

## BR11 - Scaling Up Soil Conditioner Production Using Bauxite Residue and Oil Palm Wastes

Patricia Silva<sup>1</sup>, Andre do Carmo<sup>2</sup>, Roseanne Holanda<sup>3</sup>, Robson Leite<sup>4</sup>, Alex dos Santos<sup>5</sup>,  
Caio Melo<sup>6</sup>, Raphael Costa<sup>7</sup>, Marcelo Montini<sup>8</sup> and Adriano Lucheta<sup>9</sup>

1. Researcher
2. Research Assistant
3. Research Assistant
4. Research Assistant
5. Laboratory Assistant
9. Director

SENAI Innovation Institute for Mineral Technologies, Belém, Brazil

6. Senior Specialist
7. Director of Bauxite & Alumina division
8. Chemical Consultant – Technology Area  
Norsk Hydro Brasil, Belém, Brazil

Corresponding author: [adriano.isi@senaipa.org.br](mailto:adriano.isi@senaipa.org.br)

### Abstract

The mining industry is undergoing significant transformation towards greater sustainability, striving to achieve carbon neutrality and "zero waste", in order to reduce its ecological impact. This shift is in alignment with the United Nations' Sustainable Development Goals (SDGs) as the sector endeavors to minimize its environmental footprint. In 2019, Norsk Hydro Brazil and SENAI Innovation Institute for Mineral Technologies (ISI-TM) initiated a project called "Bayer Process Towards the Circular Economy – Metal Recovery and Soil Conditioners from Bauxite Residue", aiming at bauxite residue (BR) valorization. One of the proposed alternatives to BR disposal was the formulation of a soil conditioner, for soil fertility improvement, using BR and agroindustrial residual biomass, which is also abundantly available in the state of Pará (Brazil). Previous lab scale tests (~9 kg) were conducted evaluating batch composting of 0 % (blank), 25 %, 50 %, and 75 % of BR with raw palm oil mill waste (POMW) and palm oil compost (POC). The results of the study revealed that the formulation of 25 % BR and 75 % POC had a water holding capacity (WHC)  $\geq 60$  % and a cation exchange capacity (CEC)  $\geq 200$  mmol<sub>c</sub>·kg<sup>-1</sup>, thus reaching the requirements set by Brazilian legislation for the production and commercialization of soil conditioners while also not differing from the blank control treatment (0 % BR). After establishing the technical foundation, the subsequent phase involved scaling up the production of the soil conditioner. The current paper addresses the scaling up of soil conditioner formulations, consisting of 25 % and 50 % BR, through a 200 kg batch composting process conducted under controlled conditions. After 90 days of composting, all the evaluated formulations fulfilled the minimum guarantees of WHC and CEC for the production and commercialization of soil conditioners, demonstrating the technology's potential for scale-up.

**Keywords:** Circular economy, Mining sustainability, Soil fertility, Waste management.

### 1. Introduction

Aluminium demand is projected to experience significant growth over the next decade, with an estimated increase of 33.3 Mt, reaching approximately 120 Mt by 2030. This growth is primarily driven by the transportation, electrical, construction, and food sectors. [1]. The transition towards a low-carbon economy and the strengthening of decarbonization policies in various countries will have a positive impact on the demand for aluminum, particularly in the production of electric vehicles, solar panels, and conductor cables, among other applications. At the same time, mining

companies have their own challenges to become more sustainable, net zero and waste zero, in accordance with the ESG principles claimed by society and investors. This shift is also in alignment with the United Nations' Sustainable Development Goals (SDGs), as the sector endeavors to minimize its environmental footprint.

In 2019, Norsk Hydro Brazil and SENAI Innovation Institute for Mineral Technologies (ISI-TM) initiated a project called “Bayer Process Towards the Circular Economy – Metal Recovery and Soil Conditioners from Bauxite Residue”, aiming at bauxite residue (BR) valorization [2-3]. One of the proposed alternatives to BR use was the formulation of a soil conditioner, for soil fertility improvement, using BR and palm oil mill wastes (POMW), which is also abundantly available in the state of Pará (Brazil) [3]. The main advantage is the use of the entire, unfractionated BR and not just a single part (e.g., iron, rare earth elements, etc.), which could result in another side residue stream. The incorporation of organic matter and treatment with organic acids has been suggested to ameliorate BR alkalinity [4] and remove sodium from desilication products [5], despite that the alkaline nature of BR is a desirable characteristic for a soil conditioner to be applied to Brazil's acid soils. We believe that a soil conditioner composed by BR and POMW could be applied for restoring the fertility of weathered acidic soils or as aiding material for rehabilitation of mining sites. Previous lab scale tests (~9 kg) were conducted evaluating the batch composting of 0 % (blank), 25 %, 50 %, and 75 % of BR with POMW and palm oil mature compost (POC) [6]. The outcome of the study revealed that the formulation consisting of 25 % BR and 75 % POC demonstrated a water holding capacity (WHC)  $\geq 60$  % and a cation exchange capacity (CEC)  $\geq 200$  mmol<sub>c</sub>.kg<sup>-1</sup>, reaching the requirements set by Brazilian legislation for the production and commercialization of soil conditioners [7]. After establishing the technical foundation [6], we decided to scale up the soil conditioners composting to 200 kg batch, testing two formulations containing 25 and 50 % of BR and POMW, under 90 days. Here we compare the results of composting temperature curves, CEC, WHC, and minor and major plant nutrients, assessing potential scaling up effects on soil conditioners formulations.

## 2. Experimental

### 2.1 Raw Materials

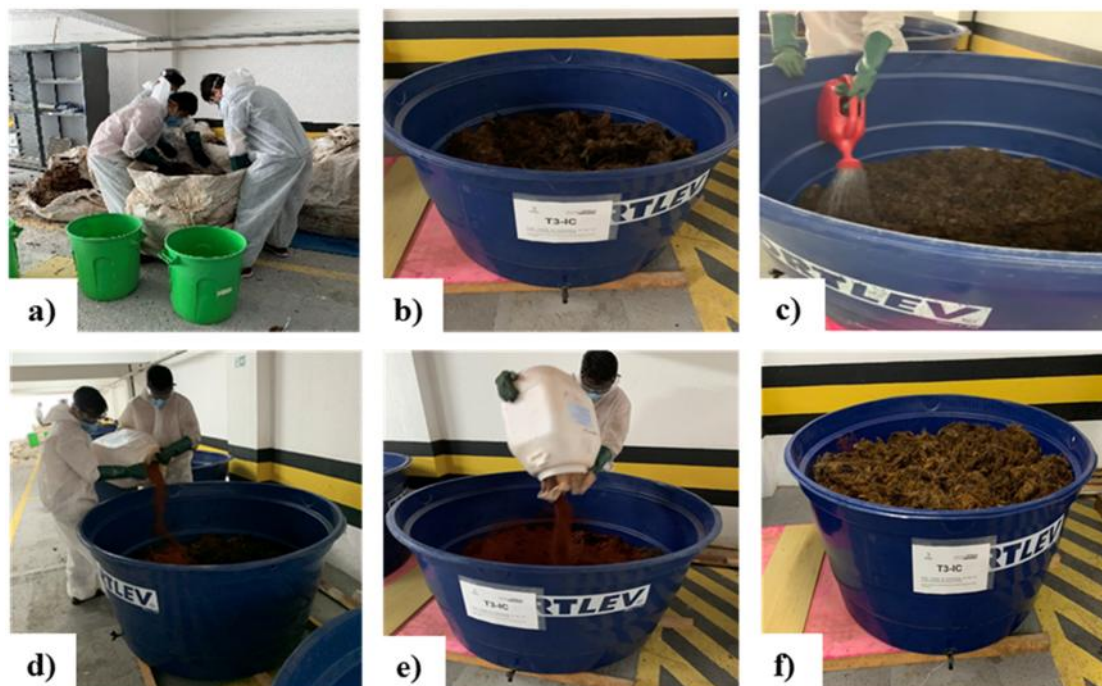
The study was conducted at the SENAI Innovation Institute for Mineral Technologies (ISI-TM), in Belém, Pará, Brazil. The BR was provided by Norsk Hydro Alunorte Refinery, whereas the palm mill wastes (POMW) were provided by Brasil BioFuels (BBF), both located in the state of Pará, Brazil. The POMW were comprised by palm mesocarp fiber (PMF), empty fruit bunch (EFB) and palm oil decanter cake (PODC). Physicochemical characterization of all raw materials was previously described in [6, 8].

### 2.2 Batch Composting Experiment

The raw materials were filled under alternating layers with 25 % (T25) or 50 % (T50) of BR into 2 000 liters polypropylene containers (Figure 1). A control unit was set by composting only the POMW without BR (Table 1). The final batch weight was approximately 200 kg of soil conditioner. Ammonium sulphate fertilizer was applied to adjust C:N ratio to 30:1 and a commercial bacterial inoculant (*Bacillus subtilis*, *Bacillus licheniformis* and *Pseudomonas fluorescens*) was added to the compost piles to accelerate organic matter decomposition. Moisture was adjusted to 60 % of WHC with deionized water and maintained throughout the experiment. The compost was manually turned every 3 days in the first 15 days, and once a week until complete 90 days, for homogenization and aeration. Temperature was checked daily using a compost thermometer (Simpla TE07) [6].

**Table 1. Composition of soil conditioner formulations.**

Batch	BR (%)	POMW (%)
Control	0	100
T25	25	75
T50	50	50



**Figure 1. Soil conditioners batch preparation. (a) Palm oil mill wastes (POMW) mixing. (b) Container filling with POMW. (c) POMW irrigation to reach 60 % moist. (d-e) Bauxite residue filling. (f) Soil conditioner formulation batch composting.**

### 2.3 Soil Conditioner Physicochemical Characterization

Representative composite samples (mix of 4 subsamples) were collected after 90 days for cation exchange capacity (CEC), water holding capacity (WHC) and chemical (major and minor plant nutrients) evaluation of the soil conditioners formulations. CEC was determined by titrimetric method, following the Brazilian's official method for plant substrate and soil conditioners analysis, adapted from Association of Official Analytical Chemists (AOAC) 973.09-1978 method – Cation exchange capacity for peat. In this method, HCl is used as a source of hydrogen ions during sites occupation and calcium acetate (pH 7,0 solution) for hydrogen ions dislocation, quantifying the formed acetic acid by NaOH titration [9]. WHC and moisture were determined gravimetrically and expressed as mass percent [9]. The pH (Orion Star A211 pHmeter, Thermo Scientific) and EC (HI 2030 conductivity meter, Hanna) were evaluated after a 1:5 (m/v) dilution with deionized water. Total organic carbon (TOC) was determined by titration, after digestion with potassium dichromate and total N was determined by the Raney's catalyst powder method for fertilizers [6]. The concentrations of Ca, Mg, Al, Fe, Mn, Cu and Zn were determined by Atomic Absorption Spectrometry (AAS) and K and Na by Atomic Emission Spectrometry (AES). Total phosphorus (P) was determined gravimetrically by the “Quimiociac” method [9]. Sulfur was determined gravimetrically after BaCl<sub>2</sub> precipitation, following the Brazilian official methods for soil analysis [9]. Bulk density was determined by gas pycnometer [10]. Exchangeable sodium percentage (ESP) was determined by equation:

$$ESP (\%) = 100 \times \frac{Na}{CEC}$$

### 3. Results and Discussion

The Eastern Amazon soils, including Brazilian Pará State, are typically acidic, having low cation exchange capacities and containing silicate minerals as main constituents. The predominant soil types are Latosols and Argisols, representing 70 % of the soils in the region. A survey of 528 samples from 88 areas at Pará State revealed that 71 % of the soils samples showed pH ranging from 3 and 4; while 36 % had pH between 4 and 5, characterized as acidic soil [11]. As result of the low fertility, forests areas are slashed and burned before sowing and then abandoned after few cultivation cycles in favor of new forests areas, resulting in a constant deforestation [11]. Since limestone sources are limiting at Pará State, representing only 1.3 % (554 million tonnes) of Brazilian's reserve, and 98 % is destined to cement production, Pará uses less than half the recommended lime to correct the acidity of the various soil types in the state [12]. Due to the inherent alkalinity of BR, the research focused on the opportunity to the soil acidity partial neutralization, replacing limestone application, increasing overall fertility and allowing a safe use of bauxite residue applying the concept of circular economy. The direct application of bauxite residue in soil was not intended for several reasons (fine particles dust formation, soil pores clogging potential, equipment corrosion, etc.), the reason why we decided to evaluate the composting process with palm oil mill waste, another abundant local available residue, as organic matter source. In our hypothesis, an organomineral soil conditioner would be more effective than a pure organic compost, due to the soil acidity neutralization potential. The initial focus of the research was to determine if the BR chemical characteristics would impact on the organic matter microbial composting process (9 kg batch composting) and if it would be possible to reach a formulation attending the Brazilian's current legislation [6]. The current manuscript evaluated the scaling up potential of composting process (200 kg batch composting) in order to obtain a soil conditioner still attending Brazilians Legislation.

#### 3.1 Composting Temperature Curves

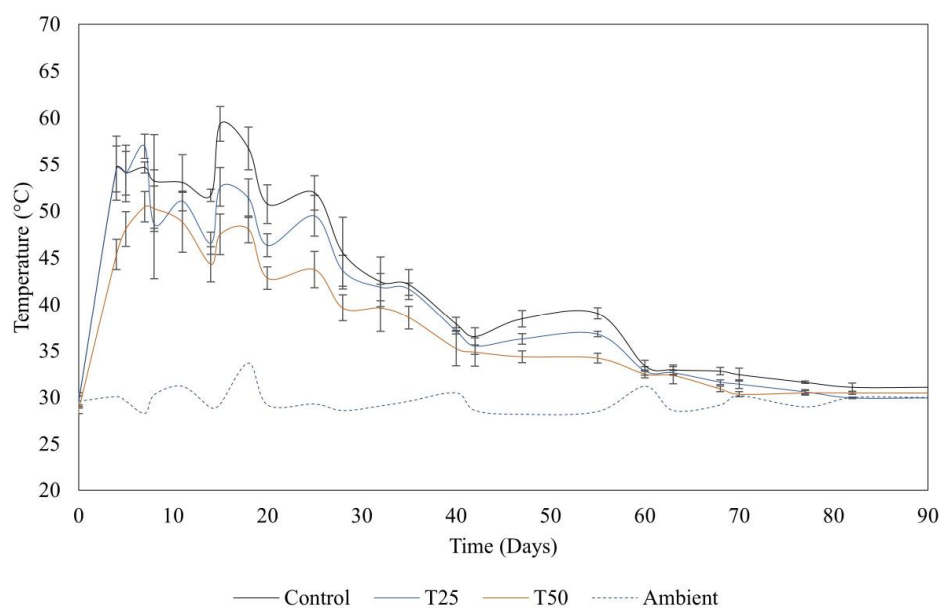
Shifts in the batch temperature were observed in agreement with the typical organic matter composting patterns [13]. After the first 10 days, we observed an increase in the heap's temperature ( $> 50\text{ }^{\circ}\text{C}$ ) at the control unit and treatments with BR (T25 and T50), corresponding to the thermophilic stage ( $> 40\text{ }^{\circ}\text{C}$ ) of organic matter composting [13]. The highest temperature ( $60\text{ }^{\circ}\text{C}$ ) was measured in the control without BR as result of the heat released from the microbial activity during POMW decomposition. Only a slightly reduction in the temperature at the thermophilic stage was observed in the formulations containing POMW and BR, suggesting the BR inherent characteristics did not limit the microbial activity during composting. As expected, average temperature declined in the interval of 30–70 days as result of the labile carbon pool being consumed by microbial activity (cooling stage), settling to room temperature after 70 days of composting (maturation stage).

The maximum temperature observed in the previously lab scale composting was  $47\text{ }^{\circ}\text{C}$  in the control without BR amendment and around  $40\text{ }^{\circ}\text{C}$  in the treatments with 25 % and 50 % of BR [6]. In this way, we can consider that scaling up the batch composting to 200 kg improved the organic matter decomposition, since heat is a direct indicator of the microbial activity and composting success.

#### 3.2 Soil Conditioners CEC, WHC, pH, EC, Minor and Major Nutrients

In Brazil, the Ministry of Agriculture, Livestock, and Supply (MAPA) provides the production and safety guidelines for soil conditioners commercialization in the market. These guidelines are

outlined in Section V of the Normative Instruction SDA No. 35, dated July 4<sup>th</sup>, 2006 [7]. According to this instruction, soil conditioners that are derived from industrial or agro-industrial raw materials and contain sodium ( $\text{Na}^+$ ) as well as potentially toxic elements (PTEs) are categorized as "Class B". To be suitable for enhancing the physical and physicochemical properties of soils, these products must meet specific criteria, including a minimum water-holding capacity (WHC) of 60 % and a minimum cation exchange capacity (CEC) of  $200 \text{ mmol}_c \cdot \text{kg}^{-1}$ . Previous lab scale tests ( $\sim 9 \text{ kg}$ ) revealed that the formulation consisting of 25 % BR and 75 % POC demonstrated a CEC  $\sim 250 \text{ mmol}_c \cdot \text{kg}^{-1}$  and a WHC  $\sim 100 \%$ , reaching the minimal requirements set by Brazilian legislation [6]. The soil conditioners formulations obtained from the scaled-up batch composting heaps (200 kg) showed an increasing in CEC to 300–400  $\text{mmol}_c \cdot \text{kg}^{-1}$  when comparing with lab scale (T2), and even the treatment receiving 50 % BR reached the minimum CEC required by the Brazilian legislation. In this study, following the official Brazilian protocol for plant substrates and soil conditioners, CEC was determined by HCl/calcium acetate method, where the exchanging sites are occupied by  $\text{H}^+$  ions. Wong & Ho (1995) indicated a selective sorption of monovalent cations (ex.  $\text{K}^+$ ,  $\text{Li}^+$  and  $\text{NH}_4^+$ ) over divalent cations (e.g.  $\text{Ca}^{2+}$ ) replacing  $\text{Na}^+$  on the BR zeolitic exchanging sites [14]. We believe HCl/calcium acetate is an appropriate method for the soil conditioner CEC determination, but other specific methods for BR CEC determination using monovalent ions other than  $\text{H}^+$  (e.g.  $\text{K}^+/\text{NH}_4^+$ ) can be compared in the next studies.



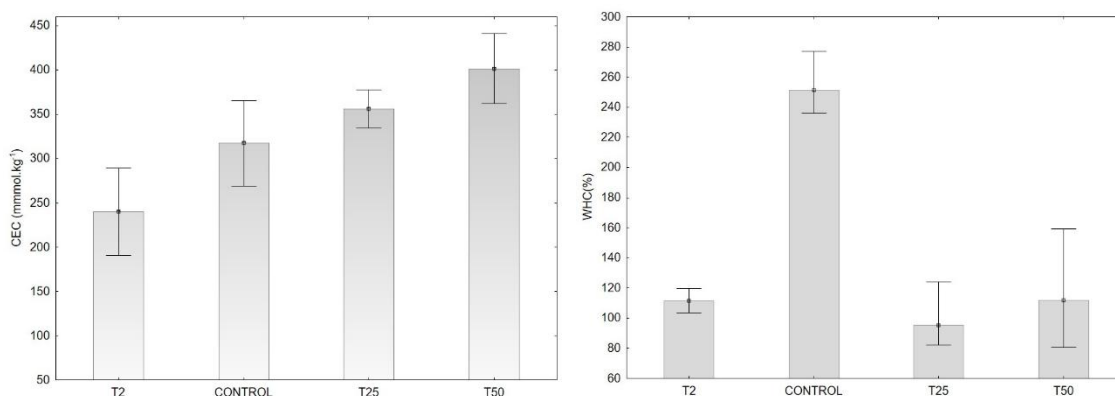
**Figure 2. Batch composting temperature (°C) along 90 days monitoring.**

Regarding WHC, similar results were obtained in the lab scale and scale up composting experiments, well above the legislation threshold of 60 %. As expected, the control containing only organic matter showed the higher WHC.

For optional labeling, but not mandatory, soil conditioners must present the same guaranties as organic fertilizers established in Normative Instruction SDA No. 61, of July 8<sup>th</sup>, 2020, regarding  $\text{C/N ratio} \leq 20$ ;  $\text{TOC} \geq 15 \%$  and total nitrogen  $\geq 0.5 \%$ . The obtained formulations (T25 and T50) fulfilled all the requirements, whereas C:N ratio was slightly above 20 in Control (23) (Table 2).

In terms of major and minor nutrients for plants, it should be noted that Brazilian legislation does not currently define tolerance levels or registration standards for soil conditioners. Considering the plant major nutrients for plants development in high weathered and low fertility Brazilian

soils, the concentrations of total N, P, K, Ca, Mg and S in the Control and T25 were quite similar, since these elements were probably derived from organic matter mineralization, and decreased in T50, due to organic matter reduced amount in this formulation. As expected, the concentration of Al, Fe and Na were higher in the treatments containing BR and proportional to the applied rate (T50 > T25). Regarding the previous lab scale tests (~9 kg), T2 treatment was composed by 25 % BR and 75 % of a mature palm oil waste compost instead of fresh palm oil mill wastes as in T25. An interesting observation was the reduction on total Al and Fe in the treatment T25 in comparison with T2, even both treatments containing 25 % BR. Further investigation might be conducted to evaluate the reasons why the batch composting reduced Al and Fe final concentration after 90 days composting. Regarding the minor plant nutrients, we observed a reduction in the levels of Mn, Cu and an increasing in Zn in the scaled-up soil conditioner (T25 and T50) when compared with lab scale composting (T2).



**Figure 3. Compost cation exchange capacity (CEC) and water holding capacity (WHC) in the soil conditioners, after 90 days composting. T2- 25 % BR and 75 % POC [6]. Control- 100 % POMW; T25 – 75 % POMW + 25 % BR; T50 – 50 % POMW + 50 % BR.**

Sodium concentration was similar in T2 [6] and T25 (~32 g/kg) carrying on 25 % BR, but the exchangeable sodium percentage (ESP) was 4.5 % lower in T25, in response to the higher CEC. T50 showed an ESP of 11.7 %, whereas ESP in Control was 0.1 % (Table 2). Sodium excess in soil can result in clay dispersal and structural disaggregation, also affecting hydraulic and electrical conductivity, inhibiting plant growth [15]. The Na in BR is mostly associated to the desilication products (e.g. sodalite), under sparingly soluble form, or under very soluble forms such as remaining alkali, sodium aluminate and sodium carbonate [16]. Residual sodium species can be partially neutralized by carbon dioxide, forming sodium carbonate or other metal carbonate [16], whereas sodium in DSP structure can be exchanged by other ions or released after DSP hydrolysis [17]. Recent works revealed that sodium removal efficiency is acid specific and low molecular weight organic acids released from plant roots and organic matter decomposition interacts with sodalite crystal changing its structure, releasing Na and reducing pH [5]. Despite the remaining sodicity, soil amendment with 40 t/ha of a soil conditioner containing 25 % of BR and 75 % POC showed a final soil ESP < 10 % [18]. To be classified as sodic, soil ESP must be  $\geq 15$  %. Indeed, the soil conditioners amendment improved the fertility of the native Brazilian soil and increased the signalgrass (*Urochloa hybrida*) production, with results similar to limestone application [18]. However, we are aware that Na level is a critical parameter for the proposed soil conditioner and further studies will focus on alternatives to Na removal from BR before composting.

Regarding pH, the scaled up T25 formulation showed a final pH of 7.9, lower than the lab scale T2 formulation (9.8), also containing 25 % BR. The almost 2 point pH reduction in the formulation could be resulted by a more efficient composting and organic acids releasing, partially neutralizing BR pH. EC values were also lower in scaled up formulations (2.1 mS/cm)

and lower than Control (2.1 mS/cm). Finally, the tapped bulk density in all soil conditioners containing BR showed values around 0.9 g/cm<sup>3</sup>. The influence of pH, EC and bulk density will be better addressed in future agronomical tests with different texture soils.

**Table 2. Physicochemical attributes of soil conditioners formulations after 90 days composting.**

Attribute	Unit	Batch			
		T2*	Control	T25	T50
Total N	%	0.9	1.5	1.4	1.1
TOC	%	18.5	35.9	24.8	21.2
C:N	-	20	23	18	19
P	g kg <sup>-1</sup>	5.0	4.8	3.7	3.2
K	g kg <sup>-1</sup>	10.7	21.8	20.4	13.4
Ca	g kg <sup>-1</sup>	8.2	5.7	3.0	3.0
Mg	g kg <sup>-1</sup>	2.2	2.1	1.7a	1.3
S	g kg <sup>-1</sup>	0.1	5.1	7.1	4.0
Al	g kg <sup>-1</sup>	53	1.1	25.1	32.8
Fe	g kg <sup>-1</sup>	111.1	4.1	84.5	115.3
Mn	mg kg <sup>-1</sup>	87.5	14.8	3.1	0.0
B	mg kg <sup>-1</sup>	-	433	233	633
Cu	mg kg <sup>-1</sup>	35	8.5	3.6	4.7
Zn	mg kg <sup>-1</sup>	35	53.6	47.2	42.3
Na	g kg <sup>-1</sup>	32.3	0.4	30.8	46.9
ESP	%	13.2	0.1	8.7	11.7
Bulk Density	g cm <sup>-3</sup>	0.90	0.49	0.82	0.89
pH	-	9.8	5.3	7.9	8.9
EC	mS cm <sup>-1</sup>	3.3	2.7	2.1	2.1

\*Data extracted from [6].

#### 4. Conclusions

In general, the Eastern Amazon soils are acidic and nutrient poor, pressuring constant deforestation of new areas for cultivation. Limestone reserves are insufficient for proper agricultural soil pH correction and BR inherent alkalinity could be an alternative for pH improvement in abandoned areas. Here, we showed the success batch composting scaling up to 200 kg of a proposed soil conditioner formulation containing BR and POMW. Even the proposed formulations fulfilling the minimal requirements of CEC and WHC set by Brazilian's legislation, a complete characterization of the soil/plant/water interactions, under fully controlled conditions, must be done before the soil conditioners production and commercialization.

#### 5. References

1. IAI - International Aluminum Institute, 2022. Opportunities for aluminium in a post-Covid economy. <https://international-aluminium.org/resource/opportunities-for-aluminium-in-a-post-covid-economy/> (Accessed on 30 June 2023).

2. Paula Araújo et al., Bayer Process Towards the Circular Economy—Metal Recovery from Bauxite Residue, *Light Metals 2020*, [https://doi.org/10.1007/978-3-030-36408-3\\_14](https://doi.org/10.1007/978-3-030-36408-3_14).
3. Roseanne Holanda et al., Bayer Process Towards the Circular Economy—Soil Conditioners from Bauxite Residue, *Light Metals 2020*, [https://doi.org/10.1007/978-3-030-36408-3\\_15](https://doi.org/10.1007/978-3-030-36408-3_15).
4. Shengguo Xue et al., Insights into variations on dissolved organic matter of bauxite residue during soil-formation processes following 2-year column simulation, *Environmental Pollution*, Vol 292, Part A, 2022, 118326, <https://doi.org/10.1016/j.envpol.2021.118326>.
5. Sicheng Wang et al., Sodium removal from bauxite desilication product (sodalite) aided by chelating effects of inorganic and organic acids, *Journal of Environmental Management*, Vol. 338, 2023, 117837, <https://doi.org/10.1016/j.jenvman.2023.117837>.
6. Robson Leite et al., Bauxite Residue Valorization — Soil Conditioners Production Through Composting with Palm Oil Mill Residual Biomass. *Science of The Total Environment*, v. 835, 155413, 2022. <https://doi.org/10.1016/j.scitotenv.2022.155413>
7. Brazil -Ministry of Agriculture, Livestock and Food Supply, 2006a. Instrução Normativa nº 35, 04 de julho de 2006a Brasília, DF.
8. Patricia Silva et al., Brazilian Bauxite Residue Physical–Chemical Characterization and Acidic Neutralization Potential, *Light Metals 2020*, [https://doi.org/10.1007/978-3-030-36408-3\\_16](https://doi.org/10.1007/978-3-030-36408-3_16)
9. Brazil - Ministry of Agriculture, Livestock and Food Supply, 2017. Manual de métodos analíticos oficiais para fertilizantes e corretivos. Ministério da Agricultura, Pecuária e Abastecimento. Secretaria de Defesa Agropecuária. – Brasília: MAPA 978-85-7991-109-5, 240 p.
10. EMBRAPA, 2017. Manual de métodos de análise de solo. [https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/1107196/1/Pt3Cap1Carbo noorganico.pdf](https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/1107196/1/Pt3Cap1Carbo%20noorganico.pdf), Brasília, DF.
11. Edna Souza et al., Physical, chemical and mineralogical attributes of a representative group of soils from the Eastern Amazon, Brazil, *Soil*, Vol. 4, 2018, <https://doi.org/10.5194/soil-4-195-2018>, 2018.
12. Pará State, Mining Plan of Pará State 2014-2030, 2011, [https://sedeme.pa.gov.br/sites/default/files/paras\\_mining\\_plan.pdf](https://sedeme.pa.gov.br/sites/default/files/paras_mining_plan.pdf).
13. Khalid Azim et al., Composting parameters and compost quality: a literature review. *Organic Agriculture*, Vol. 8, 141–158, 2018, <https://doi.org/10.1007/s13165-017-0180-z>.
14. Jonathan Wong & G. E. Ho, Cation Exchange Behavior of Bauxite Refining Residues from Western Australia, *Journal of Environmental Quality*, Vol. 24 1995, <https://doi.org/10.2134/jeq1995.004724250024000300010x>.
15. Markus Gräfe et al., Bauxite residue issues: III. Alkalinity and associated chemistry, *Hydrometallurgy*, Vol. 108, 2011, doi:10.1016/j.hydromet.2011.02.004.
16. Ken Evans, The History, Challenges, and New Developments in the Management and Use of Bauxite Residue, *Journal of Sustainable Metallurgy*, Vol. 2, 2016, DOI 10.1007/s40831-016-0060-x.
17. Hong Peng et al., Acid Leaching of Desilication Products: Implications for Acid Neutralization of Bauxite Residue, *Industrial & Engineering Chemistry Research*, Vol. 59, 2020, DOI: 10.1021/acs.iecr.0c00423.
18. Robson Leite et al., Environmental and agronomic assessment of soil conditioners produced from bauxite residue and oil palm wastes, *Environmental Research*, Vol. 233, 2023, <https://doi.org/10.1016/j.envres.2023.116474>