

Interaction between rooting volume and planting density in shaping biomass productivity of *Calliandra calothyrsus* on post-coal degraded lands

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ABSTRACT

Post-mining land rehabilitation offers potential for integrating ecological restoration with biomass-based energy production; however, optimal silvicultural configurations for degraded substrates remain insufficiently quantified. This study evaluated the interactive effects of planting density (1×2 m vs. 2×2 m), planting hole volume ($10 \times 10 \times 10$, $20 \times 20 \times 20$, and $30 \times 30 \times 30$ cm), and growing media composition (100% topsoil vs. 70:20:10 topsoil:solid decanter:biochar) on growth performance and fuel quality of *Calliandra calothyrsus* in a 18-month factorial field experiment on post-coal mining land in East Kalimantan, Indonesia. Planting density and rooting volume showed significant interaction effects on biomass accumulation (two-way ANOVA, $p < 0.05$), with 1×2 m spacing combined with $30 \times 30 \times 30$ cm planting holes producing the highest yield (62 t ha^{-1} at 24 months). In contrast, restricted rooting volume ($10 \times 10 \times 10$ cm) consistently limited growth irrespective of media composition. Biomass exhibited high fuel quality across treatments, with a net calorific value of 21.99 MJ kg^{-1} , low ash content (1.05%), and minimal sulfur concentration (0.05%), corresponding to an estimated theoretical energy potential of 386 MWh ha^{-1} . These results provide experimental evidence that planting density and soil preparation jointly regulate productivity of *C. calothyrsus* on degraded substrates and inform management strategies for biomass-oriented restoration of post-mining landscapes.

Keywords: *Calliandra calothyrsus*, short rotation coppice, post-mining rehabilitation, biomass energy, silviculture optimization.

INTRODUCTION

Indonesia faces substantial challenges in achieving its renewable energy transition targets of 23% by 2025 and 31% by 2050, as mandated by Presidential Regulation No. 112 of 2022. Despite policy commitments, renewable energy contributed only 12.5% to the national energy mix in 2023, remaining below interim targets (IESR, 2024). Among renewable sources, biomass represents a technically deployable and dispatchable option with an estimated national potential of 32.7 GW (Langer et al., 2021). In particular, biomass

cofiring in existing coal-fired power plants is considered a transitional pathway requiring relatively limited infrastructure modification while contributing to reductions in NO_x and SO_x emissions (Roni et al., 2017). However, sustainable and large-scale biomass feedstock supply remains a critical bottleneck for long-term implementation.

Short rotation coppice (SRC) systems established on marginal lands, including post-mining areas, offer a strategic approach to securing sustainable biomass feedstock without competing with agricultural production. *C. calothyrsus*, a fast-growing nitrogen-fixing legume, is widely

recognized as a promising energy crop due to its rapid biomass accumulation and favorable fuel characteristics (Narendra et al., 2020). Its reported calorific value (approximately 18–21 MJ kg⁻¹; Widyati et al., 2022) meets technical specifications for cofiring applications. Indonesia possesses extensive areas of post-coal mining land characterized by severe ecosystem degradation (Fikriah et al., 2024). These sites commonly exhibit soil compaction, disrupted structure, reduced fertility, and potential heavy metal contamination. Mining-induced disturbances significantly alter biological, geochemical, and pedophysical soil properties, thereby constraining root development and plant productivity (Rouhani et al., 2023).

Effective restoration of post-mining ecosystems requires integration of soil amelioration, appropriate species selection, and context-specific silvicultural management (Narendra et al., 2021). Previous studies have identified 2 × 2 m spacing as favorable for *C. calothyrsus* biomass production under certain site conditions (Widyati et al., 2022). However, planting density alone does not determine productivity in degraded substrates where physical soil constraints may restrict root expansion. Planting hole dimensions and growing media composition directly influence effective rooting volume, soil aeration, and nutrient availability—factors that are particularly critical in compacted post-mining soils (Lestari et al., 2020; Pratiwi and Nurcholis, 2023). Despite their recognized importance, the interactive effects of planting density, rooting volume, and soil amendment strategies on biomass productivity remain insufficiently quantified.

To address this gap, the present study experimentally evaluated the interactive effects of planting density, planting hole size (as a proxy for rooting volume), and growing media composition on biomass productivity and fuel quality of *C. calothyrsus* in a factorial field trial on post-coal mining land. It was hypothesized that: (1) increased rooting volume would significantly enhance biomass accumulation by alleviating physical soil constraints; (2) optimal planting density would depend on rooting volume due to competition-resource trade-offs; and (3) soil amendment with organic additives would further improve growth under restricted soil conditions. By quantifying these interactions, this study aims to establish mechanistic understanding of how silvicultural factors jointly regulate biomass productivity in degraded substrates, thereby informing biomass-oriented restoration strategies.

MATERIALS AND METHODS

Study site and experimental design

The field experiment was conducted at PT Jembayan Muara Bara post-mining site in Mularman Village, Separi District, Kutai Kartanegara Regency, East Kalimantan, Indonesia. Geographically located at coordinates 0°12'28" - 0°12'36" and N 117°8'50" – 117°8'50" S with an altitude of 100 m asl. Between 1990 and 2019, climate data from the Temindung BMKG Station with a Q value of 11.65, 2.101 mm of rain a year on average, and 28.64 °C for each month (Figure 1).

The site represents typical post-coal mining conditions with degraded soil physical and chemical properties. The experimental design employed a three-factor completely randomized factorial arrangement with three replications:

- Factor A – planting distance: 1 × 2 m (5.000 trees/ha) and 2 × 2 m (2.500 trees/ha),
- Factor B – planting hole size: 10 × 10 × 10 cm, 20 × 20 × 20 cm, and 30 × 30 × 30 cm,
- Factor C – growing media composition: 70:20:10 (topsoil: solid decanter: biochar) and 100:0:0 (100% topsoil).

Each experimental unit consisted of 25 seedlings arranged in a 5 × 5 configuration. Measurements were taken from the inner 9 trees to minimize edge effects. Seedlings were planted at the onset of the rainy season to ensure successful establishment.

Plant material and establishment

C. calothyrsus seedlings were planted according to treatment specifications. Planting holes were excavated to the assigned dimensions. The 70:20:10 soil mixture was prepared by mixing topsoil with solid decanter (oil palm processing waste) and biochar to enhance fertility and soil structure; 100% topsoil served as the control. Routine maintenance, including weeding and protection from herbivores, was conducted throughout the growth period.

Growth measurements

At 18 months after planting, height was measured from ground level to the highest growing point using a measuring pole. Stem diameter was measured at 10 cm above ground using digital calipers. Measurements were recorded for all sampled trees in each experimental unit.

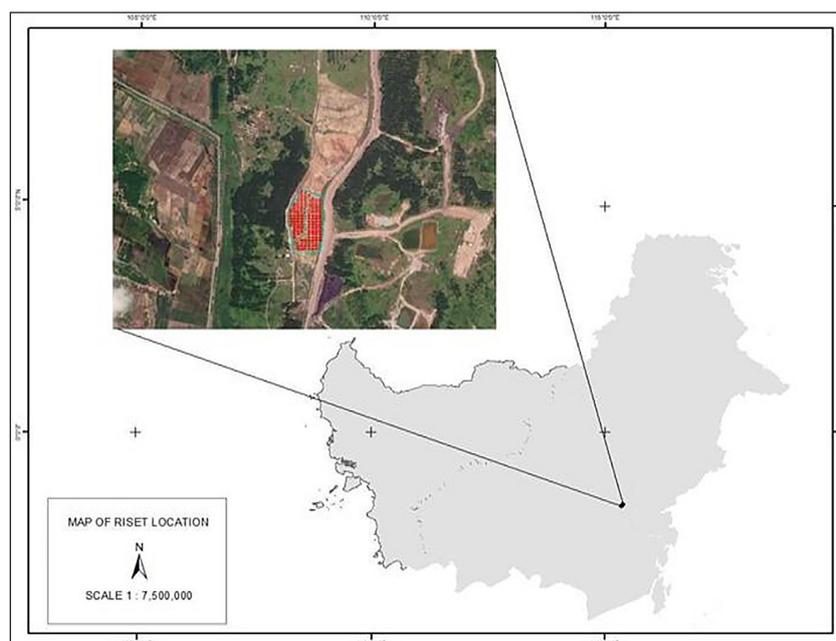


Figure 1. Research location at PT Jembayan Muara Bara post mining, Kutai Kartanegara, East Kalimantan, Indonesia

Biomass determination

Above-ground biomass was assessed via destructive sampling. Three representative trees per experimental unit were harvested at ground level. Fresh biomass was immediately weighed using digital scales. Samples were transported to the laboratory for further analysis. Per-hectare productivity was calculated based on planting density and average tree biomass.

Physico-chemical analysis

Wood samples were prepared following standard procedures. Moisture content: oven-dry method at 103 ± 2 °C until constant weight (TAPPI T 264 cm-22, 1997). Wood density: ratio of oven-dry mass to green volume, measured using water displacement (DIN 52182-76) Chemical composition: lignin (Klason method, TAPPI T222 om-98), holocellulose (chlorite delignification), α -cellulose (TAPPI T9m-54 modified). Samples were ground through 40–60 mesh before analysis. Analyses conducted at Laboratory of Forest Products Chemistry and Renewable Energy, Faculty of Forestry, Mulawarman University.

Proximate and ultimate analysis

Proximate analysis determined ash content, volatile matter, and fixed carbon following

ASTM D 3175-11 (ASTM, 2012). In the first step, 1 g of sample used ash content was measured by combusting samples at 750 °C for 6 hours. Next steps, volatile matter was determined by heating samples at 950 °C for 7 minutes in absence of air. Fixed carbon was calculated by difference. Ultimate analysis quantified carbon, hydrogen, oxygen, nitrogen, and sulfur content used 1 g of sample with using elemental analyzer (Parikh et al., 2007). For each sample was performed in triplicate. These analyses were conducted at the Integrated Laboratory, Diponegoro University, Semarang, Central Java.

Calorific value determination and energy potential calculation

Calorific value was measured using bomb calorimeter following ASTM D 5865-13 standard (ASTM, 2013). Gross calorific value (GCV) is measured directly using a formula;

$$GCV (kcal/kg) = T_2 - T_1 - 0.05 \times C_v \times 0.24 \quad (1)$$

where: T_1 – initial water temperature (°C), T_2 – temperature after combustion (°C), 0.05 – temperature increase due to wire heating, C_v – specific heat of calorimeter (73,529.6 kJ/kg), 0.24 – constant of 1 J (0.24 cal).

High heating value (HHV) was calculated from ultimate analysis using Dulong's formula.

Net calorific value (NCV) was derived accounting for latent heat of water vaporization from hydrogen content and moisture content (Parikh et al., 2005).

$$HCV = 0.3536 FC + 0.1559 VM - 0.0078 ASH \quad (2)$$

where: *HCV* – highest calorific value (MJ/kg), *FC* – fixed carbon (%), *VM* – volatile matter (%), *ASH* – ash content (%).

These analyses were conducted at the Integrated Laboratory, Diponegoro University, Semarang, Central Java.

Energy potential per hectare was calculated using the formula:

$$\begin{aligned} \text{Energy potential (MWh/ha)} &= \\ &= \text{Biomass yield (ton/ha)} \times \\ &\times \text{NCV (MJ/kg)} \times 0.2778 \end{aligned} \quad (3)$$

where: 0.2778 is the conversion factor from *MJ* to *MWh*.

This calculation assumes 100% biomass utilization for energy conversion (Francescato & Antonini, 2008).

Statistical analysis

Data were subjected to three-way analysis of variance (ANOVA) to determine main effects and interactions among factors. When significant differences were detected ($p < 0.05$). Statistical analyses were performed using SPSS software.

RESULTS AND DISCUSSION

Growth performance and biomass productivity

Plant growth showed significant variation across treatment combinations. Under 1 × 2 m spacing, trees in 100% topsoil media with 10 × 10 × 10 cm holes achieved maximum height (474 cm) and diameter (3.88 cm), producing 11.83 kg biomass per tree. The optimal combination (1 × 2 m spacing, 30 × 30 × 30 cm holes, 100% topsoil) yielded 62 ton/ha biomass productivity (Table 1). In 2 × 2 m spacing configuration, the 100:0:0 media composition with 20 × 20 × 20 cm holes produced superior individual tree biomass (17.37 kg/tree) compared to other treatments. However, lower planting density resulted in reduced per-hectare productivity (43.42 ton/ha) compared to the 1 × 2 m optimal treatment. Trees grown in 70:20:10 media with minimal hole size (10 × 10 × 10 cm) exhibited substantially reduced growth across both spacing treatments, with biomass ranging from 2.17–2.27 kg/tree, indicating severe rooting space limitation even with organic amendments (Table 2).

Physico-chemical analysis

Moisture content ranged from 12.61% to 14.72% across all treatments, falling within acceptable ranges for biomass feedstock. Wood density varied between 0.63–0.77 g/cm³, with no clear systematic pattern related to treatment factors (Table 3). The 1 × 2 m spacing with 70:20:10 media generally produced slightly higher density values

Table 1. Growth performance and biomass production of *C. calothyrsus* under varying planting distance, planting hole size, and growing media composition on post-mining land

| Planting distance | Hole Size (cm) | Media composition | Height (cm) | Diameter (cm) | Biomass (kg/tree) | Biomass (ton/ha) |
|-------------------|----------------|-------------------|-------------|---------------|-------------------|------------------|
| 1 × 2 m | 10 × 10 × 10 | 70:20:10 | 283 | 3.13 | 2.17 | 10.85 |
| | 20 × 20 × 20 | 70:20:10 | 321 | 2.82 | 2.47 | 12.35 |
| | 30 × 30 × 30 | 70:20:10 | 333 | 3.48 | 4.33 | 21.65 |
| | 10 × 10 × 10 | 100:00:00 | 474 | 3.88 | 11.83 | 59.15 |
| | 20 × 20 × 20 | 100:00:00 | 388 | 4.29 | 6.63 | 33.15 |
| | 30 × 30 × 30 | 100:00:00 | 452 | 6.24 | 12.40 | 62.00 |
| 2 × 2 m | 10 × 10 × 10 | 70:20:10 | 250 | 2.34 | 2.27 | 5.68 |
| | 20 × 20 × 20 | 70:20:10 | 408 | 3.91 | 5.40 | 13.50 |
| | 30 × 30 × 30 | 70:20:10 | 292 | 3.53 | 12.23 | 30.58 |
| | 10 × 10 × 10 | 100:00:00 | 284 | 4.20 | 9.20 | 23.00 |
| | 20 × 20 × 20 | 100:00:00 | 398 | 6.07 | 17.37 | 43.43 |
| | 30 × 30 × 30 | 100:00:00 | 388 | 5.82 | 14.13 | 35.33 |

Note: * Growing media composition: 70:20:10 (topsoil:solid decanter:biochar) and 100:0:0 (100% topsoil).

Table 2. Results of variance test on growth parameters of red calliandra (*Calliandra calothyrsus* Meisn.) in coal post-mining rehabilitation land

| Interaction between variable and treatments | Diameter | | Height | | Biomass | |
|---|----------|---------|---------|---------|---------|---------|
| | F-count | F-table | F-count | F-table | F-count | F-table |
| A | 0.359 | 0.554 | 1.211 * | 0.282 | 1.345 * | 0.258 |
| B | 2.039 * | 0.152 | 0.941 * | 0.404 | 0.745 * | 0.485 |
| C | 11.075 * | 0.003 | 5.647 * | 0.026 | 5.686 * | 0.025 |
| A × B | 0.947 * | 0.402 | 1.786 * | 0.189 | 0.665 * | 0.523 |
| A × C | 0.153 | 0.699 | 1.492 * | 0.234 | 0.004 | 0.952 |
| B × C | 0.392 | 0.680 | 0.607 * | 0.553 | 0.128 | 0.880 |
| A × B × C | 0.176 | 0.840 | 0.310 | 0.736 | 0.496 | 0.615 |

Note: (A) = planting spacing, (B) = planting hole, (C) = planting medium, (*) – significant, (**) = highly significant, (×) = interaction.

(0.72–0.77 g/cm³) compared to 100% topsoil treatments (0.64–0.70 g/cm³). These density variations remained within the typical range for *C. calothyrsus* species and are suitable for energy applications.

Chemical composition analysis revealed relatively stable lignin content ranging from 23.51% to 28.15%, holocellulose content from 77.87% to 82.74%, and α -cellulose content from 52.59% to 63.81% (Table 4). Treatment combinations did not significantly alter chemical composition patterns, suggesting that silvicultural manipulations primarily affected biomass quantity rather than fundamental wood chemistry. The balanced holocellulose-to-lignin ratio across treatments indicates consistent fuel characteristics regardless of growth conditions.

Proximate and ultimate analysis

Proximate analysis demonstrated excellent biomass quality for energy applications. Ash content remained remarkably low across all treatments, ranging from 0.50% to 2.23% with mean of 1.05% (Table 5). Volatile matter content was consistently high (94.18–99.77%, mean 97.38%), indicating favorable combustion characteristics. Fixed carbon content showed minimal variation (25.65–26.29%), ensuring stable energy conversion performance. The low ash content particularly benefits cofiring applications by minimizing slagging and fouling issues in boilers.

Ultimate analysis revealed carbon content ranging from 47.70% to 48.58%, hydrogen from 7.49% to 8.87%, oxygen from 41.74% to 44.39%, and nitrogen from 0.69% to 1.07% (Table 6). Sulfur content was exceptionally low (0.00–0.33%, mean 0.05%), substantially below

regulatory limits for biomass fuels. This low sulfur characteristic represents significant environmental advantage, as it eliminates SO_x emissions concerns during combustion. The high carbon and hydrogen content combined with low sulfur makes *C. calothyrsus* biomass highly suitable for clean energy applications.

Calorific value determination and energy potential calculation

Net calorific values ranged from 21.51 to 22.41 MJ/kg with overall mean of 22.01 MJ/kg (Table 7). Treatment effects on calorific value were minimal, demonstrating that energy density remained consistent regardless of silvicultural manipulations. This consistency is crucial for industrial applications requiring uniform fuel quality specifications. The calorific values obtained exceed typical requirements for biomass cofiring (>18 MJ/kg), confirming *C. calothyrsus* suitability as premium biomass feedstock.

Energy potential calculations revealed dramatic differences driven primarily by biomass productivity rather than energy density. The optimal treatment (1 × 2 m spacing, 30 × 30 × 30 cm holes, 100% topsoil) achieved 386.01 MWh/ha energy potential from 62 ton/ha biomass yield (Table 8, Figure 2), (1 × 2 m, 10 × 10 × 10 cm, 70:20:10 media) which produced only 66.09 MWh/ha. The second-best configuration (1 × 2 m, 10 × 10 × 10 cm, 100% topsoil) delivered 368.03 MWh/ha from 59.17 ton/ha biomass. Notably, the 2 × 2 m spacing with 100:0:0 media and 20 × 20 × 20 cm holes achieved 261.27 MWh/ha despite lower planting density, demonstrating that organic amendments combined with

Table 3. Physical properties (moisture content and wood density) of *C. calothyrsus* biomass with different silvicultural treatments

| Planting distance | Hole size (cm) | Media composition* | Moisture content (%) | Wood density (g/cm ³) |
|-------------------|----------------|--------------------|----------------------|-----------------------------------|
| 1 × 2 m | 10 × 10 × 10 | 70:20:10 | 14.72 | 0.75 |
| | 20 × 20 × 20 | 70:20:10 | 14.10 | 0.72 |
| | 30 × 30 × 30 | 70:20:10 | 13.52 | 0.77 |
| | 10 × 10 × 10 | 100:00:00 | 12.61 | 0.70 |
| | 20 × 20 × 20 | 100:00:00 | 12.87 | 0.64 |
| | 30 × 30 × 30 | 100:00:00 | 12.98 | 0.67 |
| 2 × 2 m | 10 × 10 × 10 | 70:20:10 | 13.66 | 0.69 |
| | 20 × 20 × 20 | 70:20:10 | 13.23 | 0.69 |
| | 30 × 30 × 30 | 70:20:10 | 14.18 | 0.74 |
| | 10 × 10 × 10 | 100:00:00 | 13.61 | 0.71 |
| | 20 × 20 × 20 | 100:00:00 | 13.69 | 0.63 |
| | 30 × 30 × 30 | 100:00:00 | 13.80 | 0.75 |

Table 4. Chemical composition (lignin, holocellulose, and α-cellulose content) of *C. calothyrsus* wood across different treatments

| Planting distance | Hole size (cm) | Media composition* | Lignin (%) | Holocellulose (%) | α-Cellulose (%) |
|-------------------|----------------|--------------------|------------|-------------------|-----------------|
| 1 × 2 m | 10 × 10 × 10 | 70:20:10 | 26.95 | 81.04 | 57.00 |
| | 20 × 20 × 20 | 70:20:10 | 25.48 | 77.87 | 52.95 |
| | 30 × 30 × 30 | 70:20:10 | 23.51 | 80.25 | 53.30 |
| | 10 × 10 × 10 | 100:00:00 | 28.15 | 78.77 | 54.20 |
| | 20 × 20 × 20 | 100:00:00 | 24.34 | 81.17 | 54.95 |
| | 30 × 30 × 30 | 100:00:00 | 27.30 | 82.74 | 52.59 |
| 2 × 2 m | 10 × 10 × 10 | 70:20:10 | 26.98 | 78.29 | 57.18 |
| | 20 × 20 × 20 | 70:20:10 | 24.13 | 81.57 | 57.18 |
| | 30 × 30 × 30 | 70:20:10 | 27.32 | 81.65 | 53.88 |
| | 10 × 10 × 10 | 100:00:00 | 26.82 | 81.17 | 63.81 |
| | 20 × 20 × 20 | 100:00:00 | 24.79 | 82.57 | 54.69 |
| | 30 × 30 × 30 | 100:00:00 | 26.82 | 80.34 | 56.85 |

Table 5. Proximate analysis (ash content, volatile matter, and fixed carbon) of *C. calothyrsus* biomass

| Planting distance | Hole size (cm) | Media composition* | Ash content (%) | Volatile matter (%) | Fixed carbon (%) |
|-------------------|----------------|--------------------|-----------------|---------------------|------------------|
| 1 × 2 m | 10 × 10 × 10 | 70:20:10 | 0.92 | 96.09 | 25.85 |
| | 20 × 20 × 20 | 70:20:10 | 1.03 | 99.11 | 26.29 |
| | 30 × 30 × 30 | 70:20:10 | 1.11 | 99.17 | 25.81 |
| | 10 × 10 × 10 | 100:00:00 | 0.50 | 99.63 | 25.95 |
| | 20 × 20 × 20 | 100:00:00 | 2.23 | 98.45 | 25.65 |
| | 30 × 30 × 30 | 100:00:00 | 0.6 | 99.77 | 26.24 |
| 2 × 2 m | 10 × 10 × 10 | 70:20:10 | 1.42 | 98.72 | 25.7 |
| | 20 × 20 × 20 | 70:20:10 | 1.19 | 94.18 | 26.19 |
| | 30 × 30 × 30 | 70:20:10 | 0.77 | 94.61 | 26.13 |
| | 10 × 10 × 10 | 100:00:00 | 0.93 | 99.16 | 25.85 |
| | 20 × 20 × 20 | 100:00:00 | 0.82 | 95.52 | 26.05 |
| | 30 × 30 × 30 | 100:00:00 | 1.08 | 94.43 | 25.96 |

Table 6. Ultimate analysis (C, H, O, N, and S) and sulfur content of *C. calothyrsus* biomass

| Planting distance | Hole size (cm) | Media composition* | C (%) | H (%) | O (%) | N (%) | S (%) |
|-------------------|----------------|--------------------|-------|-------|-------|-------|-------|
| 1 × 2 m | 10 × 10 × 10 | 70:20:10 | 48.11 | 7.49 | 43.36 | 0.71 | 0.33 |
| | 20 × 20 × 20 | 70:20:10 | 47.70 | 8.02 | 43.48 | 0.75 | 0.05 |
| | 30 × 30 × 30 | 70:20:10 | 48.52 | 7.88 | 42.83 | 0.69 | 0.08 |
| | 10 × 10 × 10 | 100:00:00 | 48.15 | 8.00 | 44.39 | 0.78 | 0.03 |
| | 20 × 20 × 20 | 100:00:00 | 48.58 | 8.100 | 42.56 | 0.75 | 0.01 |
| | 30 × 30 × 30 | 100:00:00 | 47.92 | 8.07 | 43.22 | 0.78 | 0.02 |
| 2 × 2 m | 10 × 10 × 10 | 70:20:10 | 47.77 | 7.83 | 43.47 | 0.92 | 0.02 |
| | 20 × 20 × 20 | 70:20:10 | 48.39 | 8.87 | 41.74 | 0.99 | 0.01 |
| | 30 × 30 × 30 | 70:20:10 | 48.34 | 7.89 | 42.77 | 0.99 | 0.00 |
| | 10 × 10 × 10 | 100:00:00 | 47.95 | 7.89 | 43.09 | 1.07 | 0.01 |
| | 20 × 20 × 20 | 100:00:00 | 48.22 | 7.95 | 42.78 | 1.05 | 0.01 |
| | 30 × 30 × 30 | 100:00:00 | 48.10 | 7.85 | 43.00 | 1.04 | 0.01 |

Note: * Growing media composition: 70:20:10 (topsoil:solid decanter:biochar) and 100:0:0 (100% topsoil).

Table 7. Calorific values (GCV, HHV, and NCV) of *C. calothyrsus* biomass across different treatments

| Planting distance | Hole size (cm) | Media composition* | GCV (kcal/kg) | HHV (MJ/kg) | NCV (MJ/kg) |
|-------------------|----------------|--------------------|---------------|-------------|-------------|
| 1 × 2 m | 10 × 10 × 10 | 70:20:10 | 4163.28 | 24.13 | 21.93 |
| | 20 × 20 × 20 | 70:20:10 | 4140.73 | 24.76 | 22.11 |
| | 30 × 30 × 30 | 70:20:10 | 4216.28 | 24.60 | 22.31 |
| | 10 × 10 × 10 | 100:00:00 | 4257.62 | 24.71 | 22.4 |
| | 20 × 20 × 20 | 100:00:00 | 4158.12 | 24.44 | 22.04 |
| | 30 × 30 × 30 | 100:00:00 | 4114.29 | 24.84 | 22.41 |
| 2 × 2 m | 10 × 10 × 10 | 70:20:10 | 4108.00 | 24.49 | 22.25 |
| | 20 × 20 × 20 | 70:20:10 | 4114.00 | 23.95 | 21.51 |
| | 30 × 30 × 30 | 70:20:10 | 4210.00 | 24.00 | 21.67 |
| | 10 × 10 × 10 | 100:00:00 | 4073.00 | 24.61 | 22.22 |
| | 20 × 20 × 20 | 100:00:00 | 4182.00 | 24.11 | 21.66 |
| | 30 × 30 × 30 | 100:00:00 | 4193.00 | 23.91 | 21.61 |

Note: * Growing media composition: 70:20:10 (topsoil:solid decanter:biochar) and 100:0:0 (100% topsoil).

adequate rooting space can partially compensate for reduced tree population. However, treatments with inadequate amelioration showed severely compromised energy potential, ranging from 35.07 to 66.09 MWh/ha.

Silvicultural factor interactions and biomass productivity

This study demonstrates that strategic silvicultural optimization can dramatically enhance biomass productivity on degraded post-mining lands (Zine et al., 2024; Rashmi et al., 2024). The superior performance of 1 × 2 m spacing with 30 × 30 × 30 cm holes and 100% topsoil aligns with findings that intensive amelioration combined with appropriate planting density maximizes

resource capture in degraded systems (Yuan et al., 2023; Mahdi et al., 2021).

The contrasting results between spacing treatments reveal complex competition-facilitation dynamics. While 2 × 2 m spacing produced larger individual trees in some treatments (up to 17.37 kg/tree), the doubled planting density at 1 × 2 m spacing ultimately delivered higher per-hectare productivity. This pattern supports resource optimization theory suggesting that in ameliorated conditions, increased plant density enhances total biomass capture before competition becomes limiting (Ng et al., 2020; Pretzsch and Schütze, 2021). Previous research on *C. calothyrsus* energy plantations reported optimal productivity at 2 × 2 m spacing under conventional conditions (Widyati et al., 2022), but our results

Table 8. Energy potential for electricity generation from *C. calothyrsus* plantations under different

| Planting distance | Hole size (cm) | Media composition* | GCV (kcal/kg) | HHV (MJ/kg) | NCV (MJ/kg) | Biomass (kg/ha) | Biomass (ton/ha) | Energy (MWh/ton) | Energy (MWh/ha) |
|-------------------|----------------|--------------------|---------------|-------------|-------------|-----------------|------------------|------------------|-----------------|
| 1 × 2 m | 10 × 10 × 10 | 70:20:10 | 4163,28 | 24.13 | 21.93 | 10,833 | 10.83 | 6.09 | 66.09 |
| | 20 × 20 × 20 | 70:20:10 | 4140,73 | 24.76 | 22.11 | 12,333 | 12.33 | 6.14 | 75.85 |
| | 30 × 30 × 30 | 70:20:10 | 4216,28 | 24.60 | 22.31 | 21,667 | 21.67 | 6.20 | 134.16 |
| | 10 × 10 × 10 | 100:00:00 | 4257,62 | 24.71 | 22.40 | 59,167 | 59.17 | 6.22 | 368.03 |
| | 20 × 20 × 20 | 100:00:00 | 4158,12 | 24.44 | 22.04 | 33,167 | 33.17 | 6.12 | 202.96 |
| | 30 × 30 × 30 | 100:00:00 | 4114,29 | 24.84 | 22.41 | 62,000 | 62.00 | 6.23 | 386.01 |
| 2 × 2 m | 10 × 10 × 10 | 70:20:10 | 4108,00 | 24.49 | 22.25 | 5,667 | 5.67 | 6.18 | 35.07 |
| | 20 × 20 × 20 | 70:20:10 | 4114,00 | 23.95 | 21.51 | 13,500 | 13.50 | 5.98 | 80.67 |
| | 30 × 30 × 30 | 70:20:10 | 4210,00 | 24.00 | 21.67 | 30,583 | 30.58 | 6.02 | 184.03 |
| | 10 × 10 × 10 | 100:00:00 | 4073,00 | 24.61 | 22.22 | 23,000 | 23.00 | 6.17 | 141.95 |
| | 20 × 20 × 20 | 100:00:00 | 4182,00 | 24.11 | 21.66 | 43,417 | 43.42 | 6.02 | 261.27 |
| | 30 × 30 × 30 | 100:00:00 | 4193,00 | 23.91 | 21.61 | 35,333 | 35.33 | 6.00 | 212.02 |

Note: * Growing media composition: 70:20:10 (topsoil:solid decanter:biochar) and 100:0:0 (100% topsoil).

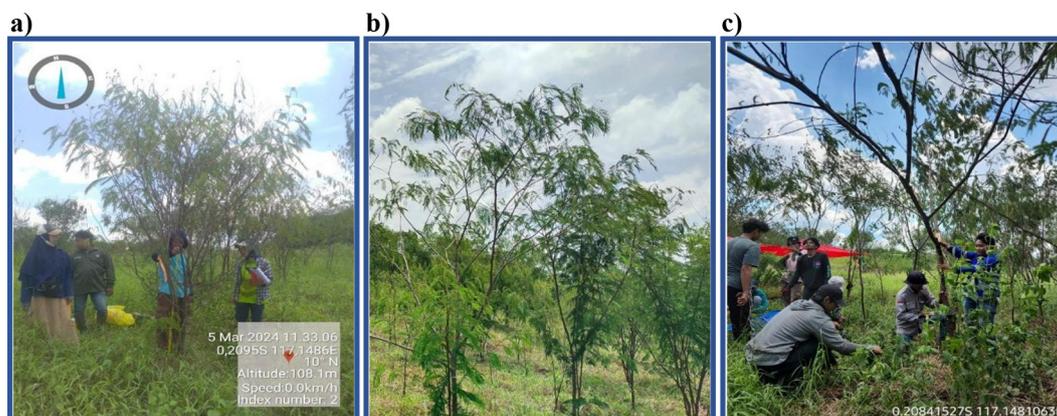


Figure 2. View of *C. calothyrsus* plants hole size : (a) 10 × 10 × 10 cm, (b) 20 × 20 × 20 cm, (c) 30 × 30 × 30 cm

indicate that on ameliorated post-mining soils, closer spacing (1 × 2 m) proves superior, likely due to initially lower resource availability requiring more intensive plant cover for maximum site utilization. The critical importance of planting hole size (30 × 30 × 30 cm) in determining productivity confirms that adequate rooting volume is essential for overcoming physical barriers in compacted post-mining substrates (Mauki and Kilonzo, 2022; Li, et al., 2024). Small holes (10 × 10 × 10 cm) severely restricted growth regardless of other factors, demonstrating that root system development represents the primary limiting factor in early establishment on degraded lands. This finding parallel results from mine reclamation studies showing that rooting space provision determines survival and growth rates more strongly than fertilization alone (Narendra, et al., 2021; Ahirwal and Maiti, 2021).

Growing media composition effects

The superior performance of 100% topsoil over 70:20:10 organic amendment mixture contrasts with expectations based on nursery studies where organic amendments typically enhance seedling growth (Indrajaya et al., 2022). This unexpected result may reflect several mechanisms. First, in field conditions, organic amendments (solid decanter and biochar) may have altered soil moisture retention or aeration in ways that limited rather than enhanced growth under local rainfall patterns (Kang et al., 2022; Wei et al., 2023). Second, solid decanter potentially introduced growth-inhibiting compounds or created temporary nutrient immobilization during decomposition (Junaidi et al., 2023). Third, the post-mining topsoil, despite degradation, may have possessed sufficient inherent fertility that

organic additions provided no marginal benefit but instead disrupted favorable physical properties (So et al., 2022).

However, the notable exception where 70:20:10 media combined with $30 \times 30 \times 30$ cm holes and 2×2 m spacing produced the largest individual trees (17.37 kg) suggests that organic amendments become beneficial when competition is reduced. This pattern indicates that amendment effects depend on resource availability context—benefits emerge when water and nutrient competition is minimized through wider spacing and larger rooting volumes (Song et al., 2023; Hendrati et al., 2020). These findings emphasize the importance of matching amelioration strategies to planting configurations rather than applying uniform treatments.

Biomass quality for energy applications

The consistent biomass quality parameters across treatments represent a crucial finding for industrial applications. Net calorific values (mean 22.01 MJ/kg) exceed published values for many conventional biomass feedstocks and fall within the range reported for *C. calothyrsus* species (18.8–21.5 MJ/kg) (Narendra et al., 2020; Putri et al., 2025). This energy density approaches that of sub-bituminous coal (~23 MJ/kg), making *C. calothyrsus* suitable for high-ratio cofiring applications (Putra et al., 2024).

The exceptionally low ash content (mean 1.05%) provides significant operational advantages over agricultural residues which typically contain 3–15% ash (Putra et al., 2024; Rahman et al., 2024). Low ash reduces boiler maintenance requirements, minimizes ash handling costs, and decreases slagging and fouling tendencies that plague many biomass fuels (Lachman et al., 2021). The high volatile matter content (mean 97.38%) ensures rapid ignition and complete combustion, characteristics essential for stable power plant operation (Yongsheng et al., 2021; Waziri et al., 2025).

Most importantly, the minimal sulfur content (mean 0.05%) represents a major environmental benefit. While coal typically contains 0.5–3% sulfur requiring expensive scrubbing systems (Roy et al., 2024), biomass *Calliandra calothyrsus* produces negligible SO_x emissions. This low sulfur characteristic aligns with Indonesian emission standards and international best practices for biomass cofiring (Vakkilainen, 2017).

Combined with the 10–30% NO_x reduction typically achieved through biomass cofiring (Roni, et al., 2017). *C. calothyrsus* feedstock offers substantial air quality improvements over pure coal combustion.

The uniformity of quality parameters across silvicultural treatments ensures that plantations can be managed for productivity optimization without compromising fuel specifications. This consistency contrasts with some agricultural biomass sources where growing conditions substantially affect ash and moisture content (Dhillon, et al., 2025; Ghaffariyan, 2023). creating quality control challenges for power plant operations.

Energy potential and economic implications

The maximum energy potential of 386.01 MWh/ha achieved in this study substantially exceeds values reported for many biomass energy crops. Converting this to annual energy output assuming 3-year rotation typical for *C. calothyrsus* SRC systems yields approximately 195 MWh/ha/year (Widyati et al., 2022). This productivity surpasses willow SRC systems in temperate regions (80–120 MWh/ha/year) and approaches the highest-yielding tropical grass systems (Albors et al., 2025).

For context, this energy yield could support cofiring at 10% biomass blend for a 100 MW coal plant requiring approximately 3000 ha of plantation area, assuming conservative conversion efficiency (Bhoi and Sarkar, 2025). The dramatic productivity differences between optimal and minimal treatments (585 vs 63 MWh/ha) emphasize that proper silvicultural management is essential for economic viability. Inadequate amelioration renders energy plantations economically unfeasible regardless of species selection (Anderson and Campbell, 2019).

The ability to achieve productive energy plantations on post-mining land provides dual benefits: fulfilling regulatory reclamation requirements while generating revenue-producing biomass crops (Anon 2025; Tudge et al., 2025). This integration of ecological restoration with economic productivity represents a paradigm shift from traditional reclamation approaches focused solely on vegetation cover establishment. Economic analyses of similar systems suggest that energy biomass production can offset reclamation costs within 5–7 years while providing long-term income streams (Tudge et al., 2025; Gairola et al., 2023).

Implications for post-mining land management

This research demonstrates that strategic silvicultural optimization transforms post-mining lands from ecological liabilities into productive assets. The success of *C. calothyrsus* cultivation on coal mining sites addresses Indonesia's dual challenges of biomass feedstock supply for energy transition and large-scale land degradation (Langer et al., 2021; Fikriah et al., 2024). The relatively simple amelioration protocol—appropriate hole size and topsoil preparation—makes this approach scalable across the thousands of hectares of post-mining land requiring reclamation.

The leguminous nature of *C. calothyrsus* provides additional ecosystem services beyond biomass production. Nitrogen fixation capability enhances soil fertility over time, potentially facilitating succession toward more complex forest communities (Tola et al., 2024). The rapid biomass accumulation (62 tons/ha in 18 months) indicates substantial carbon sequestration potential, contributing to climate change mitigation goals (Don et al., 2023). However, several considerations require attention for operational implementation. Water requirements during establishment, optimal harvest rotation length, coppice productivity in subsequent cycles, and long-term soil fertility dynamics all merit further investigation (Cao et al., 2020). Additionally, integration with biodiversity conservation objectives and socioeconomic impacts on local communities should be evaluated for sustainable landscape-level planning.

CONCLUSIONS

This study demonstrates that the interactive optimization of planting density, planting hole size, and growing media composition directly determines biomass productivity and quality of *Calliandra calothyrsus* on degraded post-mining land. The highest per-hectare biomass yield (62 t/ha) and energy potential (386.01 MWh/ha) were achieved with 1 × 2 m spacing, 30 × 30 × 30 cm planting holes, and 100% topsoil. Adequate rooting volume was essential, as small holes (10 × 10 × 10 cm) consistently limited biomass accumulation regardless of spacing or media. High planting density increased total per-hectare productivity, particularly when combined with large planting holes, confirming that density and rooting volume

jointly regulate biomass capture. Organic amendments (70:20:10 topsoil:solid decanter:biochar) increased individual tree biomass under reduced competition but did not increase total per-hectare yield relative to 100% topsoil, indicating context-dependent effects. Biomass quality parameters—net calorific value 22.01 MJ/kg, ash 1.05%, volatile matter 97.4%, sulfur 0.05%—remained within industrial cofiring specifications across all treatments. All conclusions are directly supported by experimental data, establishing that adequate planting hole volume and optimized spacing are the primary determinants of biomass productivity, while soil amendment effects depend on planting configuration and resource availability.

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REFERENCES

- Ahirwal, J., Maiti, S. K., (2021). Restoring coal mine degraded lands in India for achieving the United Nations-Sustainable Development Goals. *Restoration Ecology*, 30(5). <https://doi.org/10.1111/rec.13606>
- Albors, A. C. et al., (2025). A global short rotation coppice (SRC) willow dataset for the bioeconomy: implications for the yield in the United Kingdom. *Global Change Biology Bioenergy*, 17(9). <https://doi.org/10.1111/gcbb.70069>
- Amirta, R. et al., (2006). Methane fermentation of Japanese cedar wood pretreated with a white rot fungus, *Ceriporiopsis subvermispora*. *Journal of Biotechnology*, 123(1), 71–77. <https://doi.org/10.1016/j.jbiotec.2005.10.004>
- Anderson, N. M. L., Campbell, R. M., (2019). Comprehensive comparative economic evaluation of woody biomass energy from silvicultural fuel treatments. *Journal of Environmental Management*, 250. <https://doi.org/10.1016/j.jenvman.2019.109422>
- Anonymous., (2025). Integrating the sustainable development goals into post-mining land use selection. *Scientific report*, 15. <https://doi.org/10.1038/s41598-025-15980-z>
- ASTM., (2013). Standard test method for gross calorific value of coal and coke. *Annual book of ASTM standards*.
- ASTM, (2012). Standard test method for proximate analysis of coal and coke by macro thermogravimetric

- analysis. American Standard for Testing Materials: United States.
8. Bhoi, P. R., Sarkar, S., (2025). The co-firing of pine biomass and waste coal in 100 and 600 mw power plants: a sustainable approach to reduce GHG emissions. *Sustainability - MDPI*, 17(10). <https://doi.org/10.3390/su17104473>
 9. Cao, Y. et al., (2020). Different fertilization treatments in coal mining-affected soils change bacterial populations and enable soil reclamation. *Annals of Microbiology*, 70(47). <https://doi.org/10.1186/s13213-020-01589-2>
 10. Dhillon, M. S. et al., 2025. Landscape structure, climate variability, and soil quality shape crop biomass patterns in agricultural ecosystems of Bavaria. *Frontiers in Plant Science*, 16. <https://doi.org/10.3389/fpls.2025.1630087>
 11. Don, A. et al., (2023). Carbon sequestration in soils and climate change mitigation-Definitions and pitfalls. *Glob Chang Biol*, 30(1). <https://doi.org/10.1111/gcb.16983>
 12. Fikriah, I. et al., (2024). Acute toxicity, secondary metabolites, and antioxidant activity of *Macaranga tanarius* from post-coal mining and non-mining areas in East Kalimantan, Indonesia. *Narra J*, 4(2). <https://doi.org/10.52225/narra.v4i2.791>
 13. Francescato, V., Antonini, E., (2008). *Wood fuels handbook: production quality requirements, trading*. Italia: AIEL Agroforestry Italian Agroforestry Energy Association. <http://dx.doi.org/10.12899/asr-2171>
 14. Gairola, S. U., Bahuguna, R., Bhatt, S. S., (2023). Native plant species: a tool for restoration of mined lands. *Journal of Soil Science and Plant Nutrition*, 23, 1438–1448. <https://doi.org/10.1007/s42729-023-01181-y>
 15. Ghaffariyan, M. R., (2023). Identifying key quality characteristics of woody biomass for bioenergy application: an international review. *Silva Balcanica*, 24(3), 77–94. <https://doi.org/10.3897/silvalbanica.24.e114644>
 16. Hendrati, R. L., Hidayat, N., Nurrohmah, S., (2020). *Biomass and Coppicing Ability of Genetically Improved C. calothyrsus for Wood-Energy with Different Spacing*. Washington, IOP Conf. Series: Earth and Environmental Science. <https://doi.org/10.1088/1755-1315/522/1/012001>
 17. IESR, (2024). *Indonesia Energy Transition Outlook (IETO) 2024, Peaking Indonesia's Energy Sector Emission by 2030: The Beginning or the End of Energy Transition Promise*, Indonesia: Institute for Essential Services Reform (IESR).
 18. Indrajaya, Y. et al., (2022). Tropical forest landscape restoration in Indonesia: A review. *Land*, 11(3). <https://doi.org/10.3390/land11030328>
 19. Junaidi, M. et al., (2023). *Ameliorant application promotes growth performances of C. calothyrsus Meissn. planted on post-coal mining land*. Samarinda, East Kalimantan, Indonesia, IOP Conf. Series: Earth and Environmental Science. <https://doi.org/10.1088/1755-1315/1282/1/012051>
 20. Kang, M. W. et al., (2022). Enhancement of soil physical properties and soil water retention with biochar-based soil amendments. *Science of The Total Environment*, 836(155746). <https://doi.org/10.1016/j.scitotenv.2022.155746>
 21. Lachman, J. et al., (2021). An overview of slagging and fouling indicators and their applicability to biomass fuels. *Fuel Processing Technology*, 217. <https://doi.org/10.1016/j.fuproc.2021.106804>
 22. Langer, J., Quist, J., Blok, K., (2021). Review of renewable energy potentials in Indonesia and their contribution to a 100% renewable electricity system. *Journal MDPI, Energies*, 14(21). <https://doi.org/10.3390/en14217033>
 23. Lestari, T., Apriyadi, R., H., (2020). *Optimization of maize (ZeamaysL) cultivation in post mining land*. s.l., IOP Conference Series: Earth and Environmental Science. <https://doi.org/10.1088/1755-1315/599/1/012047>
 24. Li, C. et al., (2024). Positive effects of vegetation restoration on the soil properties of post-mining land. *Plant Soil*, 497, 93–103. <https://doi.org/10.1007/s11104-022-05864-w>
 25. Mahdi, A. H. et al., (2021). Integrated effects of potassium humate and planting density on growth, physiological traits and yield of *Vicia faba* L. grown in newly reclaimed soil. *Agronomy*, 11(3). <https://doi.org/10.3390/agronomy11030461>
 26. Mauki, D., Kilonzo, M., (2022). Planting pit size determines successful tree seedling establishment in arid and semi-arid region of Tanzania. *Environmental and Sustainability Indicators*, 15(100197). <https://doi.org/10.1016/j.indic.2022.100197>
 27. Narendra, B. H., Siregar, C. A., Salim, A. G., (2020). *The potency of wood based electricity production from critical land in Indonesia*. Bogor Indonesia, IOP Conference Series: Materials Science and Engineering. <https://doi.org/10.1088/1757-899X/935/1/012044>
 28. Ng, C. W. W., Ni, J. J., Leung, A. K., (2020). Effects of plant growth and spacing on soil hydrological changes: a field study. *Geotechnique*, 70(10), 867–881. <https://doi.org/10.1680/jgeot.18.P.207>
 29. Parikh, J., Channiwal, S. A., Ghosal, G. K., (2005). A correlation for calculating HHV from proximate analysis of solid fuels. *Fuel*, 84(5), 487–494. <https://doi.org/10.1016/j.fuel.2004.10.010>
 30. Parikh, J., Channiwal, S. A., Ghosal, G. K., (2007). A correlation for calculating elemental composition from proximate analysis of biomass materials. *Fuel*, 86(12–13), 1710–1719. <https://doi.org/10.1016/j.fuel.2006.12.029>

31. Pratiwi, D. I., Nurcholis, M., (2023). Reclamation plan for production operation phase of quartz sand mine in Riau Islands. *Journal of Earth Marine Technology*, 4(1), 68–77. <https://doi.org/10.31284/j.jemt.2023.v4i1.4828>
32. Pratiwi, et al., (2021). Managing and reforesting degraded post-mining landscape in Indonesia: A review. *Land. MDPI*, 10(6). <https://doi.org/10.3390/land10060658>
33. Pretzsch, H., Schütze, G., (2021). Tree species mixing can increase stand productivity, density and growth efficiency and attenuate the trade-off between density and growth throughout the whole rotation. *Annals of Botany*, 128(6), 767–786. <https://doi.org/10.1093/aob/mcab077>
34. Putra, H. P. et al., (2024). Investigation on combustion characteristics and ash-related issues of *C. calothyrsus* and *Gliricidia sepium* using thermogravimetric analysis and drop tube furnace. *Biore-source Technology*, 394. <https://doi.org/10.1016/j.biortech.2023.130212>
35. Putri, B. K., Salsabila, C., F., Desfitri, E. R., (2025). A review of the potential of Calliandra as a biomass power plant. *REM Renewable Energy Mechanics*, 8(1). <https://doi.org/10.25299/rem.2025.14910>
36. Rahman, W. A. et al., (2024). Optimizing calliandra (*C. calothyrsus*) biomass pellets: Impact of particle size and bark composition. *Global Forest Journal*, 2(2), 133–146.
37. Rashmi, I. et al., (2024). Impact of post-mining restoration techniques on soil health. *Ecological Impacts of Stone Mining*, 267–284. https://doi.org/10.1007/978-981-97-4746-7_14
38. Roni, M. S. et al., (2017). Biomass co-firing technology with policies, challenges, and opportunities: A global review. *Renewable and Sustainable Energy Reviews, ScienceDirect, Elsevier*, 7(8), 1089–1101. <https://doi.org/10.1016/j.rser.2017.05.023>
39. Rouhani, A., Gusiatin, M. Z., Hejzman, M., (2023). An overview of the impacts of coal mining and processing on soil: assessment, monitoring, and challenges in the Czech Republic. *Republic. Environ Geochem Health*, 45(11), 7459–7490. <https://doi.org/10.1007/s10653-023-01700-x>
40. Roy, R. et al., (2024). Synergistic reduction of SO₂ emissions while co-firing biomass with coal in pilot-scale (1.5 MWth) and full-scale (471 MWe) combustors. *Fuel*, 358. <https://doi.org/10.1016/j.fuel.2023.130191>
41. So, H. B., Silva, I. R. d., Gomes, L. C., Olivveira, T. S. d., (2022). Subsoil and surface soil constraints of mined land and tailings. *Subsoil Constraints for Crop Production*, 161–177. https://doi.org/10.1007/978-3-031-00317-2_7
42. Song, M., Li, J., Gao, L., Tian, Y., (2023). Comprehensive evaluation of effects of various carbon-rich amendments on overall soil quality and crop productivity in degraded soils. *Geoderma*, 436. <https://doi.org/10.1016/j.geoderma.2023.116529>
43. TAPPI., (1997). *Preparation of wood for chemical analysis, Test Method T 264 cm-22*, s.l.: TAPPI.
44. TAPPI., (1998). *Acid-insoluble lignin in wood and pulp. Technical Association of the Pulp and Paper Industry, T222 om-98*, s.l.: s.n.
45. Tola, F. K. et al., (2024). Role of *C. calothyrsus* alley cropping for soil fertility and maize production at Bako, Western Oromia. *East African Journal of Forestry and Agroforestry*, 7(1).
46. Tudge, S. J., Murphy, R., Harris, Z. M., Palma, A. D., (2025). Upscaling ecological restoration by integrating with agriculture. *Frontiers in Ecology and the Environment*, 23(1). <https://doi.org/10.1002/fee.2802>
47. Tudge, S. J., Murphy, R., Harris, Z. M., Palma, A. D., (2025). Balancing bioenergy expansion and restoration: Global shifts in biodiversity intactness. *Journal of Applied Ecology*, 62(7), 1587–1596. <https://doi.org/10.1111/1365-2664.14695>
48. Vakkilainen, E. K., (2017). Sulfur Emission. In: *Solid Biofuels and Combustion*. s.l.: Earth and Planetary Sciences, 18–56.
49. Waziri, S. A., Dhada, I., Das, R., (2025). A comprehensive database for characterizing potential of common biomass feedstocks. *Biomass Conversion and Biorefinery*, 15, 16737–16763. <https://doi.org/10.1007/s13399-024-06459-4>
50. Wei, B. et al., (2023). Drivers of biochar-mediated improvement of soil water retention capacity based on soil texture: A meta-analysis. *Geoderma*, 437. <https://doi.org/10.1016/j.geoderma.2023.116591>
51. Widyati, E. et al., (2022). Optimum plant density and harvest age for maximizing productivity and minimizing competition in a *Calliandra* short-rotation-coppice plantation in West Java, Indonesia. *Forest Science and Technology*, 18(1), 26–35. <https://doi.org/10.1080/21580103.2022.2039305>
52. Yongsheng, J. et al., (2021). Visualization of Combustion Phases of Biomass Particles: Effects of Fuel Properties. *ACS OMEGA*, Volume 6, 27702–27710. <https://doi.org/10.1021/acsomega.1c02783>
53. Yuan, C. et al., (2023). Vegetation restoration effects on soil carbon and nutrient concentrations and enzymatic activities in post-mining lands are mediated by mine type, climate, and former soil properties. *Science of The Total Environment*, 879(163059). <https://doi.org/10.1016/j.scitotenv.2023.163059>
54. Zine, H. et al., (2024). Revegetation and ecosystem reclamation of post-mined land: toward sustainable mining. *International Journal of Environmental Science and Technology*, 21, 9775–9798. <https://doi.org/10.1007/s13762-024-05697-3>