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# Ecological rehabilitation of post-bauxite mine spoil using a multi-strata agroforestry model with specialized soil amendments in Tan Rai, Vietnam

Ngoc Hoang Huyen Thi[1,2], Ha Nguyen Manh[1,2,*], Long Nguyen Cong[1], Trung Luu The[3], Trang Nguyen Thi Huyen[4], Thuy Nguyen Thi[1], Son Nguyen Thai[1], Men Nguyen Thanh[3], Toan Nguyen Duc[1]

[1]*Institute of Earth Sciences, VAST, Hanoi, Vietnam*
[2]*Graduate University of Science and Technology, VAST, Hanoi, Vietnam*
[3]*Forest Science Institute of Central Highlands and South of Central Vietnam, Vietnamese Academy of Forest Sciences, Lam Dong, Vietnam*
[4]*Department of Earth and Oceanographic Science, Bowdoin College, Maine, USA*

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ABSTRACT

In the face of accelerating land degradation from open-pit mining, ecological rehabilitation has become a cornerstone strategy for restoring ecosystem functions and sustainability. This study evaluated the early outcomes of a pilot multi-strata agroforestry model designed for post-bauxite mine spoil at the Tan Rai site, Vietnam. The system combined *Pinus caribaea* Morelet, *Bixa orellana* L., and *Sphagneticola trilobata* (L.) Pruski, integrated with soil amendment products such as controlled-release NPK fertilizers, superabsorbent polymers, and polyacrylamide. Over a six-year observation period, comprising two years of active management followed by four years of natural succession, plant growth performance, nine soil physicochemical properties, and eight heavy metal concentrations were assessed through six sampling campaigns. Results indicated significant improvements in vegetation structure and soil quality. *P. caribaea* showed strong height growth, while *B. orellana* exhibited rapid diameter expansion and reached reproductive maturity by year six. Vegetation cover stabilized above 75% after 12 months, accompanied by increasing species diversity. Within the first 24 months, soil organic carbon, available nutrients, cation exchange capacity, and pH improved markedly, while heavy metal levels remained within the safe thresholds specified by QCVN 03:2023/BTNMT. These findings highlight the potential of multi-strata agroforestry, when combined with targeted soil amendments, to accelerate ecological recovery on post-bauxite mine spoils. However, continued monitoring is required to ensure long-term sustainability.

*Keywords:* Post-mining rehabilitation; Agroforestry systems; Tropical degraded soils.

## 1. Introduction

Despite significant efforts to mitigate soil resource loss, ecological rehabilitation after bauxite mining remains a complex, long-term process that requires continuous monitoring and evaluation. A natural simulation approach, focused on re-establishing vegetation structure and improving soil conditions, has been widely recognized as an

*Corresponding author, Email: havdl72@ies.vast.vn

effective strategy to restore ecosystem functionality and, where possible, approximate pre-mining ecological states (Parrotta & Knowles, 2001; Di Carlo et al., 2019a; De Souza Barbosa et al., 2021; Yadav et al., 2022). Accordingly, silvicultural and technological solutions, including mixed-species planting of native trees, facilitation of natural regeneration, and the combination of fertilizers, have been widely applied to accelerate soil coverage and restore critical soil properties in various bauxite mining regions, such as in China (Gao et al., 1998), Australia (Koch & Ward, 2005; Carl et al., 2007), and Brazil (Parrotta & Knowles, 1999; Neto et al., 2021; Das Neves et al., 2024). Furthermore, continuous management interventions, integrated with livelihood and community benefit enhancement, are essential to ensure the long-term composition, structure, and function of ecosystems established on mine spoils (Annandale et al., 2021).

Beyond vegetation establishment, the success of post-mining rehabilitation, particularly in bauxite spoil areas, depends strongly on soil quality improvement, typically assessed through physicochemical indicators (Tibbett, 2010; Di Carlo et al., 2019a). Over the past decade, research has increasingly focused on soil ecosystem recovery following bauxite extraction. Orozco-Aceves et al. (2017) reported significant variation in soil physicochemical and biological properties across rehabilitation stages, while Daws et al. (2023) highlighted vegetation-nitrogen interactions in mature forests after 32 years. Vilas Boas et al. (2018) and Cavalcante et al. (2019) demonstrated that fertilizers, ground cover, and coffee plants enhance soil carbon and nitrogen levels, key indicators of recovery. Likewise, Borges et al. (2019) emphasized the value of organic amendments and intercropping, whereas De Souza Barbosa et al. (2022) compared rehabilitation strategies based on ecological metrics in degraded bauxite sites. Martins et al. (2021) further recommended long-term (≥ 20 years) soil monitoring using physical and microbiological indicators to ensure reliable evaluation of rehabilitation outcomes.

In Vietnam, bauxite ranks among the seven most abundant and strategic minerals, with a national target of 19 mining projects totaling 1,709 million tons of raw ore by 2030 (VG, 2023). The first bauxite mining activity began in 1976 at Bao Loc, Lam Dong Province, with an initial extraction area of 123 ha (Nhan, 2018). Industrial-scale mining commenced with the two integrated bauxite–alumina projects: Tan Rai (Lam Dong, 2008) and Nhan Co (Dak Nong, 2010), with a mining area of approximately 140–160 ha/year. As of March 2021, the total mining area across both projects reached 664 ha, located mainly on formerly high-yield coffee and tea plantations. However, by 2021, only 128 hectares had been rehabilitated, mostly using *Hybrid Acacia* and *Pinus caribaea* (VINACOMIN, 2021a, 2021b). On the other hand, bauxite mining in Vietnam remains a highly debated issue due to serious concerns over environmental incidents and ecosystem degradation on large-scale landscapes (Xuan et al., 2017). These concerns are consistent with broader regional patterns of long-term forest degradation driven by human activities across the Indochina Peninsula (Nguyen Dinh and Lai Vinh, 2021). Several environmental and land-use warnings have been raised (Khoa & Tu, 2014; Hoan et al., 2020), and some assessments of post-mining soil quality have been reported (Men, 2015; Ngoc, 2021; Nguyen et al., 2021). According to Nhan (2018), nine plant species are potentially suitable for post-mining and red mud areas; however, appropriate soil amendments are still essential. In addition, a 2017 pilot project on energy crops in Tan Rai tested species such as roselle *(Hibiscus sabdariffa)*, jatropha, cassava, sorghum, and VA06 grass (Müller et al., 2023). However, only preliminary results were obtained, with no conclusive evidence of technical feasibility or economic viability.

Overall, although several studies and pilot trials on soil and ecological rehabilitation in bauxite-mined areas have been conducted in Vietnam, these efforts remain fragmented and limited in both scale and scope. To date, comprehensive long-term assessments of ecological recovery and the sustainability of rehabilitation measures on post-bauxite mine spoil are entirely lacking. Although ecological rehabilitation has been widely implemented to restore post-mining landscapes, most efforts emphasize rapid revegetation, often neglecting the concurrent recovery of soil functionality and local livelihood potential. In tropical regions such as Vietnam, few studies have explored integrated approaches that combine multi-strata agroforestry with soil amendments to accelerate the restoration of severely degraded bauxite mine spoils. This study addresses this gap by presenting the outcomes of a pioneering ecological rehabilitation model established in 2018 at the Tan Rai bauxite mine, Vietnam. The model integrates a multi-strata agroforestry system with targeted soil amendment applications to enhance soil quality and ecosystem resilience, while creating opportunities for local farmers to sustainably reuse land. Specifically, this study aims to (1) evaluate the effectiveness of the combined approach in improving soil physicochemical properties and (2) assess vegetation establishment and biodiversity as indicators of ecological rehabilitation success in post-bauxite mining environments.

## 2. Case study and methods

### *2.1. Study area*

The study was conducted in the bauxite mining area operated by Lam Dong Aluminum One Member Company Limited in Bao Lam 1 Commune, Lam Dong Province (Fig. 1c). Situated on the Bao Loc-Di Linh Plateau at an average elevation of 850 m, the area has a tropical monsoon highland climate with 2,000–2,040 h of sunshine annually, mean temperatures of 22.4–22.8°C, and high rainfall of 3,000-3,500 mm.yr$^{-1}$ concentrated from June to October (LSO, 2023). The dry season is prolonged and often marked by water scarcity. Dominant vegetation includes coffee, tea, durian, and cashew plantations, while natural forests are mainly secondary evergreen or mixed broadleaf-coniferous types with 2–3 canopy layers, 0.4–0.7 canopy cover, and timber reserves of 41.9–273.7 m$^3$.ha$^{-1}$ (Ha, 2020).

Geologically, the area experienced intense volcanic activity during the Neogene-Quaternary, forming Rhodic Ferralsols developed on olivine, two-pyroxene, and olivine-augite basalts of the Tan Phat Formation. These soils typically form deep profiles with an average thickness of 40–50 meters and contain a sesquioxide ($R_2O_3$) accumulation horizon formed by lateritization under a hot, humid tropical climate (NIAPP, 2005). The local bauxite ore contains about 61.3% sesquioxides, including approximately 39.3% $Al_2O_3$ and 22.0% $Fe_2O_3$ (Men, 2015).

At Tan Rai, bauxite is mined in open-pit blocks several hectares in size. The mining process includes: (i) stripping and stockpiling the overburden soil along the edges of the pit; (ii) excavating the 3–6 m thick ore layer and transporting it to the processing plant; and (iii) backfilling the pit with the previously removed topsoil. The experimental rehabilitation site was located within one of the initial mining blocks during the early operational phase of the processing plant, covering an area of 1 hectare at coordinates 107°51'10"E; 11°39'24.5"N (Fig. 1d). Due to limited operational experience at the time, only small-sized ore particles were extracted, while larger bauxite blocks were left behind and mixed with overburden during backfilling.

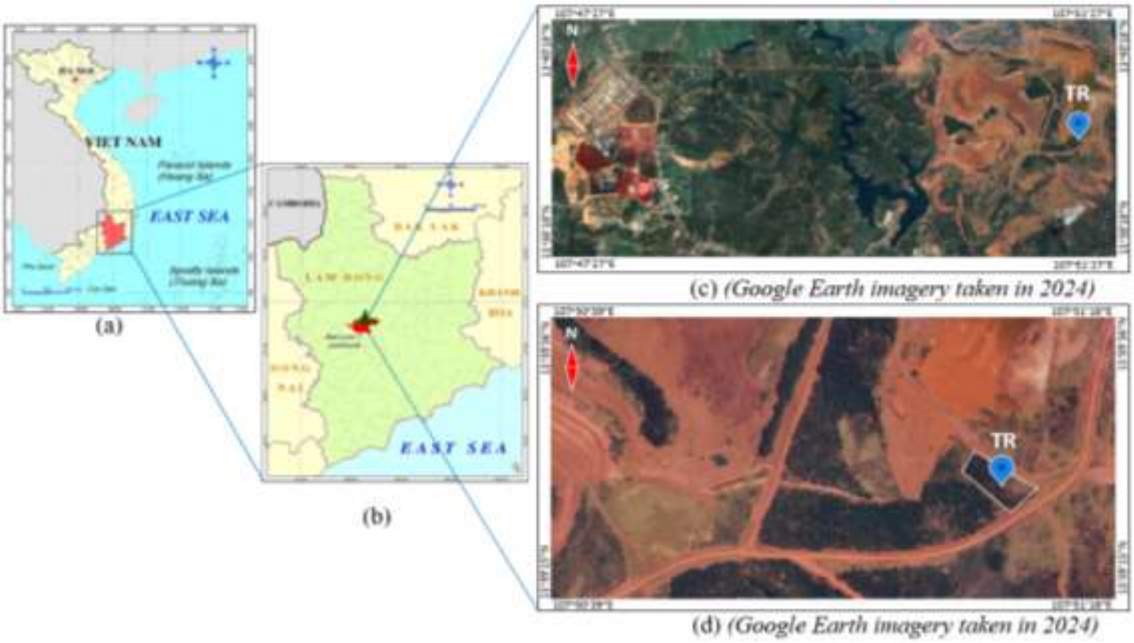


*Figure 1.* Location of the study area: (a) Vietnam; (b) Bao Lam 1 commune, Lam Dong Province; (c) Tan Rai bauxite mine (symbol TR); (d) designated area for model establishment

### *2.2. Methods*

The study was conducted over seven years following the workflow summarized in Fig. 2, consisting of four main steps:

Step 1 (2017): Mining operations, spoil-dump conditions, and the physicochemical properties of the bauxite-extraction spoil were investigated to develop a rehabilitation strategy, including the selection of plant systems and soil amendment-fertilizer combinations.

Step 2 (2018): A 1-hectare rehabilitation model was established using close-to-nature silvicultural techniques combined with a specialized soil amendment package and fertilization scheme. Terrain reshaping and soil profile reconstruction were completed before planting.

Step 3 (2018–2020): Intensive monitoring and protection were carried out during the first two years, including routine maintenance and biannual assessments of plant growth and soil quality.

Step 4 (2021–2024): A comprehensive evaluation was conducted to assess rehabilitation effectiveness over 4 years of unmanaged natural succession.

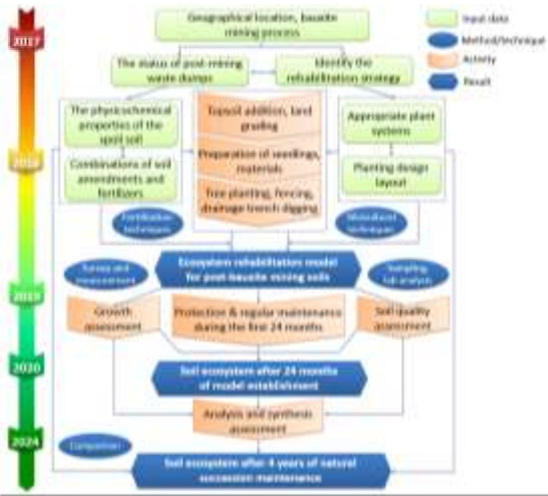

*Figure 2.* Overview of the research implementation process

*2.2.1. Close-to-nature silviculture approach*

The primary objective of establishing the rehabilitation model in this study was to achieve rapid site stabilization and soil protection through early canopy closure, minimizing erosion and nutrient loss. This was accomplished by using fast-growing, high-survival species during the initial phase of post-mining recovery. A close-to-nature silviculture approach emphasizes (i) multi-species, multi-strata planting, (ii) the use of pioneer species to improve soil conditions and facilitate subsequent colonization by native species; (iii) minimal mechanical intervention, promoting natural regeneration and closed nutrient cycling; and (iv) stand density regulation through thinning rather than clear-cutting. The rehabilitation model aimed to re-establish a post-bauxite mine spoil ecosystem characterized by a forest-like structural composition and high species diversity. Following the framework proposed by Men and Ha (2019), a three-strata agroforestry system was implemented, comprising Caribbean pine (*Pinus caribaea* Morelet), annatto (*Bixa orellana*), and *Sphagneticola trilobata*. Caribbean pine (*Pinus caribaea* Morelet, *Pinaceae*) is a fast-growing forestry species valued for its high timber productivity and ecological protection functions. Annatto (*Bixa orellana* L., *Bixaceae*) is cultivated for its fruits and seeds and also serves as a low-canopy species, contributing to soil coverage and reducing erosion. *Sphagneticola trilobata* (L.) Pruski, a fast-growing herbaceous plant in the Asteraceae family, is effective in stabilizing soil, reducing erosion, and suppressing surface runoff.

Given the terrain characteristics of the spoil site, the surface was leveled to a 3–8° slope, drainage channels were excavated, and a 50 cm-thick topsoil layer was applied. This topsoil was previously removed during bauxite mining in adjacent areas. The soil was then plowed to a depth of 30 cm. A protective fence consisting of wooden stakes and three rows of barbed wire was installed around the model to prevent livestock intrusion (Fig. 3c). Seedlings grown in polyethylene bags were selected based on uniform morphological development, absence of pests and diseases, and intact apical meristems. Planting specifications were as follows: (1) *P. caribaea*, 6-7 months old, 25-30 cm tall, root collar diameter 0.25-0.30 cm; (2) *B. orellana*, 3-4 months old, 30-40 cm tall, root collar diameter 0.40-0.60 cm. Planting was carried out at the beginning of the rainy season (June 2018), with a total of 1,100 *P. caribaea*, 370 *B. orellana*, and 730 *S. trilobata* individuals, following the design scheme (Fig. 3a). Each planting hole received a basal application of microbial organic fertilizer at rates of 1.0 kg for *P. caribaea*, 1.0 kg for *B. orellana*, and 0.3 kg for *S. trilobata*, based on the nutrient-poor characteristics of the post-bauxite mining spoil and the national technical guideline (MARD, 2004). One month after initial planting, survival rates were assessed for all species, and missing individuals were replaced using seedlings of comparable height and stem diameter to maintain stand uniformity. During the first 24 months, the model was maintained every 6 months through standard silvicultural practices, such as weeding, fertilizing, and replanting, to ensure the target planting density. Additional activities included monitoring the drainage system, reinforcing the fence, and implementing fire prevention measures.

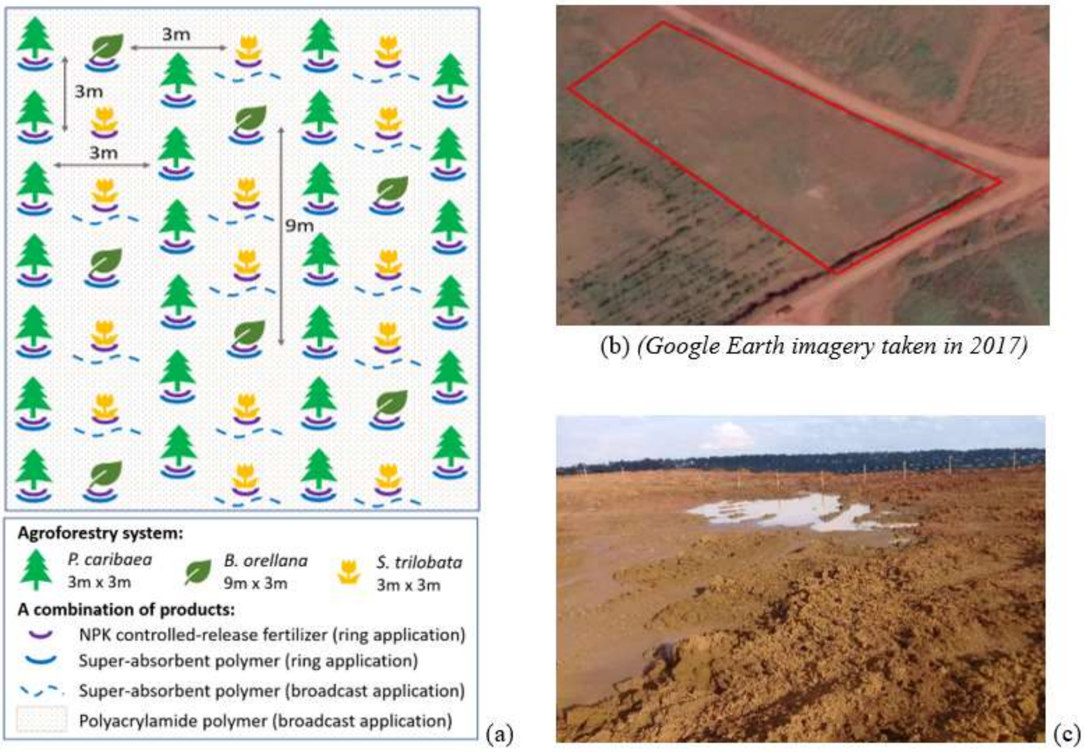


*Figure 3.* (a) Planting design layout; (b) Current condition of the model site before implementation. (c) Leveled ground and established fencing around the model area

### *2.2.2. Application of an integrated formulation for soil improvement and erosion mitigation*

The physical and chemical limitations of post-mining spoil soils at the Tan Rai bauxite mine, coupled with the region's distinctly seasonal climate, underscore the need to apply specialized soil amendment formulations. These are essential for ensuring the survival and growth of introduced plant species and for promoting long-term improvement in soil quality (Ha et al., 2024). Accordingly, a combination of products developed by the Vietnam Academy of Science and Technology (VAST) was selected for Application, including (1) A superabsorbent polymer for soil moisture retention (Tung et al., (2011); Tung (2015); (2) A polyacrylamide (PAM) (Tung, 2015); (3) A controlled-release NPK fertilizer (15-18-18 or 15-20-10) developed by Khoa et al. (2014) and Khoa (2015). These chemical-biological products have been previously tested and successfully applied to major perennial crops in the Central Highlands, including coffee and black pepper. This study represents the first attempt to use these formulations for the rehabilitation of post-bauxite mine spoil environments.

The recommended formulation and application method for the soil amendment combination are as follows: (1) The superabsorbent polymer (AMS-1) was applied once per year for three consecutive years, at the end of the rainy season. A ring application at 60 g per plant was used for *P. caribaea* and *B. orellana*, while *S. trilobata* received a broadcast application at 100 kg/ha.

(2) Polyacrylamide (PAM) was broadcast over the entire plot at a rate of 12 kg/ha at the beginning of planting (June 2018). (3) Controlled-release NPK fertilizer was applied twice per year via ring application at a rate of 100 g per plant per Application. The 15-18-18 formulation was used for *B. orellana*, while the 15-20-10 formulation was applied to *P. caribaea* and *S. trilobata*.

*2.2.3. Standardized plot-based measurements and morphological species identification*

The rehabilitation model included five fixed-area sample plots, each measuring. 100 m² (10 × 10 m), where plant growth was monitored at six distinct time points. Within each 100 m² plot, five 4 m² (2 × 2 m) sub-plots were established, totaling 25 sub-plots across the study area. In each sub-plot, the following variables were recorded: (1) percent vegetation cover and (2) mean plant height, measured for all individuals of each species from the soil surface to the apical tip and averaged per species (Krebs, 1989; Thin, 2006). After collecting temporal data on vegetation cover, height, and species richness, plant species were identified based on comparative morphological characteristics. Species identification was conducted both in the field and in the laboratory using morphological comparison and referencing standard floras by Lecomte et al. (1923), Ban et al. (1984), and Ho (1999). Growth indicators of the introduced species were measured biannually over 24 months using standard forest inventory techniques. For *P. caribaea*, root collar diameter ($D_0$) and total height (H) were measured during the juvenile stage. In contrast, dominant height (Hvn) and diameter at breast height (DBH, measured at 1.3 m) were recorded after 72 months, along with assessments of pest and disease incidence. For *B. orellana*, root collar diameter ($D_o$) and total height (H) were recorded. For *S. trilobata*, stem length was the sole growth parameter recorded.

*2.2.4. Soil sampling and analysis*

A total of 60 soil samples were collected, categorized as follows: (1) Soil from a coffee cultivation area (sampled in 2018), located approximately 2 km from the model site, unaffected by current mining activities but designated for future extraction. This site served as a reference, with six profile samples collected at 0–15 cm, 15–30 cm, and 30–110 cm depths, and two additional topsoil samples; (2) Soil from post-mining spoil at the model site (sampled in 2017), including four profile samples at depths of 0–15 cm and 15–40 cm, and two topsoil samples; and (3) Soil from the model site, collected at four vegetation monitoring intervals (6, 18, 24, and 72 months). For each interval, 24 profile samples were taken at depths of 0–15 cm, 15–50 cm, and 50–100 cm at the model center.

Soil profile samples were collected with a hand auger, and topsoil samples were collected with a stainless-steel shovel and stored in clean, labeled nylon bags. The samples were air-dried at room temperature for one week, then crushed and sieved through a 2 mm mesh. All soil samples were processed and analyzed at the Center for Analytical Laboratories, certified under VILAS 715. Analyses were conducted in compliance with ISO/IEC-17025:2005 standards for laboratory quality management. Nine soil quality indicators were analyzed in accordance with Vietnamese national technical standards (Table 1). Eight heavy metals (As, Cd, Cu, Hg, Pb, Zn, Mo, and B) were quantified using an Inductively Coupled Plasma Mass Spectrometer (ICP-MS 7900, Agilent Technologies).

*Table 1.* Parameters analyzed and corresponding methods

| Parameters analyzed | Unit | Corresponding methods |
|---|---|---|
| Particle size distribution | % | TCVN-8567:2010 |
| Soil pH | | TCVN-5979:2021 |
| Total organic carbon (OC) | % | TCVN-8941:2011 (Walkley Black method) |
| Total nitrogen | % | TCVN-6498:1999 (Kjeldahl method) |
| Total phosphorus | % | TCVN-8940:2011 (Colorimetry method) |
| Total potassium | % | TCVN-8660:2011 (UV-Vis method) |
| Available phosphorus | mg/100g | TCVN-5256:2009 (UV-Vis method) |
| Available potassium | mg/100g | TCVN-8662:2011 (Emission spectroscopy method) |
| Cation exchange capacity (CEC) | meq/100g | TCVN-8568:2010 (Ammonium acetate method) |
| Cd, Cu, Pb, Mo, Hg, Zn, As, Bo | mg/kg | EPA 3051B:2007 and SMEWW 3125:2023 |

*Note:* TCVN: Vietnamese national technical standards, SMEWW: Standard Methods for the Examination of Water and Waste Water

#### *2.2.5. Statistical analysis*

All data were statistically processed and visualized using Microsoft Excel and IBM SPSS Statistics. Reported values in tables represent arithmetic means, with standard deviations (SD) calculated to assess data variability. To examine the effects of rehabilitation duration, soil depth, and site on heavy metal concentrations, a three-way ANOVA was performed. Significant differences among factors and their interactions were determined at $p < 0.05$. Soil nutrient status was classified according to the Handbook of Agricultural Land Use (MARD, 2009), and pH was evaluated according to USDA (2017) criteria. Heavy metal levels were compared with the permissible limits for Type I agricultural land outlined in QCVN- 03:2023/BTNMT (MONRE, 2023). In addition, based on soil analytical results, we identified soil groups using the semi-quantitative classification system of Nguyen Thanh et al. (2022), while the integrated land evaluation framework proposed by Hoang et al. (2022) supported our approach for assessing post-mining soil functions.

## 3. Results

### *3.1. Growth dynamics of principal crops in the model*

#### *3.1.1. Survival rate*

During the first two years, all planted species maintained high survival rates, with *S. trilobata* performing best, followed by *P. caribaea* and *B. orellana*. Temporary declines during dry periods were offset by replanting in the rainy season, and by 24 months, most species exhibited healthy growth, though canopy closure was incomplete. The overall survival rate was 90.1% (Table 2). By month 72, however, overall survival had declined markedly due to livestock intrusion and trampling, which caused mechanical damage, particularly to *P. caribaea* and *B. orellana*. It led to surface soil compaction near open fence areas.

*Table 2*. Temporal changes in survival rates (%) of planted specie

| Plant species | Survival Rate (%) | | | | | |
|---|---|---|---|---|---|---|
| | 1 month (June 2018) | 6 months (Dec 2018) | 12 months (June 2019) | 18 months (Dec 2019) | 24 months (June 2020) | 72 months (June 2024) |
| *P. caribaea* | 100 | 92.9 | 90.9 | 91.1 | 89.4 | 63.3 |
| *B. orellana* | 100 | 90.0 | 90.0 | 90.0 | 90.0 | 65.0 |
| *S. trilobata* | 100 | 97.5 | 77.5 | 92.2 | 91.1 | 44.7 |
| **Overall mean** | **100** | **93.5** | **86.1** | **91.2** | **90.1** | **57.7** |

### *3.1.2. Growth dynamics*

During the first two years, *P. caribaea* and *B. orellana* exhibited rapid stem diameter and height growth, with *P. caribaea* showing slightly faster initial development (Table 3, Fig. 4). From 24 to 72 months, *B. orellana* maintained a steadier growth rate and eventually surpassed *P. caribaea* in stem diameter expansion. However, *P. caribaea* retained a greater overall height. After 24 months, about 15% of *P. caribaea* individuals showed signs of stem borer infestation, with some exhibiting branch drying and shoot damage. By month 72, around 8% displayed leaf yellowing and broken apical shoots. Both species generally showed healthy development with limited pest or disease impacts. By the sixth year, several *B. orellana* individuals had reached reproductive maturity, and as of the June 2024 growth assessment, approximately 15–20% were observed to be flowering and bearing fruit under stable soil and canopy conditions.

*S. trilobata* displayed variable stem elongation associated with replanting events during the first year and seasonal growth fluctuation, with a temporary reduction at 18 months, but achieved substantial recovery and ground coverage by 72 months. The observed variability, particularly during the early stages, reflects replanting practices and individual growth heterogeneity rather than environmental stress. Overall, these trends indicate the favorable adaptation of the selected species to rehabilitated soil conditions and their potential for long-term vegetation stabilization.

*Table 3*. Growth indicators of planted species in the rehabilitation model (mean ± SD, cm)

| **Growth indicator** | **Plant species** | 1 month (June 2018) | 6 months (Dec 2018) | 12 months (June 2019) | 18 months (Dec 2019) | 24 months (June 2020) | 72 months (June 2024) |
|---|---|---|---|---|---|---|---|
| Root collar diameter ($D_0$) | *P. caribaea* | 0.19± 0.02 | 1.26±0.43 | 2.14±0.59 | 3.95±1.42 | 6.04±1.34 | - |
| | *B. orellana* | 0.22±0.04 | 1.72±0.68 | 2.10±0.48 | 3.46±1.17 | 4.16±0.88 | 9.76±1.44 |
| Diameter at breast height (DBH) | *P. caribaea* | - | - | - | - | - | 9.24±2.04 |
| Total height (H) | *P. caribaea* | 18.7±1.4 | 35.7±7.0 | 71.3±9.4 | 107.2±35.4 | 160.0±38.0 | 434.0±65.9 |
| | *B. orellana* | 21.0±1.7 | 47.1±12.4 | 71.9±13.2 | 87.9±15.7 | 116.2±16.9 | 130.0±28.6 |
| Stem length (SL) | *S. trilobata* | 19.2±1.6 | 65.0±31.9 | 92.3±29.0 | 72.7±25.7 | 97.4±29.0 | 162.0±23.0 |

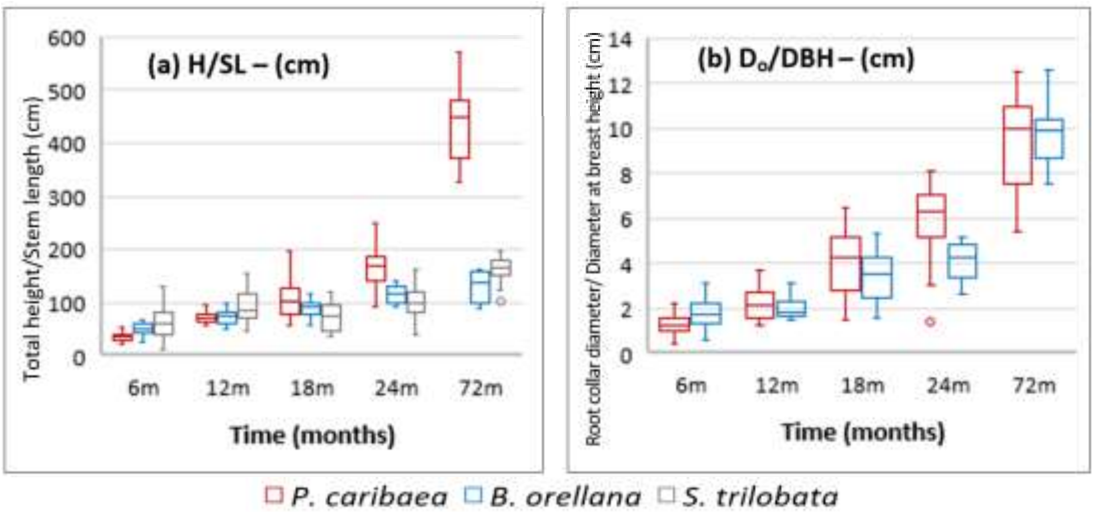


*Figure 4*. Boxplot of plant growth indicators in the rehabilitation model

### *3.2. Changes in Vegetation Cover*

During the first six months, vegetation cover in the shrub and herbaceous layer remained low and unstable. The SD of mean cover values was high due to considerable variability among sub-plots, many of which recorded 0% coverage. It then increased rapidly and stabilized at high levels from the first year onward (Table 4).

Species richness in the shrub and herbaceous layers exhibited distinct temporal dynamics: a slight decline in the early stage, a sharp increase after 12 months, peaking around the second year, and a gradual decrease thereafter due to interspecific competition for light and nutrients. The early-stage community was dominated by a mixture of native species, *Vigna trilobata* (L.) Verdc. and *Eleusine indica* (L.) Gaertn., and several naturalized or invasive alien species such as *Bidens pilosa* L., *Chromolaena odorata* (L.) R.M. King & H. Rob., *Imperata cylindrica* (L.) P. Beauv., and *Gynura crepidioides* (Benth.) Benth. Ex Hemsl., each contributing 30–55% individual cover. During later monitoring phases, additional species appeared, including native taxa (*Reynoutria multiflora* (Thunb.) Moldenke, *Melastoma candidum* D. Don) and alien species (*Lantana camara* L., *Ricinus communis* L., *Paspalum conjugatum* P.J. Bergius), reflecting progressive ecological succession and changing soil-vegetation interactions.

The average height of the shrub and herbaceous layers increased rapidly during the initial stage and fluctuated over the years. Some species, such as Imperata cylindrica, Ricinus communis, and Chromolaena odorata, exhibited rapid vertical growth, resulting in localized height peaks but diverging from the general pattern across the model.

*Table 4.* Structural indicators of the shrub and herbaceous layer during vegetation development (mean ± SD)

| **Measurement period** | **Vegetation cover** (%) | **Species richness** | **Mean vegetation height** (cm) |
|---|---|---|---|
| 1 month (June 2018) | 22.9 ± 17.6 | 13.0 ± 3.7 | 8.7 ± 5.6 |
| 6 months (Dec 2018) | 10.7 ± 8.2 | 9.6 ± 1.8 | 29.2 ± 16.9 |
| 12 months (June 2019) | 80.0 ± 17.3 | 17.0 ± 6.2 | 26.3 ± 15.4 |
| 18 months (Dec 2019) | 75.6 ± 22.6 | 20.0 ± 5.9 | 19.2 ± 12.9 |
| 24 months (June 2020) | 87.4 ± 8.1 | 20.0 ± 4.5 | 37.9 ± 34.4 |
| 72 months (June 2024) | 80.7 ± 15.1 | 18.0 ± 5.4 | 31.5 ± 26.4 |

### ***3.3. Temporal changes in soil physical and chemical properties after rehabilitation***

#### *3.3.1. Changes in soil particle size distribution during post-mining rehabilitation*

Figure 5 illustrates the temporal variation in soil particle size distribution across different depths. The reference soil (CF) exhibited a stable fine-textured profile with over half of the particles in the clay fraction, typical of basalt-derived Ferralsols. In contrast, the 2017 spoil (S17) showed clear signs of physical degradation, with coarse particles dominating the surface layers. Following the Application of topsoil and establishment of vegetation in 2018, the upper horizons (0–50 cm) became finer and more similar to the reference profile, while deeper layers remained coarse. During the early years, slight clay leaching occurred due to erosion under sparse vegetation cover, but the particle size distribution stabilized by 2020 as vegetation density increased. However, after 2024, a renewed coarsening of the upper soil was observed; this reversal may be attributed to reduced plant survival after 48 months of unmanaged natural succession, which weakened surface protection and reactivated erosion processes. Overall, these trends highlight the strong linkage between vegetation cover and soil texture stability during post-mining rehabilitation.

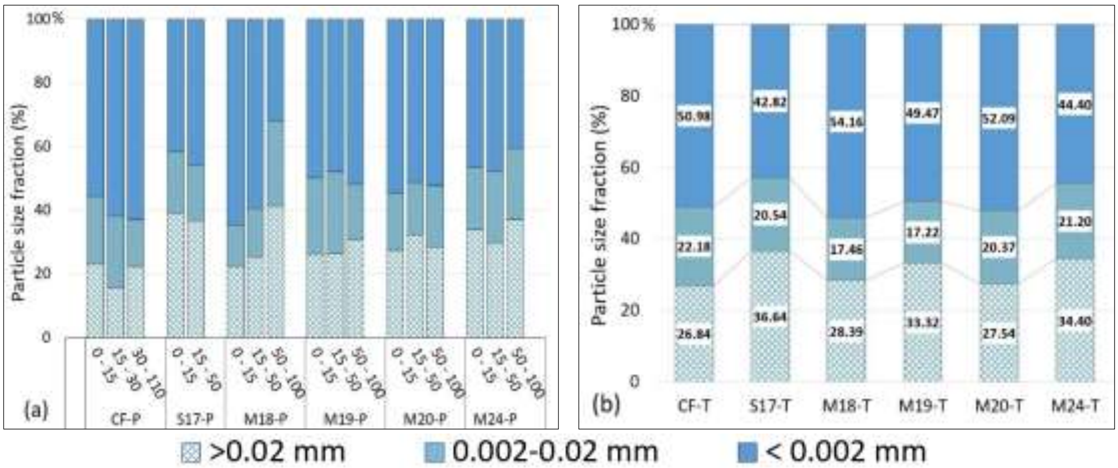


*Figure 5.* Temporal variation in soil particle-size distribution: (a) all depths; (b) 0–15 cm
*Note: CF-P: Soil profile from coffee site; S17-P: Spoil profile (2017); M18-M24-P: Profiles from rehabilitation models (2018–2024); CT-T, S17-T, M18-M24-T: Corresponding topsoil samples (0–15 cm)*

*3.3.2. Chemical properties of coffee-growing reference soil and spoil soil*

The reference soil (2018) was identified as a Rhodic Ferralsols under intensive coffee cultivation. According to the MARD (2009) system, the surface horizon contained high levels of total N, P, and OC. Basalt-derived soils in the Central Highlands generally exhibit good structure, porosity, and nutrient reserves (Ky, 1990). However, OC and nutrient contents (N, P, K) declined with depth, while soil pH remained strongly acidic (4.25–4.54). Total and available P and K were low, likely due to long-term coffee cultivation and the influence of Fe-Al-rich bauxitic parent material (Monsels and Van Bergen, 2019).

In contrast, the 2017 spoil soil consisted of repeatedly displaced overburden, forming a heterogeneous mix of topsoil, rock fragments, and weathered materials. With a weak structure and low cohesion, the site was sparsely vegetated and highly eroded before rehabilitation. Chemical analyses indicated severe degradation: very low OC, total N, P, and K, and minimal available nutrients, with firm acidity in both horizons. Compared with the reference soil, the spoil showed pronounced nutrient depletion and chemical deterioration, consistent with significant constraints to vegetation establishment on post-mining lands (Bradshaw, 1997).

*3.3.3. Chemical properties of model soils at different recovery stages*

The chemical properties of soils within the rehabilitation model at various recovery stages were evaluated in comparison with the reference soil (CF-P) and the degraded spoil soil (S17-P) (Fig. 6). Overall, the post-mining rehabilitation process exhibited a positive relationship between recovery duration, vegetation development, and improvements in major soil quality parameters, including OC, total N, total P, available P, total K, and available K.

OC was highest in the reference soil (4.23% at 0–15 cm; 3.22% at 15–50 cm) but very low in the spoil due to carbon loss from disturbance. OC in rehabilitated soils rose steadily during 2018–2020 (by 2.5–10.9%), then stabilized at 1.49% by month 72. Total N increased rapidly during the early phase, reaching values close to the reference in upper layers, but declined after 2020 once management ended.

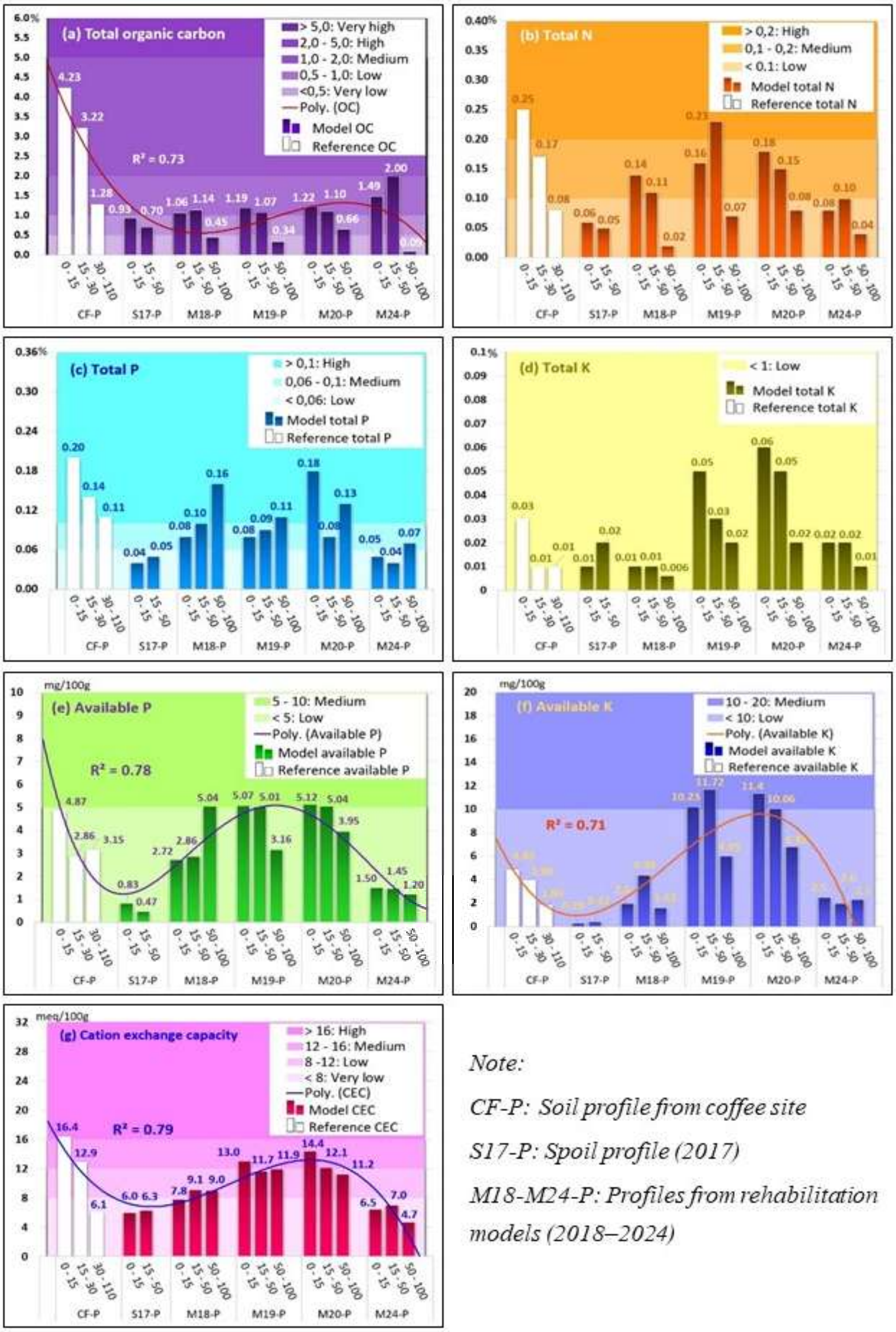


*Figure 6.* Changes in the chemical properties of soil depths over time

Total P was initially depleted (0.04–0.05% in S17-P) but recovered under vegetation establishment, peaking in 2020 before slightly declining. P content remained higher in deeper layers (50–100 cm) than in the surface horizons. Total K showed a similar trend, fertilizer-driven increases during the first 24 months, peaking in 2020, then declining under passive management.

Available P and K remained low overall but increased markedly in the 0–15 cm and 15–50 cm layers during 2018–2020, exceeding reference levels at peak vegetation cover. After rehabilitation ceased, both nutrients decreased rapidly, especially in the surface soil.

Closely associated with soil physical properties, CEC is a key indicator of the soil's ability to retain and supply nutrients. As the clay fraction increased across all depths, CEC increased and reached its highest values at 0-15 cm (Fig. 6g). After the onset of natural succession, CEC declined markedly to very low levels by 2024, corresponding to a reduction in soil clay content.

During the initial 24-month period, soil pH improved significantly, surpassing the severe acidification observed in the spoil soil (S17-P) and exceeding the levels in the reference coffee soil (CF-P). This improvement was most evident in the 0–15 cm depth, with reductions in acidity also observed in the 15–50 cm and 50–100 cm depths, indicating that the rehabilitation measures had begun to affect the entire soil profile (Fig. 7). The 2020 model represented the peak in soil pH improvement. However, by month 72, pH levels declined across all depths, with the most pronounced drop observed in the 0–15 cm depth.

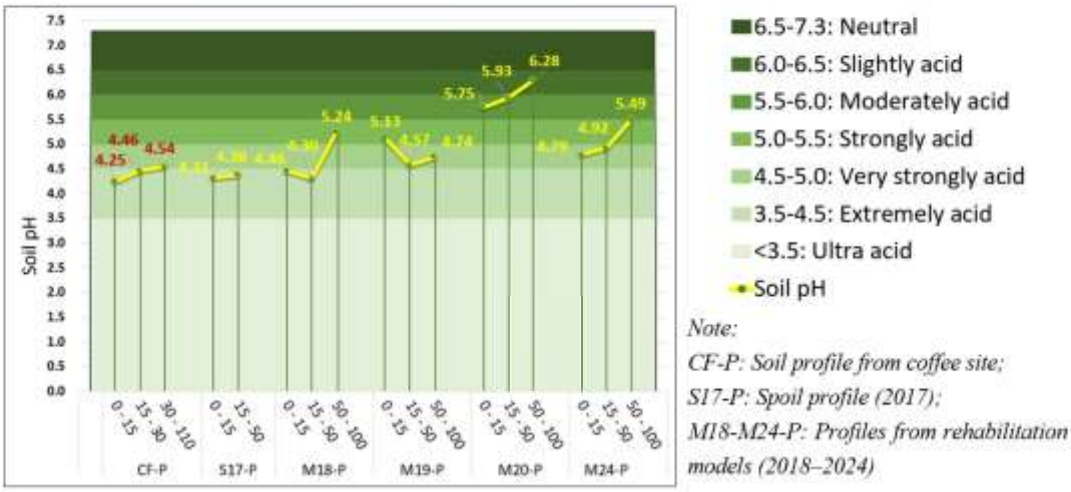


*Figure 7.* Temporal variation in pH across soil depths

Our three-way ANOVA and mixed-effects analysis confirmed that soil quality significantly improved following rehabilitation. Most key soil indicators differed substantially among sites ($p < 0.05$), with rehabilitated soils trending toward reference conditions and clearly separated from unrestored spoil (Table 5). Time had a strong effect ($p < 0.001$), indicating continuous improvement throughout the monitoring period. The significant Site×Time interactions suggest that recovery trajectories varied among sites, reflecting both ecological conditions and rehabilitation treatments. Depth effects were substantial for OC, N, and CEC, highlighting the dominant role of the topsoil layer in nutrient accumulation and restoration processes. These results demonstrate that within a relatively short period, the rehabilitation measures effectively enhanced soil fertility, moving the degraded spoil closer to reference soil conditions.

*Table 5*. Results of three-way ANOVA for the effects of Site, Time, and Depth on soil chemical properties

| Variable | Site | Site(Time) | Time | Site×Time | Depth | Site×Depth |
|---|---|---|---|---|---|---|
| pH | 0.00301 ** | 4.08e-22 *** | 3.46e-17 *** | 7.99e-20 *** | 0.593 ns | 0.279 ns |
| OC | 3.69e-06 *** | 0.888 ns | 1.1e-05 *** | 0.00123 ** | 5.02e-09 *** | 5.36e-07 *** |
| Total N | 0.0321 * | 0.203 ns | 0.000305 *** | 0.00187 ** | 0.00262 ** | 0.000645 *** |
| Total P | 0.00433 ** | 0.826 ns | 1.94e-07 *** | 0.00284 ** | 0.0586 ns | 0.355 ns |
| Available P | 0.00182 ** | 0.186 ns | 1.47e-10 *** | 6.85e-11 *** | 0.284 ns | 0.971 ns |
| Available K | 0.0124 * | 0.000284 *** | 0.00282 ** | 1.15e-12 *** | 0.527 ns | 0.401 ns |
| CEC | 0.0306 * | 9.66e-05 *** | 2.06e-08 *** | 1.7e-08 *** | 0.00678 ** | 0.837 ns |

*Note:* p-value $p<0.05$ = *, $p<0.01$ = **, $p<0.001$ = ***

### *3.3.5. Heavy metal content*

The average concentrations of eight heavy metals in the reference soil (CF, 2018), spoil soil (S17, 2017), and model-rehabilitated soils over time at the Tan Rai bauxite mine are presented in Table 6. Compared to the Vietnamese National Technical Regulation on Soil Quality (QCVN-03:2023/BTNMT), the concentrations of six regulated heavy metals, Cd, Cu, Pb, Hg, Zn, and As, remained well below the permissible limits for Agricultural Soil Type I in all samples, indicating a safe range for agricultural reuse. Relative to the reference soil, the spoil soil exhibited elevated levels of several metals, notably Cd, Pb, As, and B.

*Table 6*. Heavy metal concentrations in soil profiles over time (mg/kg)

| Soil parameters | CF-P | | | S17-P | | M18-P | | | QCVN 03:2023/ BTNMT |
|---|---|---|---|---|---|---|---|---|---|
| | 0–15 cm | 15–30 cm | 30–110 cm | 0–15 cm | 15–40 cm | 0–15 cm | 15–50 cm | 50–100 cm | |
| Cd | 0.27 | 0.2 | 0.23 | 1.62 | 1.76 | 0.38 | 0.41 | 0.49 | **4** |
| Cu | 24.89 | 22.18 | 20.49 | 27.61 | 37.61 | 20.63 | 20.97 | 35.74 | **150** |
| Pb | 3.87 | 3.63 | 2.8 | 8.7 | 10.43 | 5.56 | 5.49 | 5.33 | **200** |
| Mo | 1.23 | 2.12 | 0.91 | 4.85 | 3.12 | 3.26 | 3.03 | 1.73 | - |
| Hg | 0.14 | 0.13 | 0.12 | 3.18 | 3.03 | 0.23 | 0.21 | 0.21 | **12** |
| Zn | 24.89 | 21.61 | 19.94 | 50.9 | 62.71 | 35.87 | 39.62 | 60.58 | **300** |
| As | 2.89 | 3.47 | 2.9 | 9.36 | 9.52 | 8.01 | 7.97 | 3.76 | **25** |
| Bo | 0.95 | 0.45 | <0.1 | 4.68 | 4.11 | 3.01 | 2.54 | 1.81 | - |

*Table 6*. Heavy metal concentrations in soil profiles over time (mg/kg) *(continued)*

| Soil parameters | M19-P | | | M20-P | | | M24-P | | | QCVN 03:2023/ BTNMT |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0–15 cm | 15–50 cm | 50–100 cm | 0–15 cm | 15–50 cm | 50–100 cm | 0–15 cm | 15–50 cm | 50–100 cm | |
| Cd | 0.36 | 0.4 | 0.41 | < 0.1 | < 0.1 | < 0.1 | 0.14 | 0.14 | 0.16 | **4** |
| Cu | 12.19 | 13.04 | 26.84 | 11.16 | 11.16 | 23.83 | 17.36 | 18.75 | 32.35 | **150** |
| Pb | 4.28 | 3.49 | 3.28 | 3.76 | 0.83 | < 0.1 | 1.76 | 1.74 | 4.13 | **200** |
| Mo | 1.16 | 1.01 | 0.55 | 0.76 | 0.99 | 0.95 | < 0.1 | <0.1 | 0.22 | - |
| Hg | 0.24 | 0.23 | 0.17 | < 0.1 | < 0.1 | < 0.1 | < 0.1 | <0.1 | < 0.1 | **12** |
| Zn | 23.28 | 31.81 | 42.89 | 15.64 | 24.39 | 33.57 | 24.68 | 28.45 | 48.37 | **300** |
| As | 7.03 | 6.9 | 1.85 | 3.78 | < 0.1 | < 0.1 | 3.07 | 0.81 | 2.11 | **25** |
| Bo | 1.38 | 0.52 | 0.25 | 0.93 | 0.73 | 0.49 | < 0.1 | < 0.1 | < 0.1 | - |

*Note:* "< 0.1" indicates concentrations below the detection limit of the analytical method; CF-P: Soil profile from coffee site; S17-P: Spoil profile (2017); M18-M24-P: Profiles from rehabilitation models (2018–2024). Three-way ANOVA revealed significant site and time effects on Cu, Pb, Zn, and As concentrations ($p<0.05$), with rehabilitated soils showing decreasing trends over time and approaching reference levels

The elements Cd, Hg, Mo, and B showed a clear and sustained decline across all depths during model development: Cd and Hg in particular fell rapidly and reached or fell below detection limits within a few years, indicating effective early immobilization or removal processes. Mo and B also declined, but at a slower pace. In contrast, As, Pb, Cu, and Zn followed more complex trajectories. During the first 24 months, these metals decreased only modestly, with As and Pb tending to diminish in the surface layer while Cu and Zn remained relatively elevated at greater depths. However, after the managed phase, some metals rebounded: by 2024, Cu and Zn increased again across depths, and As and Pb showed pronounced increases in subsoil layers. Fig. 8 and Table 6 provide detailed values; here, we emphasize the contrasting fast responses of labile elements (Cd, Hg) versus the slower, depth-dependent dynamics of As, Pb, Cu, and Zn.

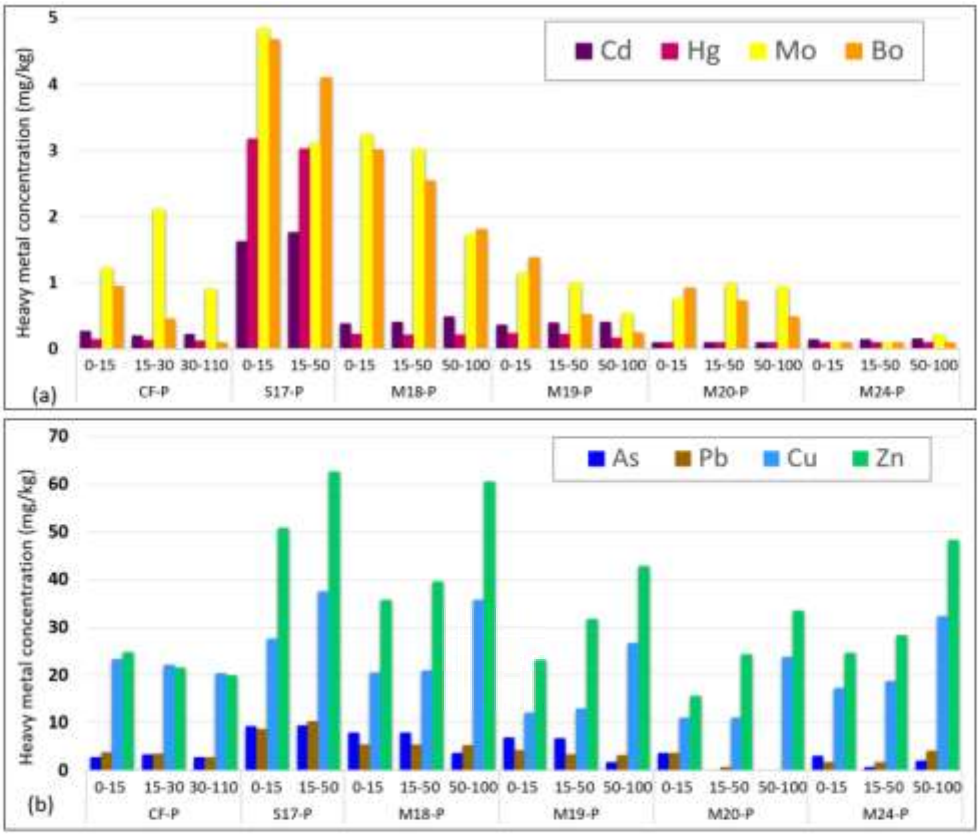


*Figure 8.* Temporal changes in heavy metal concentrations: (a) Cd, Hg, Mo, B; (b) As, Pb, Cu, Zn

## 4. Discussions

### *4.1. Agroforestry species performance after bauxite mining*

During the first 24 months, *Pinus caribaea* Morelet in the model showed vigorous growth, reaching an average height 1.3 times that of 6-year-old plantations in Gungré, Di Linh, under comparable ecological conditions (Nam et al., 2021), likely due to the specialized soil amendment package applied during the managed phase. By month 72, however, growth declined, with average height and basal diameter 1.38 and 1.3 times lower than those in Gungré, and overall rates lagging behind those of other Lam Dong sites and international benchmarks (Table 7). This decline may reflect differences in genetic material, soil fertility, and management, particularly the cessation of amendments, nutrient leaching, and root expansion into nutrient-poor spoil. Additionally, variations in growth performance may also be influenced by climatic factors such as temperature, rainfall, and light intensity across sites. Comparisons were made at the species level using available data for *P. caribaea* var. *hondurensis*, the most widely planted tropical variety.

*B. orellana* has a much lower growth index than the study by Rajan et al. (2015) under favorable conditions in India. The reduced growth likely reflects the nutrient-poor subsoil of the bauxite spoil, discontinuation of soil amendments, and increased interspecific competition during late succession. The onset of reproductive development, with 15–20% of individuals flowering and fruiting, may also have diverted energy from vegetative growth, consistent with previous findings (Louro & Santiago, 2016; Elias et al., 2002). These results indicate that *B. orellana* can persist in post-mining soils but requires continued management to achieve optimal growth.

*S. trilobata* exhibited rapid early vegetative expansion, effectively stabilizing soil surfaces and suppressing weeds during initial recovery. The considerable variation in stem length observed during the first year is attributable to supplementary planting and individual age differences, while the temporary growth stagnation around 18 months corresponds to the dry-season effect on aboveground biomass expansion. Despite these fluctuations, surviving individuals showed strong recovery and extensive ground coverage by 72 months. Given its invasive tendency (Gao et al., 2022), long-term rehabilitation may benefit from its gradual replacement with native, more stable groundcover species.

*Table 7*. Comparative growth performance of *Pinus caribaea* across regions and age classes

| Location | Age (years) | Height (m) | DBH (cm) | Reference |
|---|---|---|---|---|
| Rehabilitation model (Tan Rai, Vietnam) | 6 | 4.34 | 9.2 | This study |
| Gungre (Di Linh, Vietnam) | 6 | 5.6 | 12 | Nam et al. (2021) |
| Uganda (Gulu, Mubende) | 5 | 11.38–12.39 | 14.44–17.29 | Kalanzi et al. (2014) |
| Brazin & Venezuela | 8 | ~12 | ~18 | Hodge et al. (2001) |
| Colombia | 8 | <8 | ~13 | Hodge et al. (2001) |
| Afaka (Nigeria) | 5 | 8.8 | 10.5 | Kedeba (1991) |

*Note:* ~ indicates approximate values; < and > indicate values lower or higher than the reference, respectively

Following the establishment of the planted species, natural regeneration processes began contributing to vegetation development, particularly within the shrub and herbaceous layer. The relatively high species richness observed within the first month is ecologically reasonable for tropical post-mining environments. Three concurrent mechanisms likely drove early colonization: (i) residual propagules and vegetative fragments surviving in the replaced topsoil, (ii) rapid germination and dispersal of pioneer species during the onset of the rainy season, and (iii) invasion from adjacent vegetation. The early community, dominated by ruderal grasses and herbs, reflects typical tropical successional dynamics characterized by fast-growing, disturbance-tolerant species (Pickett & White, 1985; Garwood, 1989; Parrotta & Knowles, 1999; Holl, 1999).

Although the model demonstrated promising outcomes, the absence of experimental control plots limits the ability to draw definitive conclusions about the relative effectiveness of the applied interventions. In addition, unexpected external disturbances, such as livestock intrusion and partial damage to young vegetation, may have influenced growth dynamics and soil recovery rates. Therefore, future studies should include controlled comparative treatments to better quantify the effectiveness of restoration measures.

### *4.2. Soil nutrient dynamics and long-term limitations of the rehabilitation model*

The results highlight both the effectiveness and limitations of the post-bauxite soil rehabilitation model. During the first 24 months, fertilizers and soil amendments effectively supported vegetation establishment, reduced erosion, and initiated nutrient cycling. In the subsequent self-sustaining phase, although nutrient levels declined, soil quality remained markedly higher than in the original spoil. OC, widely recognized as a sensitive indicator of soil recovery (Borges et al., 2019; Martins et al., 2021; Song et al., 2023), was the only parameter to show a continuous, long-term increase. However, as Bradshaw (1997) noted, organic matter recovery is slow and easily reversed without continuous management. The strong OC-N correlation confirmed the key role of organic matter in nutrient cycling, while total N, P, and K declined after 48 months following fertilization cessation. Early nutrient gains were likely fertilizer-induced and diminished due to the low K retention and high P fixation capacity of Ferralsols (Ky, 1990; Thuy & Anh, 2017). Fluctuations in available P and K underscore short-term benefits but long-term instability, consistent with Bizuti et al. (2020), Martins et al. (2021), and Han et al. (2023). Polynomial regression ($R^2 > 0.7$) showed rise-fall patterns in OC, available P, K, and CEC, initially driven by amendments and later by natural succession. The pH decline during passive recovery indicates reacidification and highlights the vulnerability of post-mining soils without sustained amelioration (Juwarkar et al., 2010; Shrestha & Lal, 2011). Similar observations have been reported in acidic forest soils in central Vietnam, where surface soils showed low pH and variable chemical properties with depth (Dinh Viet et al., 2025).

Evidence from previous studies indicates that complete recovery of soil and biotic functions may take decades, emphasizing the need for long-term monitoring and adaptive management (Shrestha & Lal, 2011; Orozco-Aceves et al., 2017; Tibbett, 2024). In the Tan Rai case, the soil quality improvements achieved during the 24-month amendment phase declined after management ceased, indicating that 2 years of intervention were insufficient to ensure long-term stability. Based on this finding, we recommend a stage-based management framework comprising: (i) active management during the early establishment phase (lasting minimum of five years); (ii) continued maintenance and ecological monitoring forr approximately seven years; and (iii) an intermediate evaluation conducted after 10–15 years, followed by monitoring at decadal intervals. This recommendation aligns with industry practices, such as Alcoa's rehabilitation framework (Alcoa, 2015), and with current international recommendations for sustainable ecosystem recovery (Tibbett, 2024).

Overall, the multi-strata agroforestry model proved effective in the managed phase but less resilient under passive succession. Maintaining soil fertility will require long-term nutrient supplementation, organic matter management, erosion control, and regular monitoring to prevent degradation reversal. These findings provide an evidence-based foundation for scaling up the multi-strata agroforestry model to other post-bauxite mine areas in tropical highlands. Future research should focus on long-term monitoring of soil-plant interactions, optimization of amendment application rates, and integration of local native species to enhance ecological resilience and sustainability of rehabilitated sites.

### *4.3. Heavy metal cycling in rehabilitated spoil soil*

Post-mining bauxite spoil soils commonly contain a range of heavy metals at varying concentrations (Ren et al., 2018; Nguyen et al., 2021; Kumari et al., 2023). A comprehensive assessment of heavy metal distribution in soils is necessary to guide remediation and pollution prevention (Hoang et al., 2020). Most element concentrations in the untreated spoil were lower than those reported for other bauxite-mining regions, including Shanxi, China (Ren et al., 2018) and Pahang, Malaysia (Ismail et al., 2018).

Changes in heavy metal concentrations across soil depths reflect the influence of plant-soil interactions during rehabilitation. Essential micronutrients such as Zn, Cu, and Mn are absorbed by roots and immobilized within plant tissues. At the same time, species capable of hyperaccumulation (e.g., Cd, Hg) promote faster declines in these more mobile metals compared to less soluble elements like Mo and B (Liu et al., 2016). Coniferous species, including *P. caribaea*, are known to accumulate Pb, Zn, and Cu in their biomass (Sun et al., 2009; Alahabadi et al., 2017; Solgi et al., 2020; Çomaklı & Bingöl, 2021; Jonczak et al., 2021).

Li et al. (2020) reported that heavy metal concentrations and stocks in soil do not necessarily decline with conifer stand age. The later-stage increases in As, Pb, Cu, and Zn likely reflect enhanced biological cycling and litter decomposition that returned these elements to the upper 0–15 cm layer. This suggests an active nutrient and trace-element cycling pathway within the rehabilitation model. Metal redistribution may also occur through leaching and root-mediated mobilization, as organic acids and enzymes released by mature conifers can promote downward metal migration, explaining the higher concentrations occasionally observed at 50–100 cm. Further tissue analyses are needed to verify these uptake and cycling processes.

## 5. Conclusions

A multi-strata agroforestry model combining *Pinus caribaea* Morelet, *Bixa orellana* L., and *Sphagneticola trilobata* (L.) Pruski, integrated with two types of soil amendments and fertilizers, was established for the first time on post-mining spoil soils at the Tan Rai bauxite mine, one of Vietnam's most representative industrial mining sites. During the first 24 months, the model achieved a high survival rate (> 85%) and rapid vegetation cover (about 87%) comprising around 20 species. After 48 months without management, the overall survival rate dropped to 57.7%, especially for *S. trilobata*, and the growth of *P. caribaea* and *B. orellana* slowed, maily due to nutrient depletion and livestock disturbance.

The rehabilitation model significantly improved key soil properties, including increases in OC, total and available N, P, and K, cation exchange capacity, and pH within the topsoil during the amendment phase. Although nutrient levels gradually declined during the subsequent succession phase, they remained substantially higher than those of the degraded spoil soil. The continuous increase in organic carbon throughout the 72 months provides compelling evidence of soil ecosystem recovery driven by biogeochemical cycling. Importantly, all heavy metal concentrations remained below the permissible limits for Agricultural Soil Type 1 according to QCVN-03:2023/BTNMT.

The findings of this study suggest that a phased management strategy is required to ensure sustainable soil and vegetation recovery in post-bauxite mining areas. Continuous care and ecological monitoring for at least seven years after model establishment are essential to consolidate early restoration gains, support soil ecosystem recovery, promote optimal growth of key species, and increase understory diversity. Beyond this period, long-term monitoring and periodic evaluations over subsequent decades are strongly recommended to assess the stability of restored ecosystems and to understand better the long-term evolution of soil properties and heavy metal dynamics.

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