Demonstration of a Composting Plant for Soil Conditioner Incorporating Bauxite Residue

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Abstract

The proof of concept for producing a soil conditioner (SC) using a composting process with bauxite residue and oil palm waste had been successfully conducted at laboratory scale producing 200 kg of SC per batch at Technology Readiness Level (TRL) of 1–5 in previous feasibility studies. The study covered by this paper represents the continuation of the project "Bayer's Process Towards the Circular Economy: Recovery of Metals and Production of Soil Conditioners from Bauxite Residues", by progressing to prototype stage a soil conditioner demonstration plant (TRL 6) which will be installed at Norsk Hydro Bauxite & Alumina, in Barcarena (Pará State, Brazil). The objective is to scale up SC production using composting heaps at a pilot scale (tonnes) to validate the process efficiency and quality parameters within a simulated operational environment. Additionally, this phase aims to produce a sufficient volume of material for agronomic trials involving various plant species. This innovative product has the potential to aid the rehabilitation of degraded or low-productivity areas, recovery of post-mining sites, and even the cultivation of bioenergy-producing plant species.

Keywords: Circular economy, Sustainability, Industrial residues valorisation, Soil fertility.

1. Introduction

A soil conditioner is a product whose purpose is to improve the physical, physicochemical, and/or biological properties of the soil. It can be produced with raw materials from industrial processing like Bauxite Residue (BR) and/or agro-industry wastes (Class B). During the project "Bayer's Process Towards the Circular Economy: Recovery of Metals and Production of Soil Conditioners from Bauxite Residues" [1–3], the process of composting BR, together with the residual biomass from oil palm processing (Palm Oil Mill Waste – POMW), was evaluated on a laboratory scale (TRL 3). Batches of around 200 kg of Class B SC were produced, containing 25 % BR, in compliance with current legislation [4] and showing promising results in the recovery of soil fertility and brachiaria grass growth, when compared to control treatments [1–3]. The product from this new technology has the potential to be applied in the recovery of abandoned and/or low productivity anthropized areas, rehabilitation of post-mining areas, or even in the cultivation of species with the potential to produce bioenergy.

Brazil has around 109 million hectares (ha) of degraded areas or pastures with low fertility, of which 27 million ha are in the Amazon biome, an area equivalent to 27 million soccer fields [5]. Studies suggest that recovering the fertility of these soils would cost more than 600 billion BRL if the same fertilizers used in agriculture were applied to replace nutrients. Given this scenario, alternatives fertilizers are economically necessary for recovering the fertility of anthropized soils.

Regarding the recovery of mining areas, Norsk Hydro Brazil (Hydro) is a pioneer with the Tailings Dry Backfill (TDB) waste management system, which returns bauxite tailings to already mined areas after dehydration, without any risk to the environment and eliminating the need for tailings dams [6, 7]. Hydro also manages the Brazil-Norway Biodiversity Research Consortium (BRC) with a pillar on the "Restoration of tropical forests, including restoration of biodiversity and forest soils". Hydro also has partnerships with the Brazilian Agricultural Research Corporation (EMBRAPA) and the Vale Institute of Technology to apply innovative techniques to reforestation and biodiversity studies in the areas of Mineração Paragominas. Since plant operation began in 2006, around 2905 hectares of the Amazon biome have already been reforested, with 259 hectares in 2022 alone [8, 9]. The SC has the potential to be applied mine rehabilitation areas as a strategy to accelerate soil fertility and capture carbon. This approach can be beneficial in enhancing soil quality, where the natural recovery is limited. By improving soil characteristics, the use of SC can support faster ecosystem recovery and contribute to more sustainable and efficient rehabilitation practices in post-mining landscapes.

In addition to the benefits from revegetation and recovery of biodiversity in the mined areas, the recovered anthropized soils or conventional agricultural areas could be used for the production of plant species with potential for bioenergy production, for example: oil palm (biodiesel), agave (ethane 1G and 2G) or biomass (grasses/shrubs), further contributing to the sustainability of the Brazilian energy matrix.

As a continuation of the project, this proposal aims to scale up production to the level of tonnes of SC, using the composting process in heaps, under controlled conditions in a prototype demonstrator installed in the company itself (TRL 6). The product obtained will be extensively evaluated in terms of its composition, environmental safety, improvement of soil fertility and agronomic potential in key species for revegetation of mining areas and crops destined for energy conversion. One of the selection criteria for the plant species will be the bioeconomic potential for generating income in communities around the mining area.

The project directly addresses the United Nations (UN) Sustainable Development Goals (SDGs): 2- Zero hunger and sustainable agriculture; 7-Clean and affordable energy; 9-Industry, innovation and infrastructure; and 13-Action against global climate change, among other goals indirectly.

2. Methodology

Technology Readiness Level (TRL) methodology provides a systematic framework for assessing the maturity of a technology. The TRL scale is composed of nine levels, which are grouped into three main stages: Basic Research (TRL 1–3), where fundamental principles are observed and technologies are conceptually formulated; Development (TRL 4–6), which encompasses laboratory validation, process optimization and pilot-scale testing, and Demonstration (TRL 7–9), which includes prototype validation in operational environments, pre-commercial scaling and full industrial application [10].

E. H. Conrow [11] defined this methodology as a "logical measurement system that simplifies the evaluation of the readiness of a given technology and cohesive maturity analogy across various types of the technology". In this context, the TRL scale reflets the evolution of technology from initial concept and early laboratory studies to real word testing and demonstration.

In this context, the application of the TRL framework is essential for evaluating the scaling potential of the soil conditioner developed from BR and POMW. This work advances the technology from laboratory validation (TRL 4) – which involved physicochemical characterization, leaching assessments, and small-scale agronomic trials – to pilot-scale demonstration (TRL 4–6), including scaled experiments in controlled environments with replicated treatments and performance evaluations. Based on this TRL framework, the following sections are organized as part of this scope.

2.1 TRL 1-4: Evaluation of Bauxite Residue and Palm Oil Waste for Soil Conditioner Production

Figure 1 shows the SC project's development, focusing on TRL 1–4 stages (initial concept validation, material characterization, and laboratory-scale optimization) which were completed and published previously [1–3]. These results provide a technical basis for advancing to higher TRL levels and pilot-scale validation.

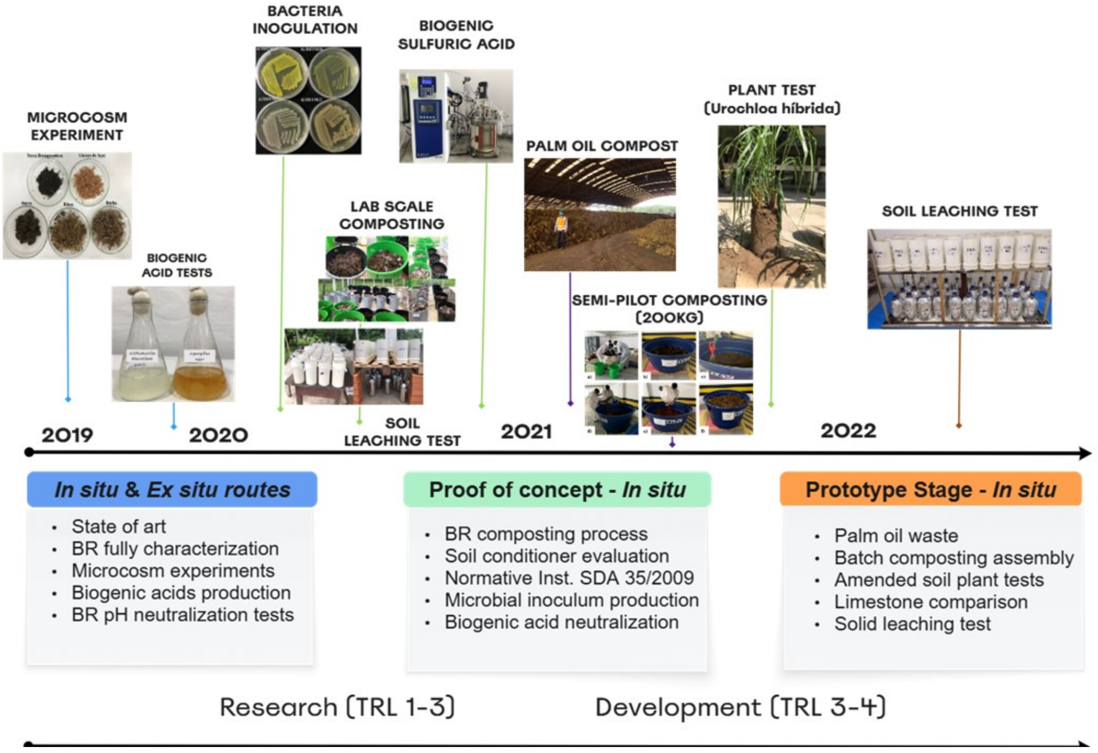


Figure 1. TRL evolution from initial research to experimental proof of concept (TRL 1–4).

2.1.1. TRL 1–3 (Basic Research and Proof of Concept)

The initial research phase (TRL 1–3) involved literature review, raw materials characterization, and exploration studies to identify the most appropriate source of organic matter for the project.

Bauxite residue is a by-product obtained from the Bayer process of alumina production. Bauxite residue is the solid mixture remaining after the lixiviation of aluminium minerals from bauxite added to other compounds formed during the Bayer process. The BR consisted of a press-filtered sample provided by Norsk Hydro Alunorte Alumina Refinery. The mineralogy includes hematite, anatase, sodalite, gibbsite, quartz and aluminous goethite, and chemical composition of Fe_2O_3 (36.75 %), Al_2O_3 (20.09 %), SiO_2 (15.55 %), Na_2O (10.27 %), TiO_2 (5.18 %), CaO (1.35 %), ZrO_2 (0.86 %), SO_3 (0.16 %), V_2O_5 (0.14 %) and loss on ignition (9.29 %) [12]. The BR presented pH in water (1:10) of 10.6 and EC (Electrical Conductivity) of 4.01 mS·cm^{-1} [13]. The alkaline nature of BR can be used to increase the pH of soils, especially acid soils [14, 15].

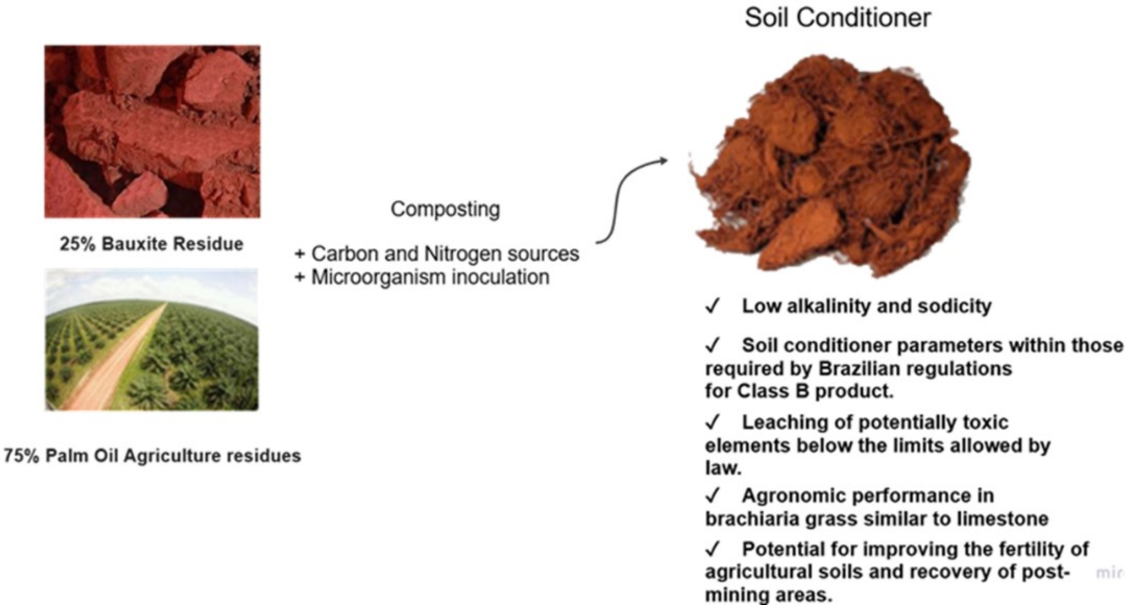
Proof-of-concept experiments were conducted using microcosm tests to evaluate "*in situ*" pH neutralization of BR due to the microbiological metabolization of the organic matter. For this purpose, various organic matter sources found in the state of Pará were used. Examples of the organic materials studied include spent seeds from Açaí (*Euterpe oleracea*), fruit bunches (EFB) and palm oil decanter cake (PODC) and spent Fuller's earth [13]. Additionally, an "*ex-situ"* approach also was tested, involving a biotechnological method to neutralize BR using sulfuric and citric acid, produced by the bacterium *Acidithiobacillus thiooxidans* and by the fungi *Aspergillus niger* [16.], respectively, however the "*in-situ*" route provided better results. Results from the "*in situ"* experiments indicated that palm oil mill waste (fiber and bunches) provided greater pH reduction rates compared to other organic matter. Consequently, POMW was selected as the carbon source. Laboratory-scale experiments were conducted to produce SC from mixture of POMW and BR using a composting process. POMW showed pH near neutrality (6.8–7.5), C/N ratio was 42:1 (mesocarp fiber, empty (palm) fruit bunches) and 32:1 (palm oil decanter cake PODC) due to the greater presence of cellulose and lignin [13]. The POMW was supplied by a palm oil refinery, also located in the State of Pará, in Brazil.

2.1.2 TRL 4 (Development and Laboratory Validation)

A Design of Experiments (DOE) to further understand the SC composting system using BR and POMW were made. Bench-scale experiments (7.5 to 9 kg) were conducted with BR: POMW ratios of 25 %, 50 % and 75 %. Key parameters were evaluated, including potential of hydrogen (pH), electrical conductivity (EC), total nitrogen and organic carbon, C:N ratio, cation exchange capacity (CEC), water retention capacity (WRC), granulometry, elemental chemical composition and potentially toxic elements (PTEs) during 90 days of composting. The results indicated effectiveness reduction in pH and EC values, as well as alkalinity and sodicity of BR. The SC formulation containing 25 % of BR and 75 % of POMW showed WHC ≥ 60 % and CEC ≥ 200 mmolc·kg^{-1} meeting the Brazilian regulatory (IN 35/2006) for the production and commercialization of soil conditioners [1]. Concentration of PTEs (As, Cd, Pb, Ni, Hg, Se and Cr^{+6}, mg/kg) were below the limits specified in normative Instruction SDA No. 27 from June 5th, 2006 [4,18] and IN SDA No. 7 from April 12th, 2016 [19].

The technical basis for a SC from BR was validated in laboratory. However, to achieve maturity level corresponding to TRL 3 and initiated TRL 4, it was decided to scale up the soil conditioners composting to 200 kg batch, testing two formulations containing 25 and 50 % of BR and POMW over 90 days. Figure 2 presents the main conclusions of these experiments. The results of these larger scale experiments also met the requirements successfully to attend the Brazil normative [17–19].

The SC formulated with BR and POMW was applied to a soil where brachiaria grass (*Urochloa híbrida cv.* Sabiá) was cultivated (Figure 3). Brachiaria grass growth was evaluated under five treatments: T1 (25 % BR + 75 % POMW), T2 (50 % BR + 50 % POMW), T3 (100 % POMW), T4 (Limestone) and T5 (native soil as control) each applied at three application rates (40, 80 and 120 t/ha). The physical, chemical and agronomic performances were evaluated. Additionally, leaching tests showed the release of useful macro (K, P, Ca, Mg and S) and micronutrients (B, Cu, Mn and Zn) from the SC, with no evidence of potentially toxic elements (PTEs) such as - As, Cd, Pb, Cr, Hg, Ni and Se - in the leachate.



- ✓ **Low alkalinity and sodicity**
- ✓ **Soil conditioner parameters within those required by Brazilian regulations for Class B product.**
- ✓ **Leaching of potentially toxic elements below the limits allowed by law.**
- ✓ **Agronomic performance in brachiaria grass similar to limestone**
- ✓ **Potential for improving the fertility of agricultural soils and recovery of post-mining areas.**

Figure 2. Optimal SC formulation from BR and POMW (production: 5–200 kg).

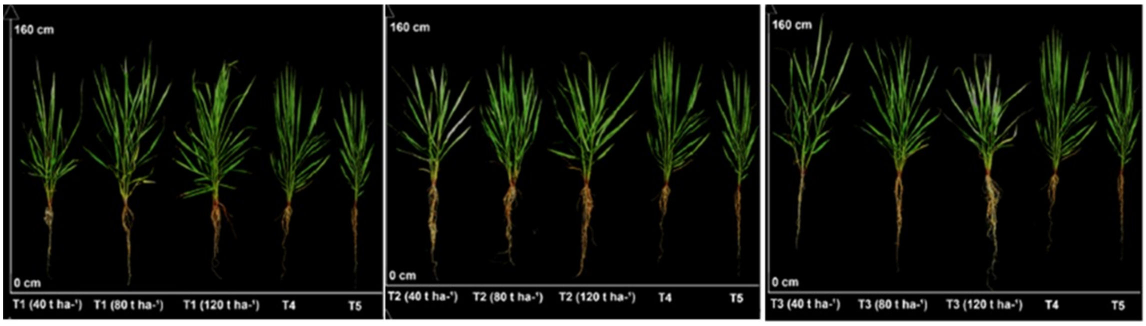


Figure 3. Brachiaria grass (*Urochloa híbrida* cv. Sabiá) cultivated using SC.

The concentrations of PTEs were below the investigation limits stablished by the National Environment Council in Brazil (CONAMA) resolution 420 standards and Brazilian drinking water standards. For instance, As was detected at 1.4 µg/L (Limit:1.4), Cd at 0.4 µg/L (Limit: 5), Pb at 1.1 µg/L (Limit:10), Cr at 18.8 µg/L (Limit: 50), Hg at 0.1 µg/L (Limit: 1), Ni at 0.7 µg/L (Limit: 20), and Se at 1 $\mu g.L^{-1}$ (Limit:10) [2].

The SC improved native soil fertility and plant growth, showing effects similar to those of limestone. This demonstrated the potential use of bauxite residue composted with palm oil waste in agriculture. Several soil variables (e.g. pH, base saturation, macro and micronutrients, and others) improved with increasing application rates of the SC doses, and aluminium toxicity decreased.

The visual observations from Figure 3 reinforce these findings, showing that treatments combining BR and palm oil waste (T1 and T2) resulted in higher plant growth and biomass production compared to the untreated soil (T5) and limestone (T4), especially at higher doses. This highlights the combined effect of BR in correcting soil acidity and reducing aluminium toxicity, together with the nutrient supply from organic residues.

Although T3 (100 % POMW without BR) improved plant growth relative to the native soil, its lower efficiency in pH correction limited its overall performance compared to T1 and T2. While limestone effectively raised soil pH, it did not contribute significantly to nutrient availability, which explains the lower biomass compared to SC treatments. Despite the positive results, sodium levels should be carefully monitored, especially at higher application rates. It is also important to note that leaching behaviour depends on multiple factors, including soil texture, mineralogy, organic matter, pH, and local climatic conditions. Therefore, more detailed studies are needed to assess the long-term performance of the SC in different soil types and under various cropping systems [1, 2].

2.2 TRL 4–6: Pilot Plant (Conceptual Design)

Following laboratory proof-of-concept experiments, the subsequent TRL stages involve validating the technology in relevant operational environments or designing a smaller-scale prototype with potential to be upscaled to full industrial application.

The SC pilot plant will be installed at the Hydro Alunorte Refinery, in Barcarena, Pará, Brazil. Figure 4 shows its location in the Bauxite Residue Disposal Area. This unit will be designed to process a mixture of BR and POMW in composting heaps, with planned capacities in tonnes per batch. The main objective is to simulate a relevant operational setting and validate the technical scalability of the process. Each composting pile is engineered to handle up to 11 tonnes per cycle, and with two piles operating in parallel, the potential batch production will be 22 tonnes per composting cycle. Figure 5 presents a simplified process flow diagram of the SC plant.

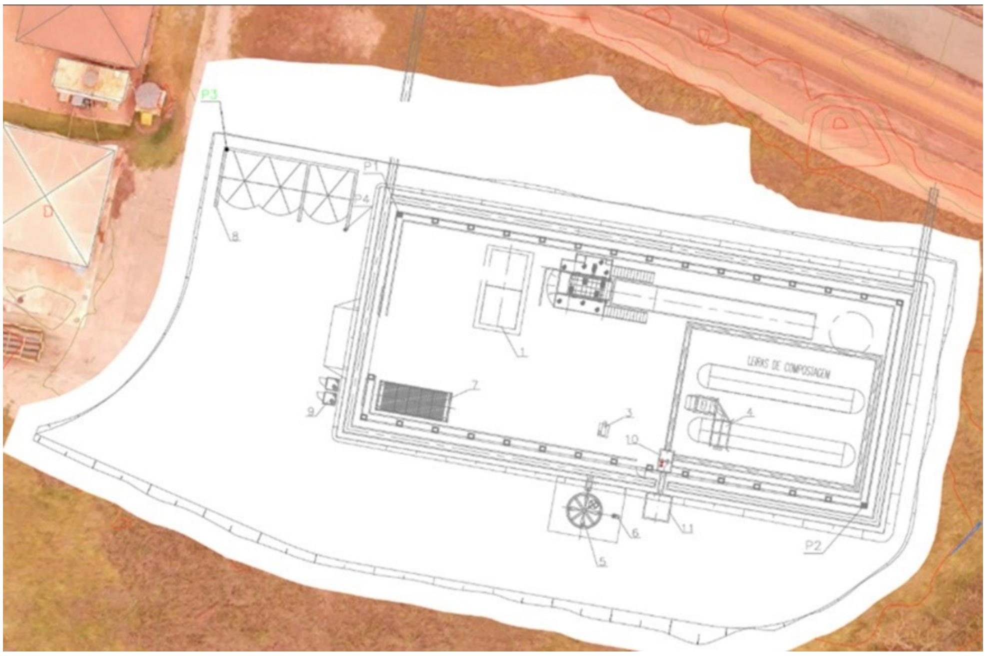


Figure 4. Pilot plant location (elaborated by Worley Brazil).

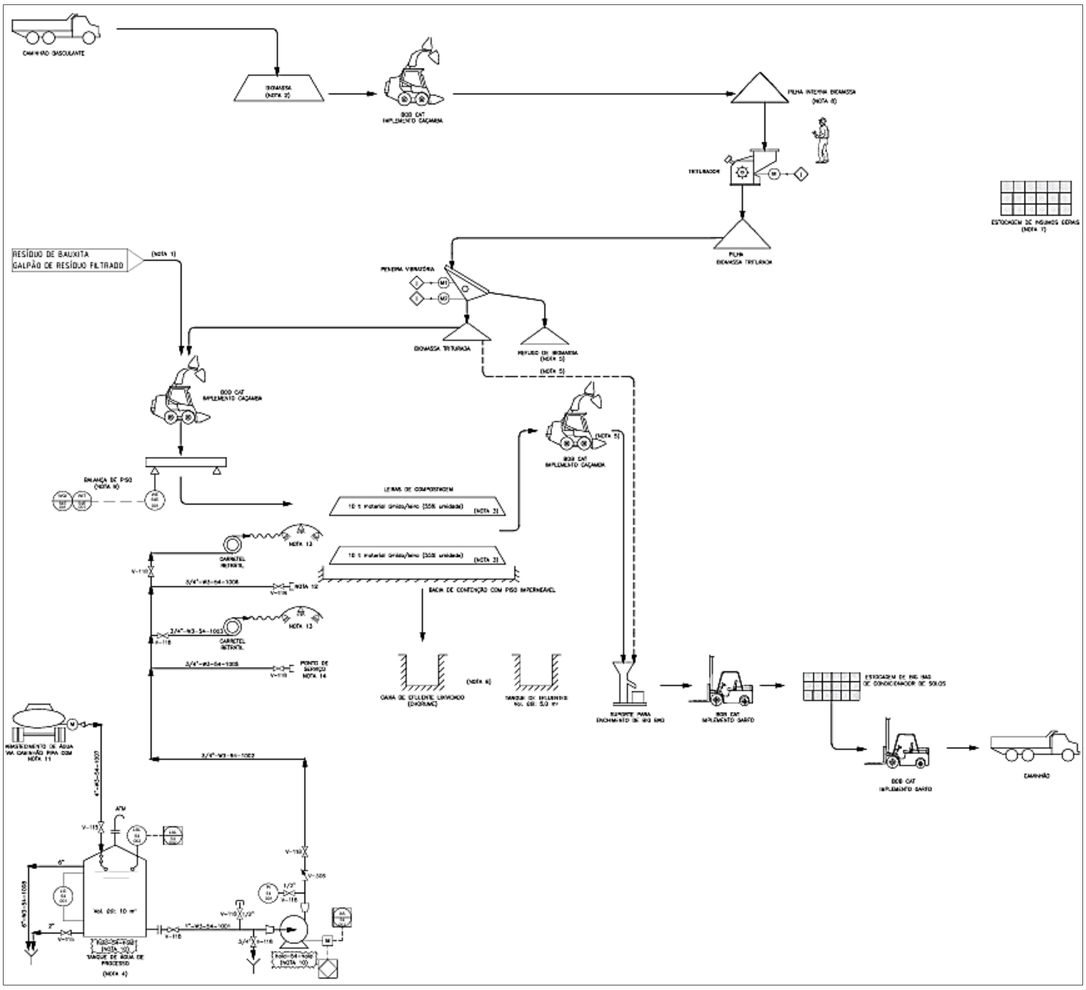


Figure 5. Pilot plant process flow sheet (elaborated by Worley Brazil).

The annual production will depend on the duration of composting and maturation cycles. Assuming an average composting cycle length of approximately 12 weeks, the estimated annual production capacity would be 88 tonnes. The plant will utilize BR and POMW as raw materials, as per defined in the laboratory tests (25 % BR). Bacteria inoculum and Carbon and Nitrogen sources may be utilized to accelerate the composting process and adjust C:N ratio, respectively.

Composting is an aerobic process involving the decomposition of organic materials by microorganisms under controlled conditions. During composting, microorganisms use oxygen (O_2) to decompose organic matter present in the raw materials, transforming them into compost and mineralizing the nutrients [20]. The composting process occurs in three main phases: active phase, thermophilic phase and maturation phase. In the active phase, the raw materials are piled together to activate naturally present microorganisms like bacteria and fungi. In the next phase, there is intense microbial activity that further decomposes organic material, with increased temperature. In the final phase, the microbial activity rate slows reducing composting temperature until the compost stabilizes [20]. Therefore, the pilot plant will include systems to measure and control aeration, moisture and temperature, and compost turning. Operational parameters, including pile dimensions, composting time and environmental controls, will be carefully defined to ensure consistent SC quality and accordance with Brazilian regulations (IN SDA No. 35/2006). All water and effluent leachate generated during the process will be collected and characterized as per the National Environment Council protocol (CONAMA) for water and effluent quality. These analyses will also include the quantification of potentially toxic elements, trace elements, rare earth, and other elements of interest to ensure that the leachate meets environmental safety standards.

The raw materials and the SC produced in the pilot plant will undergo comprehensive characterization to carry out physical, chemical, and microbiological evaluation and an ecotoxicology evaluation to ensure quality and safety. Physical properties such as moisture content, density, particle size distribution, porosity and water retention capacity will be monitored to assess the suitability of materials for composting and soil application. Chemical analyses will include measurements of pH, electrical conductivity (EC), available macro and micronutrients, cation exchange capacity (CEC) and saturation by aluminium and sodium. Additionally, the presence of potentially toxic elements (e.g. As, Ba, Co, Cr, Cu, Mo, Pb, V e Zn), trace elements (Cs, Ga, Hf, Rb, Sc, Sr, Ta, Th, U, Y e Zr), rare earth elements (Ce, Eu, La, Lu, Nd, Sm, Tb e Yb) and radioisotopes will also be monitored. Elemental analysis for carbon, hydrogen, nitrogen, and sulphur content will also be performed. Microbial assessments will include 16S rRNA gene sequencing for microbial community profiling, physiological fingerprinting using Biolog EcoPlates, and identification of potential pathogens (e.g. *Escherichia coli*, *Salmonella spp.*) through culture-based methods. Ecotoxicological testing will be conducted to evaluate the environmental safety of the composted material, including escape tests, acute toxicity test (DSL determination), and chronic toxicity tests using soil organisms such as earthworms (Oligochaeta), Enchytraeidae, and Collembola, as well as aquatic organisms like algae and Daphnia.

After completion of the technical requirements detailed above, the SC will be tested in a controlled environment with low-fertility soils typical of Amazon region and/or soils and substrates from post-mining areas for cultivating bioenergetics crops and native plants of Amazonia. The effects on surface run off water, groundwater, soil macro and microbiota, and plant health will be evaluated. The results will be compared with reference treatments using lime and/or conventional fertilizers. The project is expected to be implemented and validated in a representative and scalable environment to achieve the maturity level corresponding to TRL 6, as illustrated in the schematic shown in Figure 6.

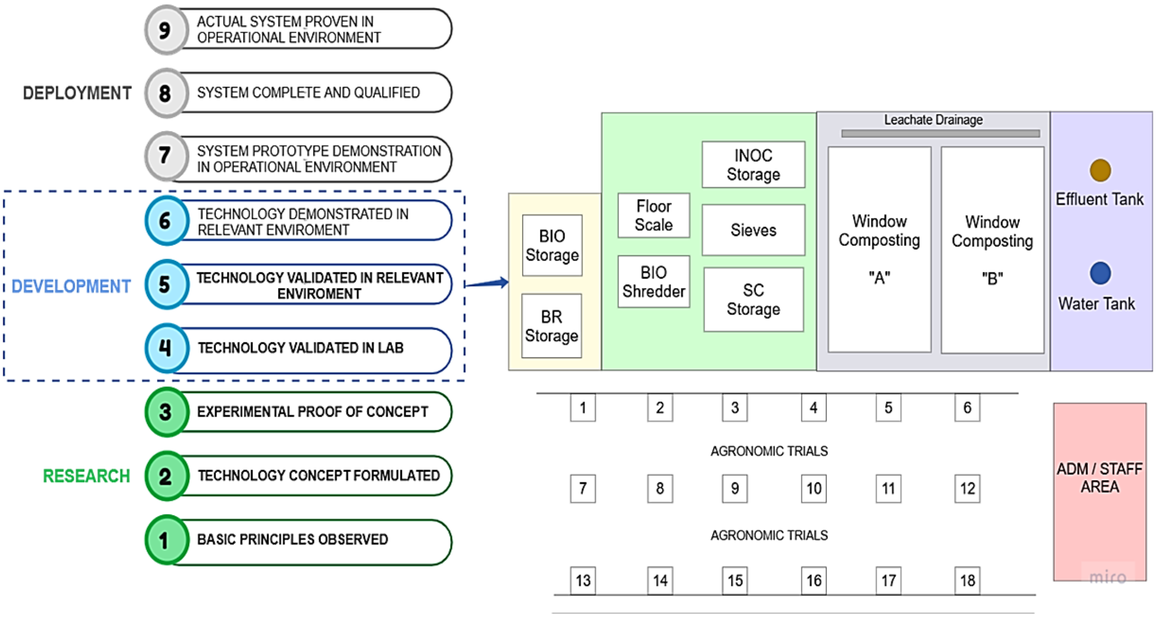


Figure 6. Schematic representation of the TRL and the pilot plant for SC production.

3. Conclusions

The project represents a significant advancement in the sustainability of industrial and agro-industrial residues contributing with economic circularity in aluminium sector. By scaling up from laboratory to pilot production with the aim of reaching TRL 6, this initiative might demonstrate the strong potential for environmental restoration, particularly in degraded and post-mining areas in Amazon region. The pilot composting plant to be installed at Hydro Alunorte, in Brazil, will not only validate the operational feasibility and safety of SC production at scale, but also ensure its compliance with Brazilian regulations and suitability for agronomic application through rigorous physical, chemical, microbiological, and ecotoxicological assessments. The SC has the potential to enhance soil fertility, support revegetation efforts, and serve as a foundation for the cultivation of bioenergy crops, contributing both to environmental rehabilitation and socio-economic development in surrounding communities.

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