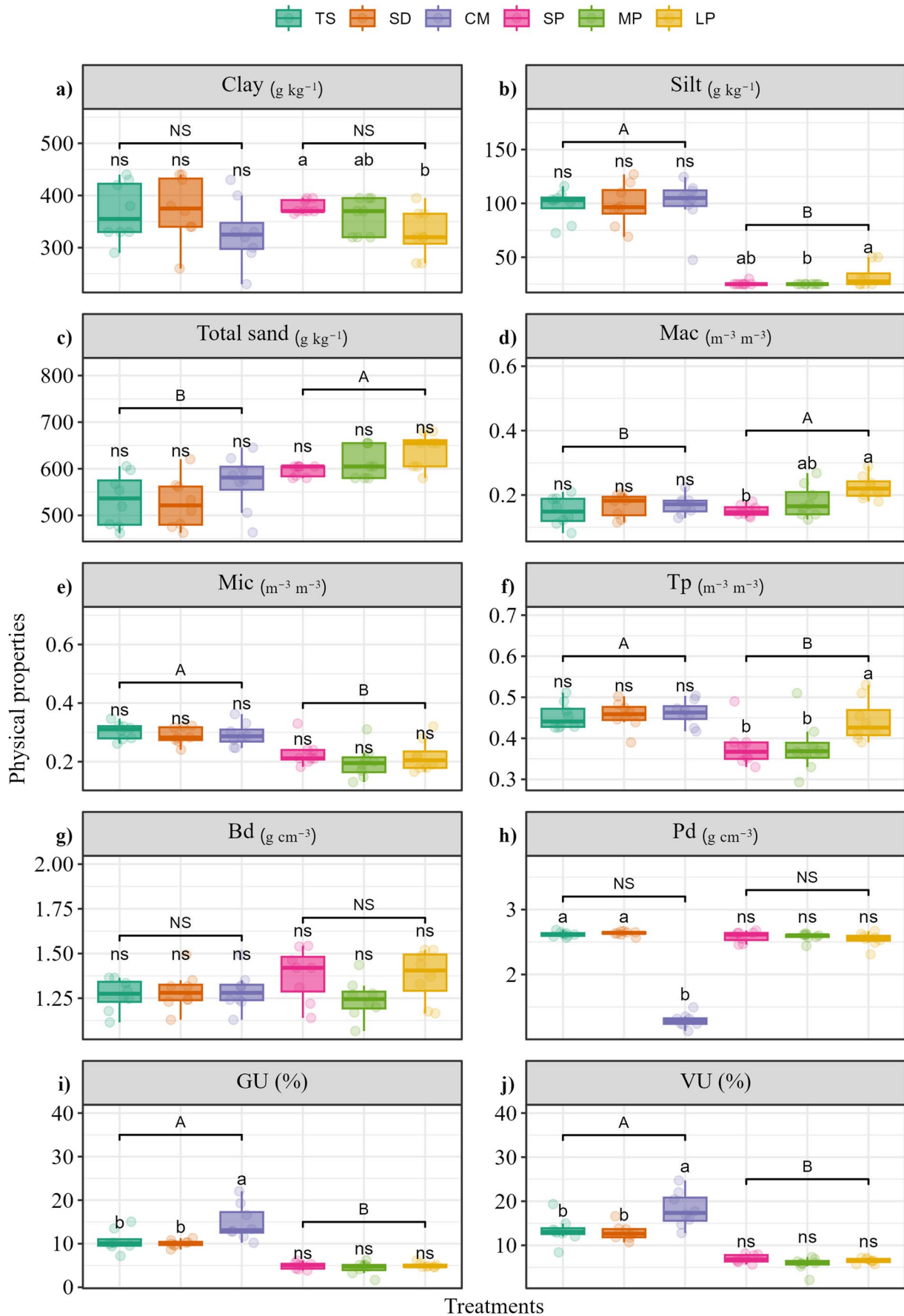
### 2.5 Data Analysis

All the physical and chemical properties of Technosol were previously subjected to the Shapiro-Wilk normality test ( $p > 0.05$ ) and Bartlett's homoscedasticity test ( $p > 0.05$ ). The data did not meet the assumptions of normality and homoscedasticity, even after transformation using the Box-Cox method. Therefore, non-parametric statistics were used through the Kruskal-Wallis test to evaluate the treatments individually for each mine. In the case of rejection of the null hypothesis ( $p < 0.05$ ), the Dunn post hoc test ( $p < 0.05$ ) was applied for median comparison. The Mann-Whitney test (Wilcoxon rank-sum test) was also used to compare the two mines, considered independent samples. To assess the dissimilarities and groupings in the properties of Technosol, a Principal Component Analysis (PCA) was performed using the Partitioning Around Medoids (PAM) technique. PAM was appropriate in this study due to its robustness against outliers and its ability to identify clusters in complex data, such as those related to the properties of Technosol. This technique was selected for its ability to optimize the ideal number of clusters for each dataset (Rousseeuw 1987). All analyses were conducted using the statistical software R, version 4.0.2, utilizing the packages *ExpDes.pt*, *FactoMineR*, *lme4*, *pamk*, and *ggplot2* (R Development Core Team 2023).

## 3 Results

### 3.1 Effects of Management on the Physical Properties

Evaluating the 10 physical properties of Technosol, significant differences were observed for the treatments of the IRCC mine in Clay, Silt, Mac, and Tp (Fig. 3A-F). For the treatments of the PPSA mine, significant differences were noted in Pd, GU, and VU (Fig. 3H-J). When comparing the mines as unpaired samples, significant differences were found in 7 of the 10 physical properties of Technosol. The management applied in the PPSA mine promoted better responses for the physical properties Mic, Tp, GU, and VU (Fig. 3E-J, Table S1).



**Fig. 3** Boxplots of the physical properties of Technosol after kaolin mining, eastern Amazon, Brazil. Lowercase letters above the boxplots compare treatments within each mine by Dunn's post hoc test. Capital letters above the boxplots compare mines using the Mann-Whitney test. NS: Non-significant statistical difference ( $p > 0.05$ ). The (A) Clay, (B) Silt, (C) Total sand, (D) Macroporosity (Mac), (E) Microporosity (Mic), (F) Total Porosity (Tp), (G) Bulk density (Bd), (H) Particle density (Pd), (I) Gravimetric humidity (GU) and (J) Volumetric humidity (VU). Legend: TS (Topsoil), SD (Sawdust), CM (Cow manure), SP (Small pit), MP (Medium pit) and LP (Large pit)

### 3.2 Effects of Management on the Chemical Properties

The applied management techniques resulted in significant differences in the chemical properties of Technosol only for Cu and Zn for the IRCC mine treatments (SP, MP and LP) (Fig. 4G-I). When comparing the mines as unpaired samples, significant differences were observed in 14 out of the 17 chemical properties of Technosol (Fig. 4A-Q). The management applied at the IRCC mine promoted better responses for the chemical properties Al, Mg, P, Fe, Cu, Mn, Zn, H+Al, pH, V, m, and total CEC. In contrast, the management applied at the PPSA mine promoted better responses for the chemical properties K and O.M (Fig. 4A-Q, Table S1).

### 3.3 Multivariate Analysis of Physical and Chemical Properties

The first two principal components separated the treatments into two clusters, where TS, SD, and CM (PPSA mine) formed one group and SP, MP, and LP (IRCC mine) formed a second group, explaining 62.66% of the variance in the 27 physical and chemical properties of the Technosol (Fig. 5A). For the PPSA mine, the PCA explained 66.72% of the total variance in the data (Fig. 5B), and for the IRCC mine, the PCA explained 70.54% of the total variance in the data (Fig. 5C). A similarity was also observed among all treatments, with an explanation of 91.79% (Fig. 5D).

## 4 Discussion

### 4.1 Impacts of Different Management Conditions on the Physical Properties of Technosol

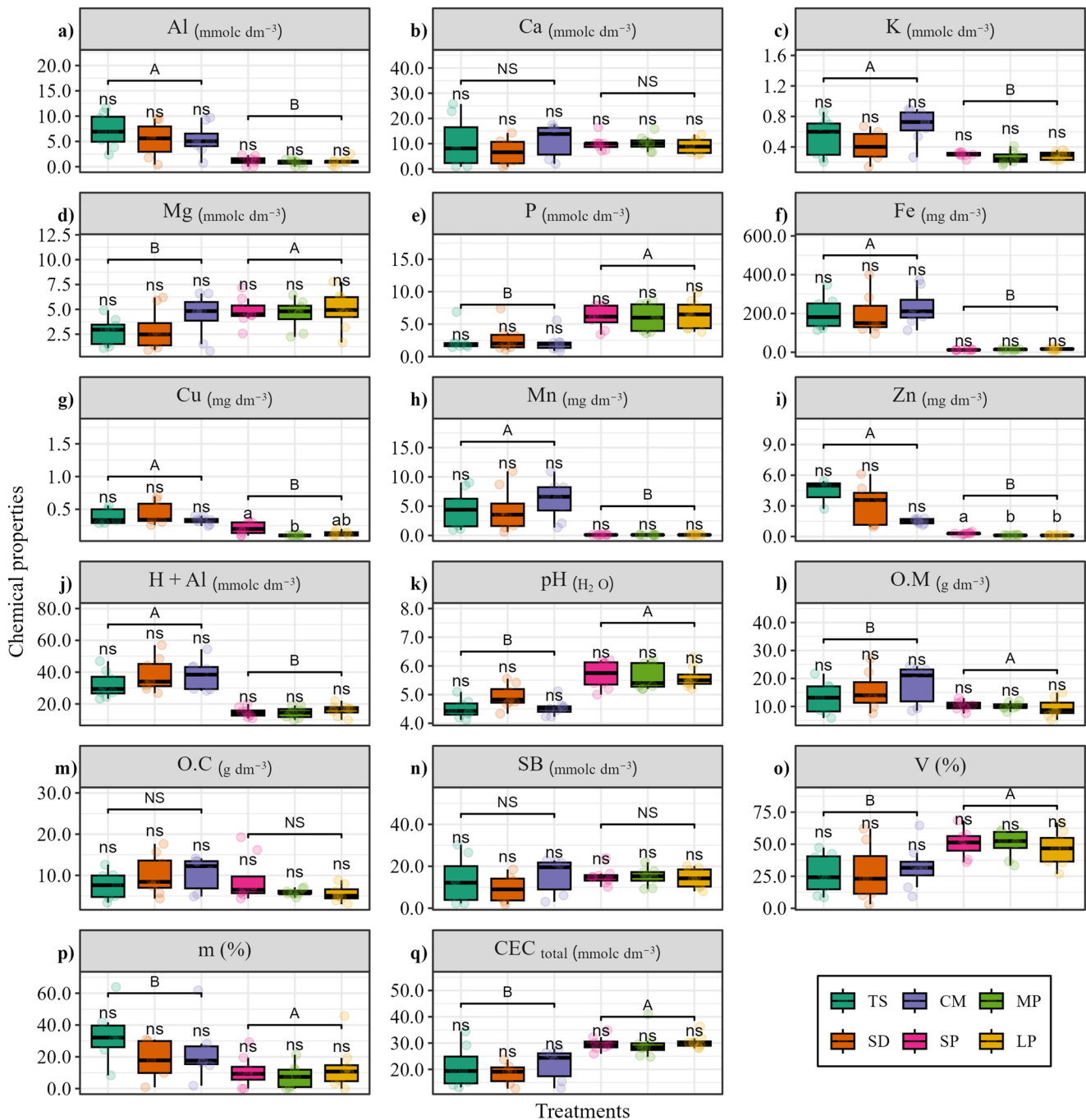
Open-pit mining activities significantly degrade original geological formations and ecosystems, causing extensive damage to the soil and adversely impacting its physical, chemical, and biological properties (Ribeiro et al. 2021). In this study, we assessed the effects of different management practices on the physical and chemical properties of Technosol following kaolin mining in the eastern Amazon. Our

findings demonstrated that Technosol properties respond distinctly depending on the post-mining management strategies, supporting our initial hypothesis. The physical properties of Technosol are critical indicators of restoration success but often experience extremely slow recovery following overuse (Trujillo-Miranda et al. 2018). Intense heavy machinery traffic further exacerbates this issue, leading in the Technosol compaction and increased Bd (Shrestha and Lal 2011). In both mines, the Bd remained below the critical limit ( $1.55 \text{ g m}^{-3}$ ), which ensures plant growth in agricultural and forest environments (Guzman and Lal 2014) for soils with Clay content between 200 and  $500 \text{ kg g}^{-1}$ . This favorable result can be attributed to the mechanical interventions employed, such as trenching, the creation of larger planting pits, and subsoiling to a depth of 60 cm, all of which likely contributed to the reduction of Bd.

The statistical differences observed regarding Tp may be related to the use of cattle manure and sawdust, which rapidly increased O.M. and had profound effects on this physical property (Abu 2013). O.M, when acting as a cementing agent that forms aggregates, directly contributes to the increase of macropores, improving soil structure and, consequently, its Pt (Oades 1984). The results for Mac were higher than those considered critical ( $< 0.100 \text{ m}^3 \text{ m}^{-3}$ ) in the literature (White 2006). Porosity is a key physical attribute that impacts water retention, nutrient availability, and root development in plants (Launiainen et al. 2022). In sandy soils, water retention is impaired, and part of the water that enters the profile is quickly drained (Troeh and Thompson 2007), as is the case with the IRCC mine. Furthermore, sandy soils have low Tp and a higher proportion of macropores, while clayey soils have high Tp and a higher proportion of micropores, which are responsible for water retention in the soil (Phogat et al. 2015).

The management practices of Technosol largely depend on its texture, which refers to the prominent size range of mineral particles and is defined by the relative proportion of Total sand, Silt and Clay (Kercheva et al. 2021). The Total sand fraction was higher in SP, MP, and LP (Table S1), but this did not negatively affect nutrient content and CEC, which contradicts findings reported in the literature (Sansupa et al. 2021). This higher proportion of Total sand may be explained by the lower O.M content in these treatments, as O.M increases the Silt and Clay fractions, which we observed for Silt in TS, SD, and CM. However, there is little experimental evidence on the combined effects of O.M and Clay in macroaggregate stabilization in relation to the properties of sandy Technosol (Abbot and Hinz 2012).

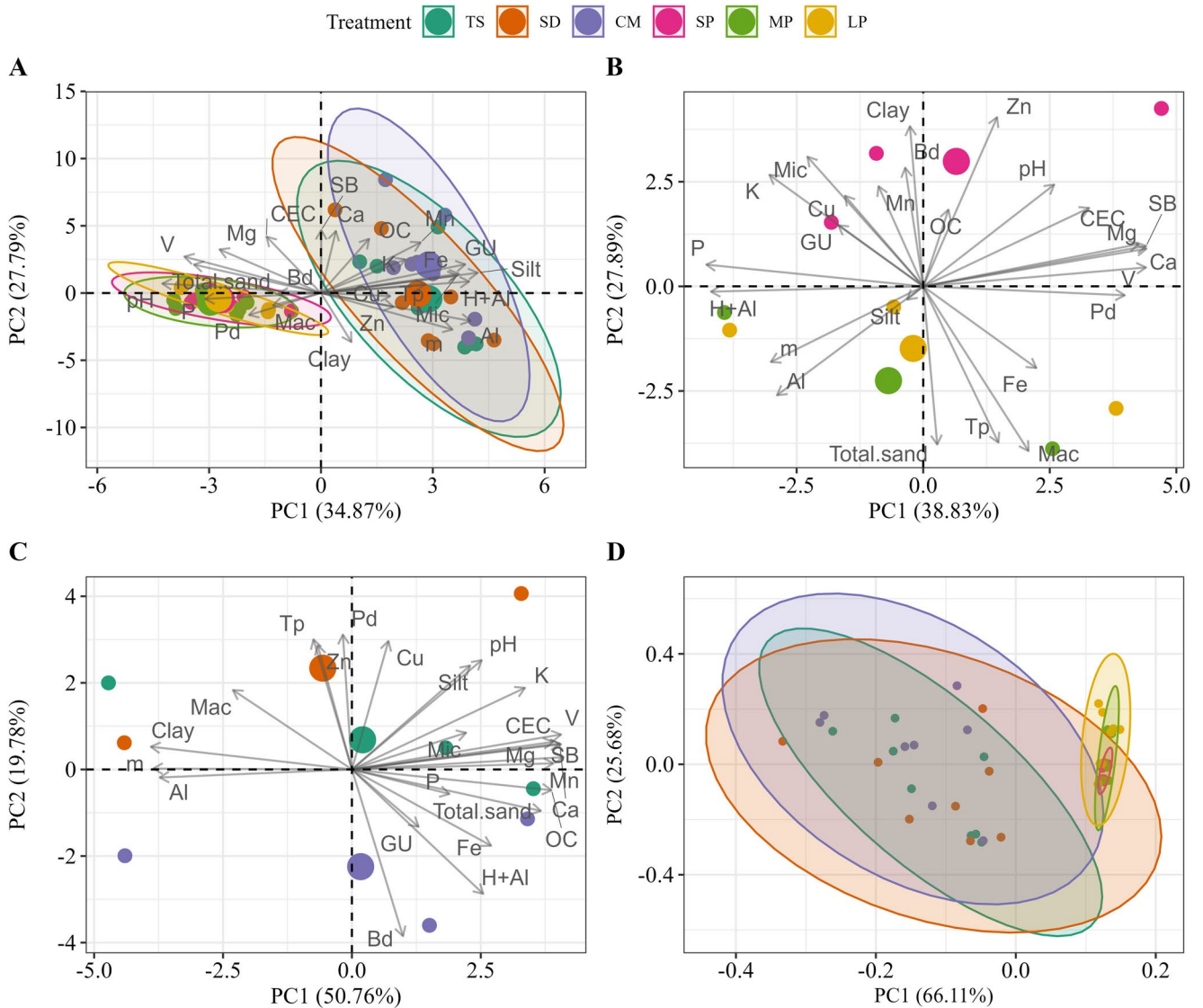
The incorporation of organic compounds contributes to moisture conservation in Technosol compared to Technosol without cover or incorporation of organic residues (Azevedo-Lopes et al. 2024). Regarding the moisture



**Fig. 4** Boxplots of the chemical properties of Technosol after kaolin mining, eastern Amazon, Brazil. Lowercase letters above the boxplots compare treatments within each mine by Dunn's post hoc test. Capital letters above the boxplots compare mines using the Mann-Whitney test. NS: Non-significant statistical difference ( $p < 0.05$ ). The (A) Aluminum (Al), (B) Calcium (Ca), (C) Potassium (K), (D) Magnesium (Mg), (E) Phosphorus (P), (F) Iron (Fe), (G) Copper (Cu), (H) Manganese (Mn), (I) Zinc (Zn), (J) Potential acidity (H+Al), (K) Hydrogen potential (pH), (L) Organic matter (O.M), (M) Organic carbon (O.C), (N) Sum of bases (SB), (O) Base saturation (V), (P) Al Saturation (m) and (Q) Cation exchange capacity (CEC). Legend: TS (Topsoil), SD (Sawdust), CM (Cow manure), SP (Small pit), MP (Medium pit) and LP (Large pit)

content of Technosol, the use of organic compounds at the PPSA mine site contributed to water retention at a depth of 0–20 cm, being higher than 10% for TS, SD, and CM. On the other hand, for SP, MP, and LP, the moisture

content was below 7%. This clearly demonstrates that the use of organic compounds is effective in increasing moisture in newly constructed sites after mining (Jourgholami et al. 2021).



**Fig. 5** Partitioning around the medoid cluster (PAM). The (A) Dimensionality reduction of the physical and chemical properties of Technosol in the PPSA and IRCC mines based on PCA, (B) PCA with the physical and chemical properties of Technosol in the PPSA mine, (C) PCA with the physical and chemical properties of the Technosol from the IRCC mine and (D) Cluster analysis for treatments at the PPSA and IRCC mines after kaolin mining in the eastern Amazon, Brazil.

## 4.2 Impacts of Different Management Conditions on the Chemical Properties of Technosol

Comparing the two evaluated sites, we observed that, regardless of the pit size (SP, MP, and LP), the application of dolomitic limestone in the IRCC mine treatments reduced the concentration of sesquioxides Al, Fe, and Mn, which are toxic elements in Technosol and severely limit plant development (Oliveira et al. 2022). Another benefit of applying dolomitic limestone to the Technosol was the increase in pH, observed in all treatments at the IRCC mine,

Legend: TS (Topsoil), SD (Sawdust), CM (Cow manure), SP (Small pit), MP (Medium pit) and LP (Large pit). Note: The variables VU and O.M were removed from the analysis. The objective of this removal was to prevent the artificial inflation of the variance in the statistical analyses, since the behavior of these variables is highly correlated with respect to GU and O.C, respectively

compared to the use of organic compounds at the PPSA mine ( $\text{pH} < 5.0$ ). pH is a fundamental chemical property for the complete restoration of Technosols, and in an adequate range ( $> 5.5$  to  $6.5$ ), it favors the development of pioneer vegetation (Olaya-Montes et al. 2021). pH is essential for estimating Technosol improvements due to its influence on nutrient cycling and other Technosol properties (Buta et al. 2019).

For Ca and Mg, although dolomitic limestone provides these nutrients in significant amounts, we expected SP, MP, and LP to have superior results when compared to TS, SD,

and CM. The similarity between the treatments reinforces the potential of agroforestry residues as fertilizers in the Amazon (Silva and Franzini 2024) and can be explained by the presence of these nutrients in the organic compounds (Mensah et al. 2022) used at the PPSA mine, as well as the mechanical protection and water retention benefits provided by mulch in the Technosol. The results also suggest that at the IRCC mine, where no mulch was used, nutrient leaching was stronger due to the finer texture of the Technosol, the higher Total sand content, and the heavy rainfall typical of the region (Fig. 1). A similar situation occurred with K, as this chemical property was higher in the treatments at the PPSA mine.

P is the main limiting nutrient for plant growth in weathered tropical soils (Elser et al. 2007), the results indicated average values higher than  $6.0 \text{ mg dm}^{-3}$  for the IRCC mine treatments and lower than  $3.0 \text{ mg dm}^{-3}$  for the PPSA mine treatments. These results can be explained by the high levels of Al and Fe in the TS, SD, and CM treatments, as large amounts of Fe and Al sesquioxides chemically bind to P, making this nutrient unavailable for plant root absorption (Guedes et al. 2020). This phenomenon can also be intensified in low pH values due to the presence of positive charges that promote adsorption (Vieira et al. 2022), as observed in the TS, SD, and CM treatments. On the other hand, considering the critical threshold for P in Technosol ( $2.6 \text{ mg dm}^{-3}$ ) (Almeida and Sánchez 2015) (*In Portuguese*), all treatments present sufficient P concentration for the development of pioneer plants. Furthermore, in tropical conditions, available soil P is scarce, and plants have adaptive mechanisms and a range of strategies to enhance the absorption of this nutrient (Sulieman and Tran 2015).

O.M is a chemical property that is positively correlated with the chemical, physical, and biological properties of Technosol (Gastauer et al. 2020). The restoration of O.M in sites degraded by mining is essential to increase CEC and overall fertility. Thus, the addition of organic compounds such as sawdust and cattle manure, used at the PPSA mine in the SD and CM treatments, reduces the deficiency of O.M caused by the removal of vegetation and surface and subsurface soil layers (Gupta et al. 2019). It is important to note that the appropriate O.M value is between  $15$  and  $30 \text{ g dm}^{-3}$  (Sobral et al. 2015) (*In Portuguese*), and the values reported in SP, MP, and LP are below the ideal scenario. Additionally, improvements in this chemical property for areas with surface soil removal are expected in the medium and long term, especially after the establishment of natural regeneration and the decomposition of litter.

CEC is one of the main chemical properties of Technosol and indicates the maximum possible availability of

nutrients for the establishment and growth of plants (Ruiz et al. 2020). In all treatments, CEC values did not exceed  $35 \text{ mmol}_c \text{ dm}^{-3}$ , which may still be associated with the recent process of topographical reshaping and the low levels of exchangeable cations. In V, the TS, SD, and CM treatments were characterized as dystrophic, with saturation below 50%. On the other hand, SP and MP were characterized as eutrophic, with saturation above 50%, indicating better nutrient availability for pioneer colonizing plants in these IRCC treatments.

### 4.3 Evaluation and Future Perspectives for the Restoration of Mining Areas in the Amazon

Overall, our results highlighted that the proper management of Technosol in areas post-mining is essential to mitigate the adverse impacts of open-pit mining activities in the Amazon. We emphasize that medium-term and long-term assessments should be conducted for comparative purposes, monitoring the trajectory and resilience of the ecosystem, correcting potential shortcomings, and evaluating the main advancements achieved. Although the absence of a control area limits our conclusions, it opens the opportunity for future studies to explore how different soil properties change in similar contexts, providing a more detailed understanding. Additionally, the economic feasibility of these techniques must be evaluated to guide management policy and practice, ensuring widespread adoption in post-mining landscapes. By adopting such comprehensive approaches, we can advance the restoration of degraded areas, promoting biodiversity conservation and ecosystem services in the Amazon.

## 5 Conclusion

The study confirmed the hypothesis that proper management can restore Technosol properties in areas impacted by kaolin mining in the Amazon. The implication and novelty of our results lie in demonstrating the interdependence between the incorporation of organic compounds and the application of lime for the re-establishment of Technosol conditions, reducing the dependence on ecological succession processes and decreasing long-term environmental impacts, highlighting a promising path for the bioengineering of degraded ecosystems. We highlight that future research could incorporate a control group to more rigorously compare changes in Technosol properties and provide stronger conclusions. Consequently, the successful restoration of degraded sites after mining hinges on the techniques and strategies employed by multidisciplinary teams of ecological restoration specialists.

**Abbreviations**

Al	Aluminum
Aw	Tropical wet
B	Boron
Bd	Bulk density
Ca	Calcium
CEC	Cation exchange capacity
CM	Cow manure
Cu	Copper
Fe	Iron
GU	Gravimetric humidity
H+Al	Potential acidity
K	Potassium
LP	Large pit
m	Aluminum saturation
Mac	Macroporosity
Mg	Magnesium
Mic	Microporosity
Mn	Manganese
MP	Medium pit
O.C	Organic carbon
O.M	Organic matter
P	Phosphorus
PAM	Partitioning Around Medoids
PCA	Principal Component Analysis
Pd	Particle density
pH	Hydrogen potential
SB	Sum of bases
SD	Sawdust
SP	Small pit
TP	Total porosity
TRNP	Total Relative Neutralizing Power
TS	Topsoil
V	Base saturation
VU	Volumetric humidity
Zn	Zinc

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**Declarations**

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