

Transforming Organic Waste into Forests

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Abstract

Reforestation and waste management are critical environmental challenges in mining, especially when topsoil is unavailable for reclamation, and incineration of organic waste proves to be an unsustainable option. This study aimed at improving the conditions of barren soils through the application of processed organic waste, creating a technosol that enhances the reclamation of mined areas. The experiment involved processed organic waste applied at three dosages (10, 20, and 40 t/ha) and a control, with five replications in a randomized block design. Guandu beans (*Cajanus cajan*) were used as an indicator plant. Physical properties (density and total porosity) and chemical properties (organic carbon) were evaluated in the 0–5, 5–10, 10–20, and 20–40 cm soil layers, as well as dry biomass and plant height at 6 and 14 months. The results showed that doses of 20 and 40 t/ha of organic waste significantly increased plant height and dry biomass compared to the control. Statistically, significant differences in organic carbon were observed in the 0–5 cm layer (p -value < 0.05). Although density and total porosity did not respond significantly to the doses of organic matter, treatments with 20 and 40 t/ha of organic waste exhibited better performance in soil recovery. Incorporating 40 t/ha of organic waste into sterile soil had a positive effect on organic carbon. These findings suggest that the application of organic waste, particularly at doses of 20 and 40 t/ha, is promising for increasing soil carbon content and dry biomass production. Furthermore, since 2015, mining has avoided the incineration of over 1165 tonnes of waste, converting it into 303.75 t of soil-enriching organic material, contributing to sustainability, reducing CO₂ emissions, and generating significant cost savings.

Keywords: Rehabilitation of mined areas, Carbon emission reduction, Soil carbon, Organic residue, Technosol.

1. Introduction

Hydro Bauxite & Alumina is a leading company in aluminium and renewable energy, committed to a sustainable future. Its goal is to create viable societies by developing industries that matter to people and society. [1], Hydro Bauxite & Alumina has transformed natural resources into innovative solutions and businesses, creating a safe workplace for 33 000 employees across more than 140 operations in 40 countries.

In Brazil, Hydro operates across the entire aluminium value chain, employing nearly 7000 people. From bauxite extraction and renewable energy generation to alumina refining, aluminium production and extrusion, Hydro supplies essential materials that drive innovation and sustainability in key sectors such as construction, automotive, and packaging.

Paragominas is an important part of Hydro Bauxite & Alumina’s strategy as a global supplier of innovative and sustainable aluminium solutions. The mine in Paragominas is responsible for bauxite extraction, located about 70 km from the municipality center, in northeastern Pará, at the Miltônia 3 Plateau [1].

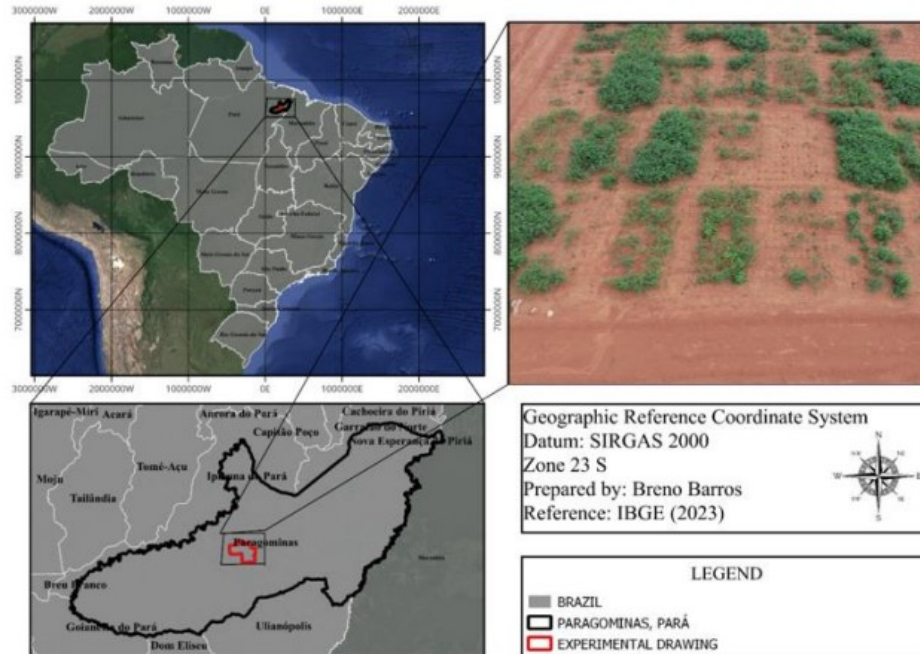


Figure 1. Location of Paragominas Mining – Hydro, according to IBGE (2023).

Hydro Bauxite & Alumina brings an innovative initiative for mined land rehabilitation: Technosol, a project that transforms organic waste, that would otherwise be incinerated, into nutrient-rich material for sterile soils (overburden), called "organic cake" [1].

The Paragominas operation began in 2007 and currently moves about 16 Mtpa, with an annual production of 11.4 Mt of bauxite. The material is transported through a 244-kilometer pipeline to Barcarena — the first in the world designed for this purpose. By 2024, the company had promoted the environmental rehabilitation of 3467 ha [1].

Currently, Hydro Bauxite & Alumina uses three techniques for mined land rehabilitation: (1) Traditional Planting, involving seed collection, seedling production, and planting; (2) Induced Natural Regeneration, involving the transport and spreading of organic soil in the area to be rehabilitated; and (3) Nucleation, involving the transport of organic soil and forest residues (branches and roots) to the areas to be rehabilitated. All these techniques rely on the use of organic soil, a natural and limited resource.

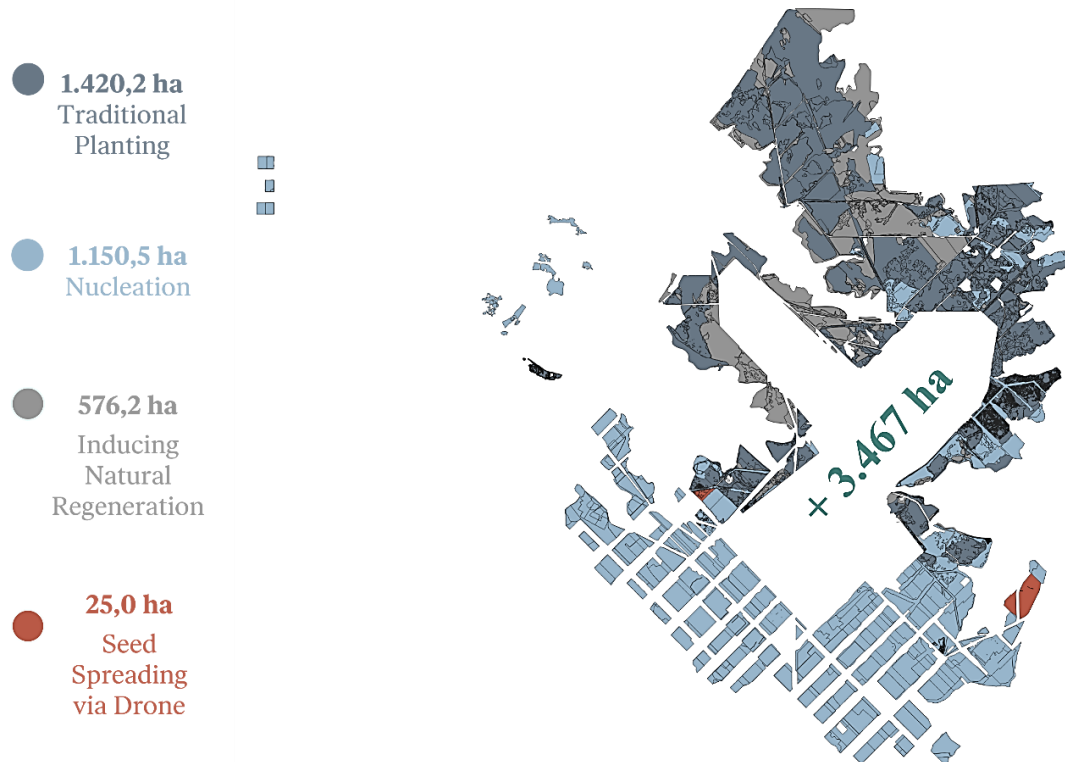


Figure 2. Areas under environmental rehabilitation process (illustration).

Hydro Bauxite & Alumina developed the Tailings Dry Backfill technology, which enables the return of inert bauxite mining tailings to previously mined areas, preceding environmental rehabilitation. This approach replaces the traditional model of permanent storage, preventing the elevation of existing starter dikes and the construction of new tailings storage structures [1] (Figure 3).

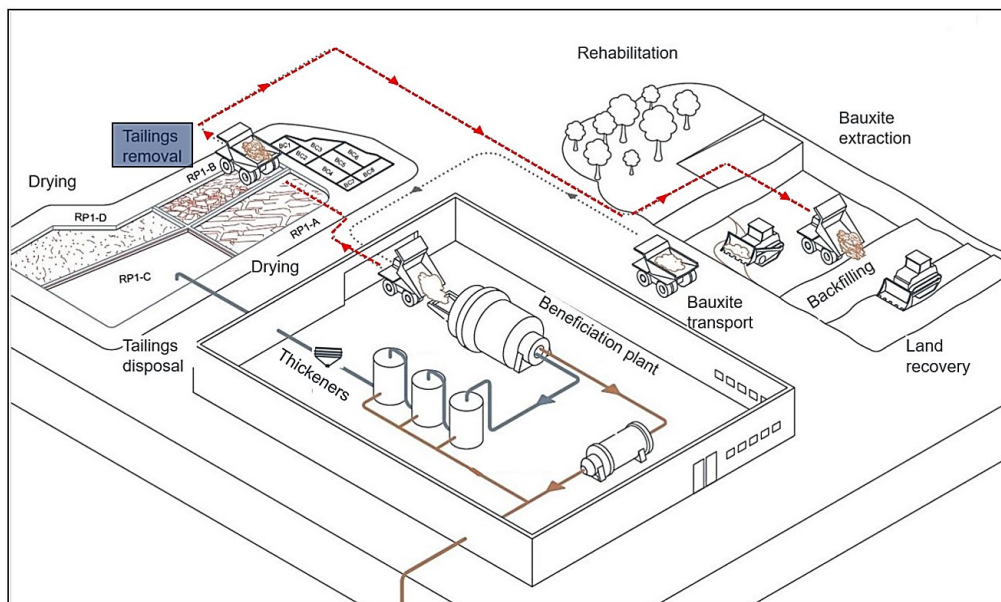


Figure 3. Schematic of Tailings Dry Backfill (illustration).

Initially, at the Paragominas bauxite mine, an area of 1326 ha was reserved on the plateau for tailings dam construction. With the adoption of the new technology, this area was reduced to

472 ha, freeing up 854 ha for environmental rehabilitation. However, this additional area available for rehabilitation lacks topsoil for immediate recovery (Figure 4).

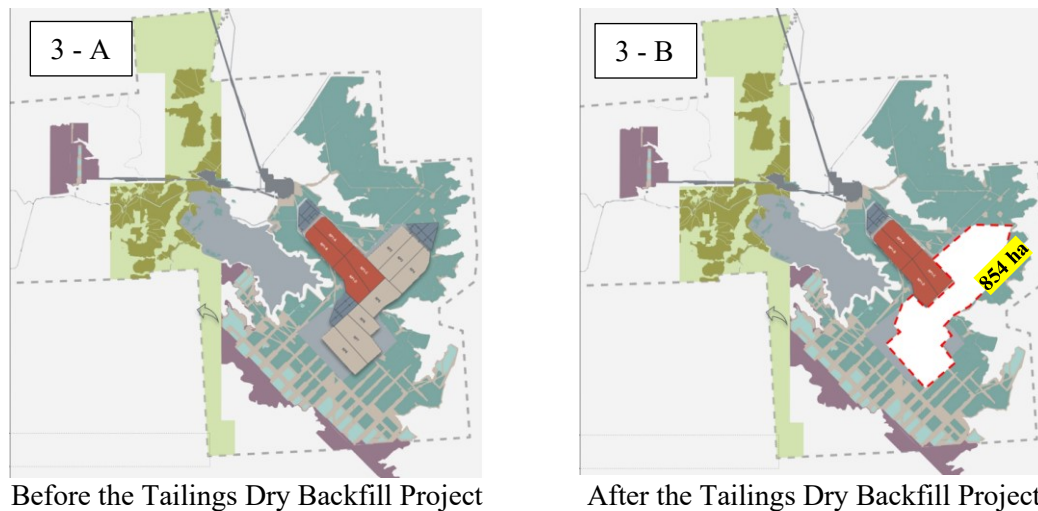


Figure 4. Areas available for environmental rehabilitation without topsoil – (illustration).

Faced with this scenario, Hydro Bauxite & Alumina in Paragominas pioneered sustainable practices in the Bauxite and Alumina (B&A) chain, converting food waste into nutrient-rich soil material — organic cake. Since 2015, in nearly a decade of action, the mine has avoided incinerating over 1165 tonnes of waste, transforming it into 303.75 tonnes of soil-enriching material.

The organic cake is mixed with sterile soil, creating a fertile substrate – the Technosol – which enables vegetation restoration in the absence of topsoil. This work resulted in a master’s dissertation conducted by an environmental department’s employee at the Paragominas mine, serving as a reference for new studies in Technosol applications.

2. Objectives

2.1 General Objective

Hydro Bauxite & Alumina aims to enrich the sterile soil from bauxite mining (overburden) with organic matter derived from a mechanical dehydration process using a TOPEMA® machine. This technology removes most of the moisture content from food waste generated in the mining company’s own canteens, producing a dry, powdery “organic cake” that is not composted. The material is then used to create a technosol capable of replacing topsoil and allowing environmental rehabilitation to begin.

2.2 Specific Objectives

- Identify the optimal organic matter dosage to formulate a technosol capable of supporting vegetative cover in sterile substrates (originally designated for tailings dams) and nutrient-poor soils with potential for forest regeneration.
- Analyse the chemical effects of organic matter incorporation into sterile soils.
- Evaluate vegetation development in treated areas, measuring the effectiveness of environmental rehabilitation.
- Assess the amount of avoided carbon equivalent emissions achieved by transforming organic waste from Paragominas Mining operations into technosol from 2015 to 2024.

3. Materials and Methods

3.1 Study Area

The study area is located at the bauxite deposit in the Brazilian Amazon, owned by the Norwegian group Norsk Hydro (3° 15' 38"S and 47° 43' 28"W), in Paragominas (Figure 1), northeastern Pará, Brazil [2]. The regional climate is tropical, according to the Köppen classification, characterized as hot and humid, with well-defined wet and dry seasons. The average annual temperature is 26.3 °C and the relative humidity is around 81 % [3]. The region has Amazonian rainforests with characteristics of dense ombrophilous forest, although altered by logging [4]. The soils are classified as dystrophic Yellow Latosols, with textures ranging from medium to very clayey [5].

3.2 Mining Method

The strip-mining method is used, starting with vegetation suppression and topsoil removal (horizon A and, occasionally, parts of subsequent horizons) to start rehabilitation in other areas. This is followed by subsurface soil removal (Overburden: horizons B and C), varying from 10 to 12 meters deep, after which bauxite extraction occurs (average of 2 m). The landscape is then reshaped and leveled with residual soil, and normally, about 30 cm of topsoil is spread over the surface (Figure 5).

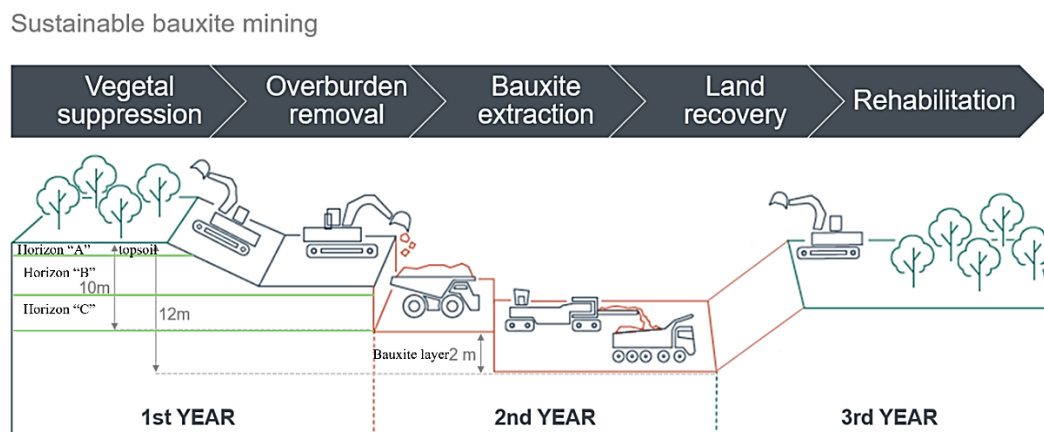


Figure 5. Scheme of bauxite mining process at Paragominas.

3.3 Study area and substrate conditions

Table 1 presents the chemical characteristics of the residual soil used in this study. As shown, the low Cation Exchange Capacity (CEC), high aluminium content, and low base saturation – especially calcium and magnesium – indicate poor fertility conditions. These factors restrict vegetation reestablishment and highlight the need for soil improvement interventions.

As illustrated in Figure 6, the post-mining landscape is composed of recontoured and scarified B and C horizons, which represent sterile substrates that naturally lack the structure and nutrients required for forest regeneration.

Table 2 summarizes the main operational stages of the field experiment. Land preparation was performed using a crawler tractor (D6) equipped with a front blade, reaching a depth of 1 meter. After repositioning the material, the area was scarified with a three-tooth scarifier featuring 70 cm tines.

Organic residues (referred to as "organic cake") were incorporated into the substrate at dosages of 10, 20, and 40 t/ha. Limestone was uniformly applied according to the Lime Requirement (LR = 0.0534 t/ha).

Following substrate conditioning, *Cajanus cajan* was sown in linear meters with 5 cm spacing. Fertilization was carried out using a standard formula: 20 kg/ha of nitrogen (N), 80 kg/ha of phosphorus (P₂O₅), and 90 kg/ha of potassium (K₂O).

Table 1 – Characterization of the chemical properties of the residual soil.

Depth (cm)	O.M	pH	Ca ²⁺	Mg ²⁺	K ⁺	Al ³⁺	H+Al	BS	t	T	V	m
	g/kg		----- cmolc/dm ³ -----								--- % ---	
0-20	1.2	4.5	0.5	0.2	0.03	0.1	2.1	0.7	0.83	0.93	78	12
20-40	1.0	4.8	0.3	0.2	0.03	0.1	2.0	0.5	0.63	0.73	73	19

O.M: Organic Matter; **pH:** Hydrogen potential; **Ca:** Calcium; **Mg:** Magnesium; **K:** Potassium; **Al:** Aluminium; **H:** Hydrogen; **BS:** Base Saturation; **t:** Real Cation Exchange Capacity; **T:** Potential Cation Exchange Capacity; **V** Base Saturation by percentage; **m** Aluminium Saturation.



Figure 6. Soil decompression activity with a scarifier, after topographic recomposition with residual soil.

Table 2 – History and description of the project activities.

Action	Activities	Description
01	Land preparation	The operation was carried out using the front blade of a crawler tractor (D6), with the equipment pushing the implement to a depth of 1 meter. After this step, the material is returned to the site, and scarification begins using a three-tooth scarifier with a 70 cm tine.
02	Incorporation of Organic Cake and limestone	The organic residues from each source were applied at the following dosages: 10, 20, and 40 t/ha (R) Limestone was applied over the entire area according to the Lime Requirement (LR): 0.0534 t.
03	Sowing	<i>Cajanus cajan</i> was sown in linear meters with a spacing of 5 cm.
04	Fertilization	Fertilization was applied at the following rates: N = 20 kg/ha; P ₂ O ₅ = 80 kg/ha; and K = 90 kg/ha.

3.4 Experimental Design

The study was conducted in a post-bauxite mining site under environmental rehabilitation, where the residual soil substrate is notably poor in nutrients and organic matter (OM), as determined by analyses performed at the depths of 0 to 20 cm and 20 to 40 cm, following the guidelines of the Soil Analysis Methods Manual [6].

The experiment was carried out in a randomized block design with four treatments applied to plots measuring 5 × 10 m, with five replicates per treatment, totalling 20 plots. The treatments consisted of mixing organic residues with the residual soil. These residues were applied from the following source and at the following dosages: cafeteria waste — dehydrated food from the mining company's cafeteria — at rates of 10, 20, and 40 t/ha; and finally, the control treatment without organic matter application (TT), as illustrated in Figure 7.



Figure 7. Layout of the plot demarcation for the study area.

Table 3 summarizes the description of each treatment. The organic residues corresponding to each source and dosage were manually incorporated into the residual soil to a depth of approximately 10 cm using a hoe. As vegetative cover and indicator species, *Cajanus cajan* (pigeon pea, var. Super N) was planted.



Figure 8. Steps of refectory waste dehydration until its effective use in the study area.

Table 3. Treatments applied in the experimental area.

Treatment	Soil treatment
TT	Residual soil without addition of organic sources
R10	10 t/ha of dehydrated food from the mining company's cafeteria
R20	20 t/ha of dehydrated food from the mining company's cafeteria
R40	40 t/ha of dehydrated food from the mining company's cafeteria

3.5 Soil and Plant Material Sampling

3.5.1 Soils/Technosols

In each plot, soil was collected at depths of 0–5, 5–10, 10–20, and 20–40 cm. For soil sampling aimed at evaluating chemical property, collections were carried out in mini trenches at three points per depth, randomly distributed within each plot. Subsequently, the collected material was mixed in a bucket to form a composite sample per depth and plot, totalling 80 composite samples for each sampling period. Chemical analyses were performed at 6 and 14 months after the experiment was completed.

Undisturbed soil samples intended for density and total porosity analyses were also collected at three points per plot in mini-trenches and were performed at 14 months after the experiment's completion. For this sampling, steel volumetric rings of approximately 100 cm³ were used, along with a “castelinho-type” auger.

3.5.2 Sampling for Aboveground Biomass and Estimation of Indicator Plant Height

At the beginning of flowering, six months into the experiment, the height and canopy of the *Cajanus cajan* tree were measured and collected. The plants were cut at 5 cm above the soil surface, where the height of the individuals cut per treatment and the lodged vegetative material in the plot were recorded. To quantify biomass, plants were collected from three subplots within each experimental plot, each measuring 1 × 1 m, totaling one square meter. The samples of plant material were placed in paper bags and transported to the laboratory at the Federal Rural University of the Amazon (UFRA), where they were dried in an oven at 65 °C.



Figure 9. Collection of biomass samples of *Cajanus cajan*.

4. Analytical Methodology

4.1 Soil/Technosol Analysis

Soil analysis is a critical step in characterizing the study area, as it provides essential data on chemical properties that directly influence the interpretation of experimental outcomes and the design of effective rehabilitation strategies following ore extraction. Due to its relevance, the soil

samples were collected (Figure 10) and submitted to the Soil Science Department at the Federal Rural University of Amazonia (UFRA), a specialized institution equipped to conduct standardized laboratory procedures with precision and reliability.

4.2 Chemical Analysis

To characterize the chemical property of all soil and technosol layers, the following were determined: pH in water, available phosphorus, basic exchangeable cations (Ca^{2+} , Mg^{2+} , and K^{+}), potential acidity ($\text{H}^{+} + \text{Al}^{3+}$), and organic matter. All analyses followed the Manual of Methods for Soil Analysis published by Embrapa [7].

From the obtained values of exchangeable cations, the following were calculated: base sum (SB) = $\text{Ca}^{2+} + \text{Mg}^{2+} + \text{K}^{+}$; cation exchange capacity (CEC) = SB + (H + Al); base saturation (V%) = $(\text{SB} / \text{CEC}) \times 100$; and aluminium saturation (m%) = $(\text{Al}^{3+} / \text{CEC}) \times 100$ [12].



Figure 10. Sampling of Technosol Samples.

4.3 Statistical Analysis

The data were initially subjected to the Shapiro-Wilk test for residual normality; for datasets that did not meet normality, a Box-Cox transformation was applied. Subsequently, analysis of variance (ANOVA) and mean comparison using Tukey's test at 5 % significance were performed.

5. Results and Discussion

5.1 Chemical Property of the Soil

Amazonian soils naturally tend to exhibit characteristics of high acidity, low natural fertility (with low levels of P, K, Ca, Mg), high aluminium saturation, and low cation exchange capacity [8]. Although most of the technosol composition (newly formed soil) originates from the natural Amazon soil as described above, some variations among treatments were identified concerning the chemical property of the technosol.

Regarding the soil chemical properties, the incorporation of organic cake into the residual soil resulted in more significant improvement in the 0–5 cm layer and only for the variables soil organic carbon (SOC) and potential CEC. In this layer, the addition of higher doses of organic residue resulted in a higher SOC after 6 and 14 months of treatment. The R40 test showed an SOC of 7.6 and 5.6 g/kg while the TT test (baseline) resulted in an SOC of 1.7 and 2.0 g/kg and test R10 showed an SOC of 1.5 g/kg after 14 months. Thus, higher doses of organic residues ensured an increase in SOC content in the 0–5 cm layer up to the last sampling period.

The increase in SOC content observed in the highest dose treatments in a short period is due to the addition of dehydrated food waste from the mining company's restaurant (similar to the experiment presented here). This supports the results of Roset [9], who observed a 74.73 % difference in total organic carbon (SOC) content in less than a year using mineral fertilizer and organic matter sources (cattle manure and chicken litter). [10] obtained similar results, with SOC increasing according to the dosage of mineral and organic fertilizers, presenting higher SOC levels in the 0–5 cm depth layer. Several other factors can influence the total soil organic carbon levels and the rate of decomposition, such as the amount of phytomass, added by vegetation, the carbon-to-nitrogen (C/N) ratio, among others, [11].

The results reiterate the importance of organic matter for increasing CEC in technosol formation in bauxite mines, since in soils dominated by iron and aluminium oxides, organic matter has a direct relationship with CEC, as noted by Novais [12], Brady and Weil [13], and Souza [14]. Due to its high SOC and therefore, CEC, even small amounts of organic matter prevent the positive charges developed on Fe and Al oxides from surpassing the negative charges [15].

Moreover, the presence of organic compounds served as an energy source for beneficial microorganisms, favouring aggregate formation processes and soil structure stabilization, which are fundamental for the functional recovery of degraded ecosystems [16].



Figure 11. Internal area of the technosol at different dosages.

Table 4. Chemical properties of the technosols evaluated at 6 and 14 months of the experiment at different depths.

Treatments	pH		Corg		CEC	
	-----H ₂ O-----		-----g/kg-----			
Sampling	6 months	14 months	6 months	14 months	6 months	14 Months
0 – 5 cm						
TT	5,24 ^{ab}	5,4 ^a	1,7 ^b	2,0 ^c	1,64 ^b	2,61 ^{ab}
R10	5,12 ^{ab}	5,1 ^a	3,4 ^{ab}	1,5 ^c	2,25 ^{ab}	2,5 ^{ab}
R20	5,20 ^{ab}	5,3 ^a	4,0 ^{ab}	3,5 ^{abc}	2,18 ^{ab}	2,9 ^{ab}
R40	4,95 ^b	5,4 ^a	7,6 ^a	5,6 ^{ab}	2,71 ^{ab}	3,2 ^{ab}

Treatments	pH		Corg		CEC	
	-----H ₂ O-----		-----g/kg-----			
Sampling	6 months	14 months	6 months	14 months	6 months	14 Months
5 – 10cm						
TT	5,35 ^a	5,1 ^a	3,2 ^a	1,4 ^a	1,7 ^a	2,6 ^a
R10	5,24 ^a	4,9 ^a	2,1 ^a	0,8 ^a	2,3 ^a	2,4 ^a
R20	5,12 ^a	5,2 ^a	2,6 ^a	1,6 ^a	2,08 ^a	2,6 ^a
R40	5,26 ^a	5,2 ^a	3,5 ^a	2,9 ^a	1,8 ^a	3,0 ^a
10 – 20cm						
TT	5,2 ^a	5,0 ^a	1,4 ^a	1,2 ^a	1,6 ^a	2,4
R10	5,2 ^a	5,0 ^a	2,1 ^a	0,7 ^a	1,9 ^a	2,2
R20	5,2 ^a	5,0 ^a	2,2 ^a	1,6 ^a	1,8 ^a	2,5
R40	5,0 ^a	4,9 ^a	2,1 ^a	1,5 ^a	2,0 ^a	2,9
20 - 40cm						
TT	5,2 ^{ab}	4,9 ^a	2,2 ^a	1,1 ^a	1,4 ^a	2,8 ^a
R10	5,2 ^{ab}	4,8 ^a	2,3 ^a	0,9 ^a	2,0 ^a	2,3 ^a
R20	5,2 ^{ab}	4,9 ^a	3,5 ^a	1,3 ^a	1,2 ^a	2,4 ^a
R40	5,0 ^b	4,8 ^a	1,6 ^a	2,2 ^a	1,6 ^a	2,5 ^a

5.2 Height and Dry Biomass of *Cajanus Cajan* (Pigeon Pea)

In the two sampling periods (i.e. 6 and 14 months), the doses of dehydrated food waste from the mining company's cafeteria at 20 and 40 t/ha (R20 and R40) resulted in average pigeon pea heights of 134.0 and 130.9 cm, respectively, in the first sampling, and 229.0 and 279.0 cm, respectively, in the second sampling. These doses positively influenced the height growth of pigeon pea compared to the control treatment (TT), which showed heights of 60 and 144 cm in the first and second samplings, respectively (Figure 12).

Although, in the last sampling period the R40 and R20 treatments did not differ significantly from R10 for this variable, the latter also did not differ from TT. This suggests that the application of dehydrated food waste at doses ≥ 20 t/ha for technosol formation was effective in increasing the height of pigeon pea plants.

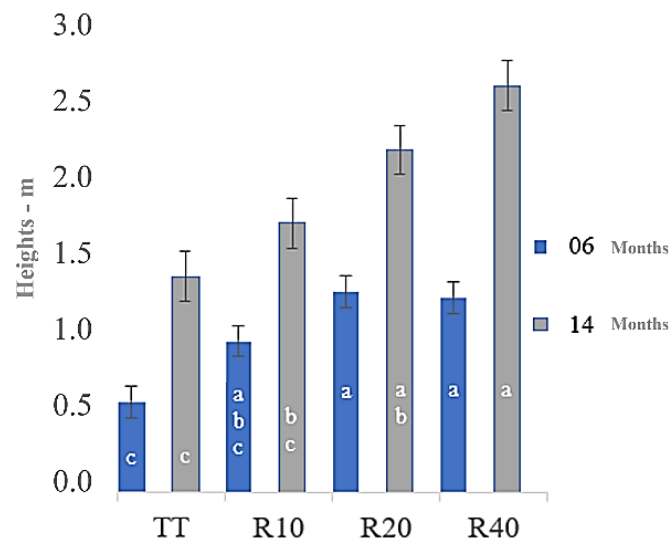


Figure 12. Height of pigeon pea at 6 and 14 months after the start of the experiment (m). For this variable, means followed by the same letter do not differ significantly according to Tukey’s test at 5 %.

Regarding the dry biomass production of pigeon pea in the two sampling periods, the best results were also obtained in the treatments with applications of dehydrated food waste from the mining company’s restaurant at doses ≥ 20 t/ha, reaching 13.12 t/ha for R20 and 19.39 t/ha for R40, while the other treatments did not differ significantly from the control (TT), which showed 2.25 t/ha (Figure 13).

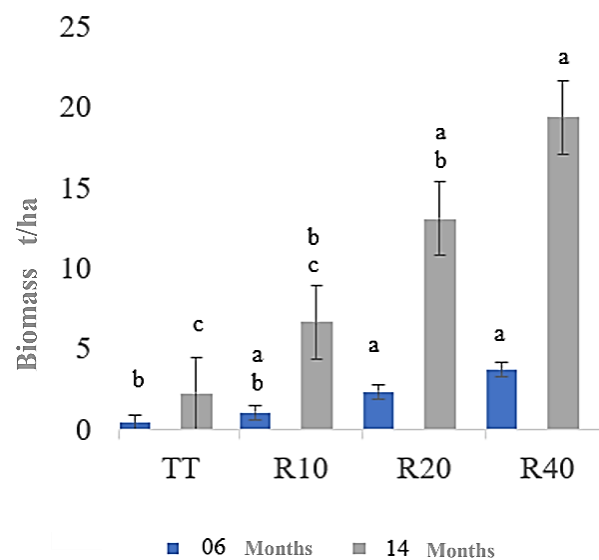


Figure 13. Biomass of pigeon pea at 6 and 14 months after the start of the experiment (t/ha). For this variable, means followed by the same letter do not differ significantly according to Tukey’s test at 5 %.

When comparing the pigeon pea height values in the R20 and R40 treatments obtained in this study with those reported by other authors in arable soils, no significant disparity was observed. For example, Azevedo [17] reported maximum height values of 257.5 cm and 260.7 cm, close to the results by Miranda [18], who recorded 270 cm in soils.

Regarding the dry biomass of pigeon pea at first flowering in this experiment, values ranged from 0.45 t/ha in the control treatment (TT) to 3.70 t/ha in treatment R40. These results are lower than those observed by Cavalcante [19], who reached 8.70 t/ha at first flowering in arable soils. However, after 14 months, the results found in treatments R20 and R40 were 13.12 and 19.39 t/ha, respectively, thus exceeding those reported by Fonseca [20] after 18 months in an environmental compensation area, where biomass of 8.54 t/ha was detected.

As shown, the technosols presented better results when compared to agricultural soils that were not tilled and, in that case, lacked the organic soil layer (topsoil) during bauxite mining activities. Both the height and dry biomass of pigeon pea showed clear positive responses to the application of dehydrated organic matter, especially at doses equal to or above 20 t/ha. The R20 and R40 treatments significantly outperformed the control (TT) and R10, particularly after 14 months of growth. Despite R40 achieving the highest average biomass yield (19.39 t/ha), the difference compared to R20 (13.12 t/ha) was not statistically significant at 5%, as shown in Figure 13.

From an operational and economic perspective, this finding is critical: applying 20 t/ha instead of 40 t/ha allows for similar vegetation development while doubling the area that can be treated with the same amount of organic input. This efficiency makes the R20 dose particularly suitable for large-scale rehabilitation strategies in mining areas.

When comparing our results with values reported in the literature for arable soils, such as those by Azevedo [17], Cavalcante [19], and Fonseca [20], it becomes clear that, even in technosols without topsoil, the treatments R20 and R40 reached biomass levels that are compatible with or superior to those reported in agricultural or environmental compensation contexts — despite the limitations of degraded mining substrates.



Figure 14. Monitoring of the experimental area in the Amazon climatic transition zone.

5.3 Avoided CO₂ Emissions

Since Hydro began processing its organic waste, it has avoided the burning of more than 1165 t of restaurant organic waste, converting it into 303.75 t of Organic Cake, a material with the potential to enrich soils with nutrients and organic matter. Besides contributing to environmental rehabilitation, this process prevented the emission of more than 2.14 tonnes of CO₂, representing a significant reduction in the operation's carbon footprint, according to IPCC [21] and J.T Houghton [22].

$$\text{CO}_2 \text{ Emissions (t)} = \text{Residue Mass (t)} \times \text{Carbon Fraction} \times 44/12 \quad (1)$$

where:

- Residue Mass (kg): total weight of the analysed organic residue (dry basis, if possible).
- Carbon Fraction: proportion of the residue mass composed of carbon. For food waste, it is generally estimated as 50%, i.e., 0.5.

- 44/12: conversion factor from elemental carbon (C) to carbon dioxide (CO₂), based on molar masses:
 - Carbon (C) = 12 g/mol
 - Carbon dioxide (CO₂) = 44 g/mol

Values' application:

- CO₂ Emissions (t) = 1165.55 × 0.5 × 44/12
- CO₂ Emissions (t) = 0.58 × 3.67
- CO₂ Emissions (t) = 2.13

Although the amount of waste avoided from incineration – over 1165 t since 2015 – might seem modest compared to global carbon emissions, which exceed 37 billion metric tonnes of CO₂ annually [23], it is significant within the mining sector's context. For comparison, tropical forests typically sequester around 2.5 to 3.5 metric tonnes of carbon per hectare per year [24]. Thus, the application of processed organic waste not only avoids emissions but also enhances carbon sequestration potential in degraded mining soils. While the contribution is relatively small in the global context, initiatives like this, when scaled or replicated, can meaningfully contribute to climate mitigation and sustainable land management.

5.4 Financial Savings

This sustainable model not only benefits the environment through avoided emissions and the creation of a technique for recovering sterile substrate, but it also generated considerable savings, reducing costs by more than 66 % (701.6 kBRL – equivalent to 130 kUSD) compared to the expenses that would have been incurred for incineration. This positive financial impact reinforces the economic viability of the proposed solution, highlighting its efficiency both environmentally and financially.

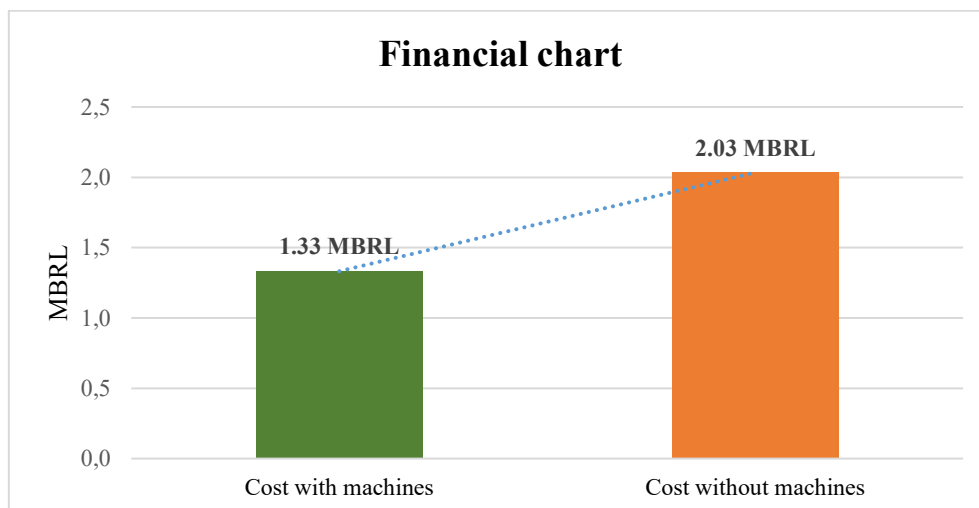


Figure 15 – Cost savings of 66% (701.6 kBRL) achieved with the use of machines.

6. Conclusions

It is noteworthy that the composition of the technosol, enriched with organic residues rich in nutrients and bioactive compounds, contributed not only to the improvement of the soil's chemical properties but also to the enhancement of physical and biological processes essential for soil health and the reconstruction of the Amazon biome. The addition of organic matter increased water retention capacity, improved soil structure, stimulated microbial activity, and accelerated nutrient cycling processes [25].

This more favourable environment contributed to greater plant species growth, as it promoted suitable conditions for aeration, nutrient availability, and root system development [26].

However, the recovery of chemical and physical properties at greater depths in technosols may require more time due to the absence of organic sources and ongoing pedogenetic processes.

It can be highlighted that the formation of technosols from residual soils of bauxite mining, combined with organic matter sources derived from the operation's own waste, such as those generated in the dining facilities, proved to be an effective and efficient strategy to improve the growth conditions of *Cajanus cajan* and restore the biome of mined areas. This technique, based on the concepts of ecological engineering, represents a viable alternative from both economic and environmental perspectives for the rehabilitation of areas altered by mining, where residual soils typically exhibit low physico-chemical quality.

Furthermore, the use of this approach contributes to the reduction of CO₂ emissions, since the organic waste used is no longer incinerated. The success of this strategy led Hydro Bauxite & Alumina to expand the production of organic cake to two additional units in Brazil.

Another relevant point in the bauxite supply chain is that other major mining companies in the sector have adopted technologies similar to Tailings Dry Backfill, aiming to reduce the construction of new dams. Since mining companies plan in advance, they are likely to face challenges with areas no longer required for dam installation and lacking topsoil to initiate environmental recovery. In this context, the use of technosols emerges as an effective alternative to address these challenges.

Among the tested doses, 20 t/ha of dehydrated organic matter proved to be the most effective and efficient option. It provided significant gains in plant height and dry biomass yield, similar to the higher dose of 40 t/ha, but with half the input cost. This makes R20 the recommended dose for large-scale application in post-mining soil rehabilitation projects, offering the best balance between biological performance and economic viability. Unlike standardized industrial inputs, there is no “supermarket” where Technosol can be purchased – it must be carefully created in the field. Identifying the appropriate proportion is essential to ensure sustainability, optimize the use of limited organic material, and maximize the impact of land reclamation efforts. This pursuit of efficiency recalls Greco-Roman architecture, when massive columns were built due to a lack of knowledge about material resistance. In similar fashion, this study helps “calculate the column’s diameter” – that is, to technically calibrate the amount of organic amendment required to support vegetation growth and ecological recovery. Knowing how much to apply is as crucial as the application itself. Like spreading butter on bread, the challenge is to apply the same amount more evenly over a larger area. This work provides concrete data to help the mining and aluminium industries apply that principle with technical precision.

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