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Application of *pre-Terra Preta* to enhance soil fertility and productivity of marginal land cultivated with *Pennisetum purpureum* cv. Mott

Dewi Priany Nasution[1,2]*, Udiansyah[3], Fakhrur Razie[4], Nursyam Andi Syarifuddin[5], Dora Neina[6]

[1] Doctoral Program of Agricultural Science, Lambung Mangkurat University, Banjarmasin, 70714, Indonesia
[2] Department of Agricultural Technology, Sheikh Salman Al-Farisi Islamic Polytechnic, Rantau, Tapin, Kalimantan Selatan 71181, Indonesia
[3] Department of Development Studies, Graduate Program, Lambung Mangkurat University, Banjarmasin, 70123, Indonesia
[4] Department of Soil Science, Faculty of Agriculture, Lambung Mangkurat University, Banjarbaru, 70714, Indonesia
[5] Department of Animal Science, Faculty of Agriculture, Lambung Mangkurat University, Banjarbaru, 70714, Indonesia
[6] Department of Soil Science, School of Agriculture, College of Basic and Applied Sciences, University of Ghana, P.O. Box LG 245, Accra, Legon, Ghana

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Corresponding Author
Email address:
* *dewi.priany22@gmail.com*

ABSTRACT

Indonesia's national agriculture production is increasingly constrained by the expansion of marginal lands with low productivity, many of which have undergone severe degradation from mining and other land uses. These lands are characterized by low soil fertility and acidic pH, posing a challenge for sustainable forage production. This study investigates the application of *pre-Terra Preta* - a soil amendment composed of biochar, organic matter, animal manure, topsoil, and fermented microorganisms—to enhance the productivity of marginal land, using *Pennisetum purpureum* cv. Mott (Dwarf elephant grass) as a forage crop. The field experiment was conducted in Swarangan Village, Tanah Laut Regency, South Kalimantan, Indonesia. Soil chemical properties were analyzed before and after planting. A total of 36 plots (5 × 5 m) were treated with four levels of *pre-Terra Preta* biochar composition (0%, 20%, 40%, and 60%) and three application rates (10, 20, and 30 t ha^{-1}). The results showed significant improvements in soil chemical properties, including total N (↑ 73.47%), organic C (↑ 35.20%), K_2O (↑ 33.64%), and pH (↑ 148.89%). The optimal treatment—30 t ha^{-1} with 60% biochar—yielded the highest plant height (16.875 cm), number of leaves (12.900), and number of tillers (3.791). These differences were significant ($p < 0.05$), confirming the effectiveness of both biochar levels and application rates. *Pre-Terra Preta* offers a sustainable, cost-effective strategy for rehabilitating marginal lands in tropical regions. Further studies are recommended to assess long-term soil health, economic viability, forage quality, and livestock performance.

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1. INTRODUCTION

Indonesian's national agricultural production faces significant challenges due to the limited availability of fertile land and the widespread presence of underperforming marginal areas (Suwardi, 2025). This condition is exacerbated by the conversion of productive land into industrial and mining areas, which reduces space for sustainable agriculture and increases inequality in access to fertile land. Marginal lands are generally characterized by low fertility, poor soil structure, limited water retention capacity, and low nutrient content, rendering them incapable of supporting optimal plant growth (Burland & von Cossel, 2023; Csikós & Tóth, 2023; Ollila & Kotavaara, 2023). These conditions not only reduce agricultural productivity but also pose threaten national food security and livelihoods of farmers, especially in tropical regions.

In Swarangan Village, Jorong Subdistrict, Tanah Laut Regency, South Kalimantan Province, marginal land is distributed across tidal ecosystems, peatlands, and severely degraded post-mining area. Long-term exploitation has led to the depletion of organic matter and essential nutrients (Kurniawan et al., 2022). Previous assessments using the Universal Soil Loss Equation (USLE) have shown that open-pit mining area in Tanah Laut experiences erosion rates of 173.1 t ha^{-1} year^{-1}, far exceeding those of natural and cultivated

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lands. Moreover, the high annual rainfall (>2,500 mm year^{-1}) and elevated daily temperatures accelerate soil weathering and nutrient leaching, further exacerbating soil fertility degradation (Sazali et al., 2025). According to KLHK (2024), 726.13 hectares of degraded land have been identified in South Kalimantan. As a result, rehabilitation and productivity optimization efforts have become strategic priorities in promoting sustainable agricultural development.

In response to the challenges of marginal land degradation, various soil amendment strategies have been developed to restore soil health and enhance agricultural productivity. Among these, biochar-based technologies have gained prominence due to their ability to improve soil structure, increase water retention, and enhance nutrient availability. Inspired by the highly fertile *Terra Preta de Índio* soils of the Amazon, the concept of *pre-Terra Preta* has emerged as a promising innovation. This formulation combines biochar, organic biomass, and local soil to replicate the physical, chemical, and biological benefits of *Terra Preta* in tropical agroecosystems (Kern et al., 2019; Neina & Agyarko-Mintah, 2023; Orozco-Ortiz et al., 2021). Studies have shown that biochar application significantly increases cation exchange capacity, stimulates microbial activity, and contributes to long-term carbon sequestration, especially when co-applied with compost or fermented biomass (Holatko et al., 2022; Iacomino et al., 2024; Mawalla & Gülser, 2023; Melo & Sánchez-Monedero, 2024). These characteristics make *pre-Terra Preta* a compelling option for sustainable land rehabilitation, particularly in tropical regions where soil degradation and climate stressors intersect.

Despite the growing body of research on biochar and compost synergy, studies specifically addressing *Terra Preta*-inspired amendments remain scarce, particularly in South Kalimantan. While numerous studies have demonstrated the benefits of biochar-based formulations in enhancing soil fertility, microbial activity, and crop productivity, their contextual application in Kalimantan's unique agroecological conditions has not been extensively explored. This region, characterized by diverse marginal land types and pressing agricultural challenges, presents a valuable opportunity to develop locally adapted formulations that honor the principles of *Terra Preta* while responding to contemporary ecological needs. Addressing this knowledge gap is essential to ensure that soil amendment strategies are not only scientifically sound but also socially and environmentally relevant within the local context. With consideration to Kalimantan's complex agroecological challenges, the *pre-Terra Preta* approach not only offers a technical solution but also opens space for locally rooted innovation. This formulation has the potential to become an adaptive, sustainable rehabilitation model for tropical marginal lands.

Building on previous findings, this study investigates the effects of *pre-Terra Preta* formulations—comprising biochar, organic biomass, and local soil—on the vegetative growth of *Pennisetum purpureum* cv. Mott in the marginal lands of South Kalimantan. This forage crop is favored for its adaptability to suboptimal soils, rapid biomass accumulation, and high nutritional value, making it a strategic choice for smallholder livestock systems (Anda et al., 2022; Yang et al., 2020).

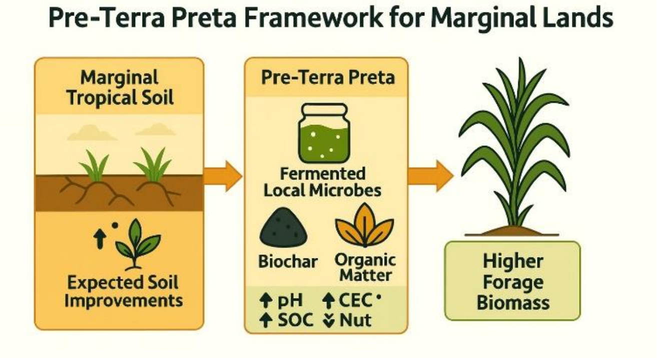

Figure 1. *Pre-Terra Preta* as a soil improver for marginal lands

However, its productivity in South Kalimantan remains limited due to poor soil conditions and low input availability (Kurniawan et al., 2022). By evaluating variations in composition and application rates of *pre-Terra Preta*, this study offers new insights into sustainable forage production and agroecological land management. The novelty lies in its contextual application within South Kalimantan, where such integrated amendments have not been extensively tested. The results are expected to provide a scientific basis for productive and sustainable marginal land rehabilitation, while promoting the adoption of environmentally friendly technologies at the farmer level. Specifically, it evaluates the effect of variations in composition and application rates of *pre-Terra Preta* on the vegetative growth of *Pennisetum purpureum* cv. Mott in marginal lands in South Kalimantan (Fig. 1).

2. MATERIAL AND METHODS

2.1. Site description and sampling

This research was conducted for ten months, from June 2024 to March 2025, located at the Ranch of the Jorong Livestock Community Academy, Tanah Laut Regency, South Kalimantan, Indonesia (114°58'1.352" E – 4°0'30.009" S) (Fig. 2). Further analyses were conducted at the Soil Laboratory of the Faculty of Agriculture, Lambung Mangkurat University. The site is situated within a tropical humid climate zone, with annual rainfall ranging from 2,182 to 2,454 mm year^{-1}. The soil at the research site is classified as a Dystric Histosol according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2022). The area is ecologically degraded, with *Imperata cylindrica* dominating the landscape, indicating low fertility and poor nutrient cycling (Fig. 3).

Composite soil samples were collected from two depth layers (0–20 cm and 20–40 cm) across each experimental plot. Following Descriptive analyses of soil chemical and physical properties were conducted to establish baseline conditions prior to treatment application, the Draft Indonesian National Standard (RSNI3 8473:2024) issued by the National Standardization Agency of Indonesia (INS) (BSN, 2024). Five subsamples were taken per plot—four from the corners and one from the center—using a soil auger. These subsamples were homogenized to form a composite sample per depth, ensuring spatial representativeness and minimizing microsite variability.

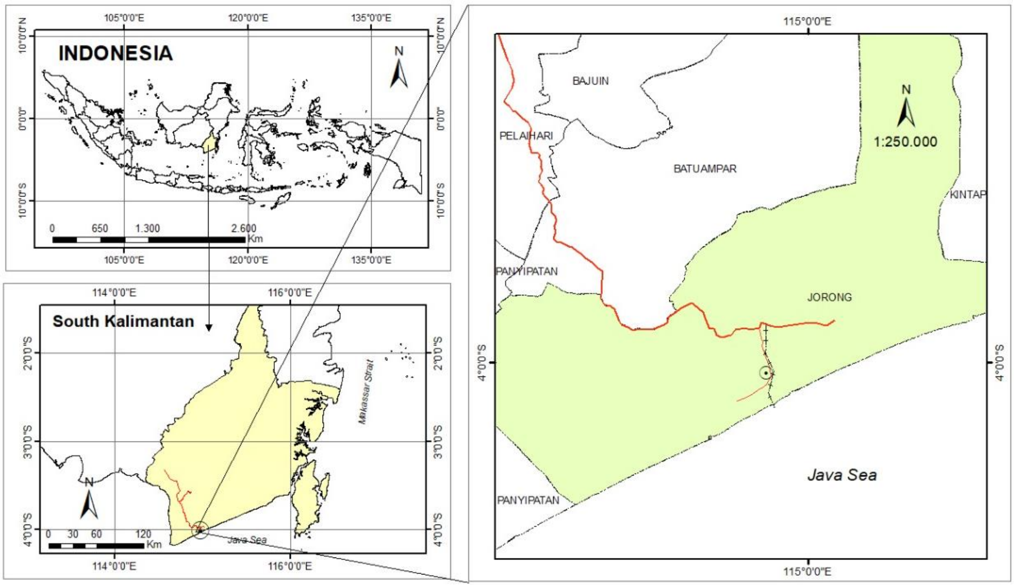

Figure 2. Map of the research location

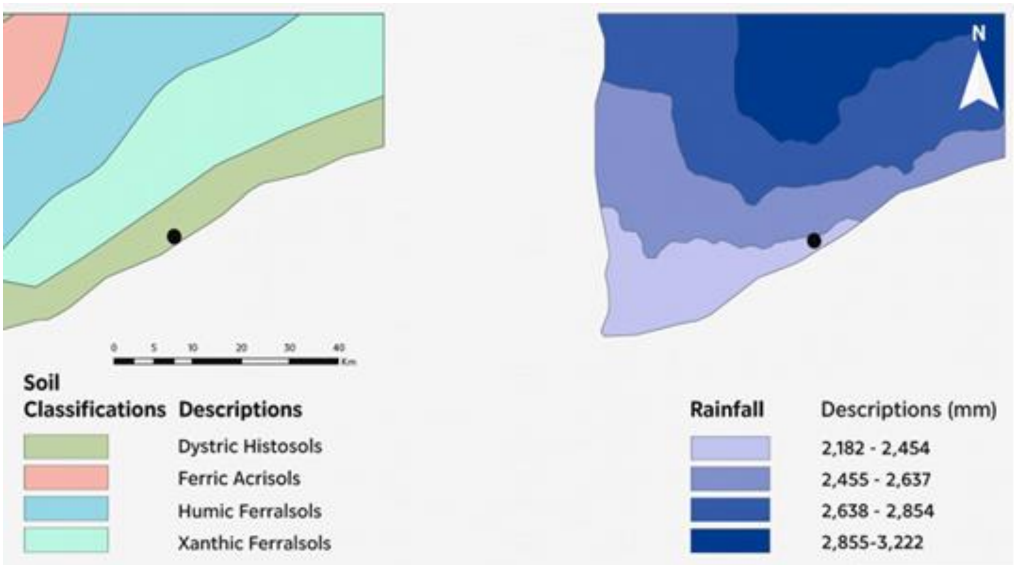

Figure 3. a) Soil map (source: *Harmonized Word Soil Database Veiwer* ver. 1.21); b) Rainfall map (source: https://www.chc.ucsb.edu/data/chirps)

2.2. Preparation and composition of *pre-Terra Preta*

Pre-Terra Preta was prepared using variations in the composition of different organic materials, including sawdust (biomass), animal manure, topsoil (as filler), and biochar. Four formulations were anaerobically fermented for 15 days with EM4®, a microbial consortium known to accelerate organic matter decomposition and enhance nutrient availability – applied uniformly across all treatments during substrate preparation to activate microbial processes. The treatments were as follows: (a) non–*pre-Terra Preta* (0% biochar), (b) *pre-Terra Preta* (20% biochar), (c) *pre-Terra Preta* (40% biochar), and (d) *pre-Terra Preta* (60% biochar). Samples of each composition formulation were sent to the laboratory in fresh (wet) condition for analysis. All subsequent preparation steps–including drying, homogenization, and sieving–were conducted by laboratory technicians following established protocols. Descriptive analyses were conducted and compared with laboratory test results from before and after planting.

2.3. Laboratory analyses

Soil analyses were conducted at two stages: prior to planting (baseline condition) and after harvesting (post-treatment condition). All samples were submitted to the Soil Laboratory of the Faculty of Agriculture, Lambung Mangkurat University, Indonesia, in fresh (wet) condition. The research team submitted a formal request specifying the analytical parameters relevant to the study, including total nitrogen (N-total), organic carbon (C-organic), available phosphorus (P_2O), exchangeable potassium (K_2O), soil pH, electrical conductivity (EC), and cation exchange capacity (CEC). All laboratory procedures—including sample preparation, instrumentation, and testing—were performed independently by certified technicians following institutional standards. The research team did not conduct the analyses directly but ensured that the requested parameters aligned with the study's objectives. Documentation of the analytical request and associated receipts is provided in the supplementary materials to ensure transparency and reproducibility.

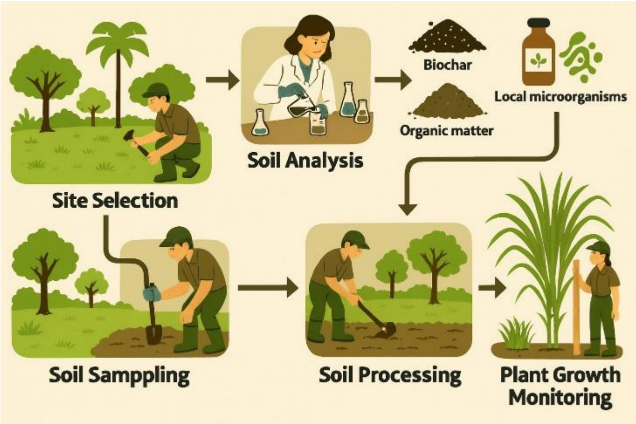

Figure 4. Stages of research activities

2.4. Field experiment

Analyses of soil's chemical and physical properties were carried out descriptively on soil samples from two depth layers (0-20 cm and 20-40 cm) within the research plot. The laboratory testing parameters and methods included: total N (Kjeldahl method), organic C (Walkley & Black method), phosphorus (P_2O_5) and potassium (K_2O) using wet-soaking extraction using 25% HCl, soil pH measured in a 1:5 soil-to-water (H_2O) solution, and cation exchange capacity (CEC) using 0.1 N KCl solution.

Pre-Terra Preta was prepared using variations in organic matter composition, including sawdust (biomass), animal manure, topsoil (as filler), and biochar. Four formulations were anaerobically fermented with EM4 for 15 days: non–*pre-Terra Preta* (0% biochar), *pre-Terra Preta* (20% biochar), *pre-Terra Preta* (40% biochar), and *pre-Terra Preta* (60% biochar). Samples from each composition were then tested for physical and chemical properties in the laboratory. Descriptive analyses were conducted and compared with laboratory test results from before and after planting.

The field experiment was conducted for ten months, from June 2024 to March 2025, on 5 × 5 m plots. *Pennisetum purpureum* cv. Mott was planted according to the treatments using a completely randomized design in a nested pattern with two treatment factors. using a completely randomized design in CRD) in a nested pattern. The main factor was the composition of composition *pre-Terra Preta* formulation (main factor) with four levels: k1 = non–*pre-Terra Preta* (0% biochar), k2 = *pre-Terra Preta* (20% biochar), k3 = *pre-Terra Preta* (40% biochar), and k4 = *pre-Terra Preta* (60% biochar). The second factor was application rate with three levels: a1 = 10 t ha^{-1}, a2 = 20 t ha^{-1}, and a3 = 30 t ha^{-1}. The composition factor was nested within the application rate, each replicated three times. A total of 576 cuttings of dwarf elephant grass (*Pennisetum purpureum* cv. Mott) were obtained from the Pelaihari Livestock Research Centre and planted according to the treatment combinations. Growth parameters observed included plant height, number of tillers, and number of leaves, which were recorded weekly for 10 weeks (10 WAP). The research activity flow is shown in (Fig. 4).

2.5. Statistical analyses

All statistical analyses were conducted using RStudio version 4.3.1. A nested analysis of variance (ANOVA) was performed based on a completely randomized design (CRD), where application rate (10, 20, and 30 t ha^{-1}) was nested within biochar composition (0%, 20%, 40%, and 60%). This structure reflects the experimental focus on evaluating the effects of *pre-Terra Preta* composition, with application rates tested within each composition level. Each treatment combination was replicated three times. Post-hoc comparisons were carried out using Duncan's Multiple Range Test (DMRT) at a 5% significance level to identify significant differences among treatment means.

Linear regression analyses were used to examine the predictive relationships between soil chemical properties (organic carbon, total phosphorus, cation exchange capacity, and pH) and vegetative growth parameters (plant height, leaf number, and tiller count). Pearson correlation coefficients were calculated to assess the strength and direction of associations among soil and plant variables.

Polynomial regression (quadratic) was used to model the relationship between biochar composition and plant growth parameters (leaf number, tiller count, and plant height). The coefficient of determination (R^2) and corresponding p-values were calculated using RStudio to assess model fit and statistical significance.

3. RESULTS

3.1. Pre-experimental measurement of chemical and physical properties of the research site soils

3.1.1. Baseline soil properties

The laboratory test results of the composite preliminary properties of composite soil samples collected before planting in the research demonstration plots are presented in Table 1. These data indicate that the soils at the study site exhibit characteristics typical of marginal soils—namely, low fertility due to limited organic matter content, acidic pH, and medium to low cation exchange capacity (CEC) values. These criteria align with the FAO definition of marginal soils, which are characterized by biogeophysical limitations such as poor soil quality and high acidity. Analysis of soil physical properties revealed variations between the two soil depth layers: 0–20 cm and 20–40 cm. The sand content in both layers was relatively consistent, ranging from 35.56% to 36.11%, while silt content ranged from 30.38% to 30.11%. Clay content was slightly higher in the upper layer (34.06%) compared to the lower layer (33.43%). Soil permeability slightly decreased with depth, from 1.74 cm h^{-1} in the 0–20 cm layer to 1.69 cm h^{-1} in the 20–40 cm layer.

3.1.2. *Pre-Terra Preta* nutrient content

The results of the chemical analysis (Table 2) showed that the *pre-Terra Preta* used in this study had a diverse nutrient profile. Organic carbon (OC) content ranged from 57.70 to 114.90 g kg^{-1}; total nitrogen (TN) ranged from 3.30 to 4.70 g kg^{-1}; and potassium (K_2O) showed wide variability, ranging from 0.70 to 6.30 g kg^{-1}. Total phosphorus (TP) ranged from 2.63 to 7.01 g kg^{-1}. The pH of *pre-Terra Preta* tended to be neutral to slightly acidic, with values between 5.89 and 7.89, while moisture content ranged from 26.33% to 45.31%. The overall average of the *pre-Terra Preta* compositions and application rates demonstrated strong potential for improving soil chemical properties—especially in marginal soils—as indicated by the high OC content and relatively neutral pH compared to initial soil conditions.

Table 1. Result of chemical analysis of soil samples of research plots

Soil depth	Chemical properties				
	$C_{organic}$ (g kg^{-1})	N_{total} (g kg^{-1})	P_{total} (g kg^{-1})	CEC (cmolc kg^{-1})	pH (H_2O)
0 – 20	8.20	0.80	0.64	15.37	4.60
20 – 40	4.40	0.70	0.44	14.22	4.42
	Physical properties				
	Sand (%)	Silt (%)	Clay (%)	Texture	Permeability (cm h^{-1})
0 – 20	35.56	30.38	34.06	Clay loam	1.74
20 – 40	36.11	30.11	33.43	Clay loam	1.69

Table 2. *Pre-Terra Preta* content analysis results

Treatments	$C_{organic}$ (g kg^{-1})	N_{total} (g kg^{-1})	P_{total} (g kg^{-1})	K_2O (g kg^{-1})	Water content (%)	pH (H_2O)
a_1k_1	94.80	3.70	2.63	0.70	36.68	5.89
a_1k_2	102.90	3.70	4.09	1.30	34.65	6.70
a_1k_3	57.70	4.00	4.09	1.30	35.05	6.94
a_1k_4	96.20	2.70	3.21	1.30	36.81	7.58
a_2k_1	114.90	3.50	3.50	6.30	45.31	6.65
a_2k_2	97.20	4.70	5.26	1.30	38.94	7.40
a_2k_3	97.40	4.70	7.01	1.30	38.59	7.89
a_2k_4	90.20	3.90	5.84	1.30	34.13	7.63
a_3k_1	145.70	3.30	3.50	1.30	36.17	6.98
a_3k_2	111.30	4.20	4.38	2.40	26.33	7.24
a_3k_3	99.00	4.70	2.92	2.70	40.91	7.79
a_3k_4	87.20	3.90	3.50	2.10	43.10	7.70
Average	99.54	3.92	4.16	1.48	37.22	7.20

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3.1.3. Residual soil properties after treatment

These data provide an important baseline for understanding crop responses to the *pre-Terra Preta* treatments. The results of the residual (post-treatment) soil analysis are presented in Table 3. The analysis of soil chemical properties after treatment and planting showed a significant increase in several key soil fertility parameters, particularly organic carbon (OC), total phosphorus (TP), and cation exchange capacity (CEC). The OC content increased substantially, with the highest value recorded at 76.80 g kg^{-1} under the 40% biochar composition applied at 30 t ha^{-1}, compared to the overall average of 35.80 g kg^{-1}. This increase reflects the positive contribution of organic matter from the *pre-Terra Preta* treatment. The TP and CEC values also showed increasing trends. The TP had an average value of 9.16 g kg^{-1}, with the highest value of 17.65 g kg^{-1} observed in treatment a_3k_3 (30 t ha^{-1}, 40% biochar). The CEC averaged 37.97 me 100g^{-1}, with a maximum of 64.34 me 100g^{-1} recorded in treatment a_1k_4 (10 t ha^{-1}, 60% biochar). These increases suggest that the treatments not only improved the macronutrient status of the soil but also enhanced its nutrient retention and exchange capacity. The total nitrogen (TN) content remained relatively stable, averaging 2.04 g kg^{-1}, indicating that the treatments had less impact on total nitrogen compared to their effects on organic carbon and total phosphorus. The soil pH also increased after planting, ranging from 5.60 to 6.29, indicating a shift toward a more neutral soil condition and overall improvement in soil chemical properties.

3.2. Toxicity test

Available iron (Fe) concentration in the soil increased substantially after planting *Pennisetum purpureum* cv. Mott with the application of *pre-Terra Preta*. The available Fe content rose from 29.49 ppm before planting to 47.88 ppm after planting. In parallel, the exchangeable aluminums (Exch. Al) concentration, which was initially undetectable (0.00 me 100 g^{-1}), increased to 2.01 me 100g^{-1} after planting. The results of laboratory tests on soil samples before and after planting are presented in Table 4.

3.3. Growth of *Pennisetum purpureum* cv. Mott

Analysis of variance (ANOVA), as shown in Table 5, indicates that the composition treatment nested within the *pre-Terra Preta* application had a highly significant effect on all plant growth parameters: number of leaves ($F = 24.866$; $p < 0.001$), number of tillers ($F = 49.107$; $p < 0.001$), and plant height ($F = 48.656$; $p < 0.001$). The nested ANOVA models demonstrated strong explanatory power, with a coefficient of determination for each growth metric (R2 = 0.9274 for leaf number, R2 = 0.9615 for tiller number, and R2 = 0.9661 for plant height), indicating treatment structure effectively captured the variability in plant growth responses.

The variation in *pre-Terra Preta* composition within each application also contributed significantly to these parameters, with a high coefficient of determination ($R^2 > 0.894$), indicating that the model effectively explained most of the variability in the data. Significant differences between treatments are illustrated by the lettering in Table 5, based on the results of the Duncan test at the 95% confidence level ($p < 0.05$). The treatment with 60% biochar content applied at 30 t ha^{-1} consistently produced the best results across all observed parameters.

Table 3. Result of soil samples analysis after planting

Treatments	$C_{organic}$ (g kg^{-1})	N_{total} (g kg^{-1})	P_{total} (g kg^{-1})	K_2O (g kg^{-1})	CEC (cmolc kg^{-1})	pH (H_2O)
a_1k_1	17.20	3.20	1.65	0.78	34.66	5.60
a_1k_2	15.80	1.80	1.72	0.77	19.40	5.84
a_1k_3	15.10	2.20	0.64	0.77	25.71	6.11
a_1k_4	73.90	2.80	14.37	0.88	64.34	5.95
a_2k_1	25.10	1.60	2.31	0.78	50.66	6.15
a_2k_2	48.70	1.50	7.67	0.77	26.94	6.29
a_2k_3	24.50	1.70	8.96	2.33	33.79	6.26
a_2k_4	62.80	1.80	16.58	1.58	36.62	5.99
a_3k_1	31.60	1.80	12.57	1.73	55.52	6.17
a_3k_2	31.20	2.30	10.23	2.34	45.75	5.96
a_3k_3	76.80	2.10	17.65	2.61	39.95	6.22
a_3k_4	6.90	1.70	15.64	1.61	22.28	6.16
Average	35.80	2.04	9.16	1.41	37.97	6.06

Table 4. Iron (Fe) and aluminium (Al) concentration analysis results

No	Treatments	soluble – Fe (ppm)	Al-exch (cmolc kg^{-1})
1	Before planting	29.49	0.00
2	After planting	47.88	2.01

Figure 5 presents the growth response of *Pennisetum purpureum* cv. Mott in terms of leaf number, plant height, and tiller number under varying levels of biochar composition (0%, 20%, 40%, and 60%) and application rates (10, 20, and 30 t ha^{-1}) of *pre-Terra Preta*. Across all growth parameters, a consistent upward trend was observed with increasing biochar composition, particularly at higher application rates. The highest values for each parameter were recorded at 60% biochar and 30 t ha^{-1}, indicating a synergistic effect between biochar content and application rates. The error bars represent the standard error (SE), showing relatively low variability among replicates and reflecting the consistency of plant responses under the tested treatments.

Figure 6 provides a conceptual synthesis of the soil enhancement strategy using *pre-Terra Preta*. It visually summarizes the transition from marginal land conditions to improved soil health and plant growth, reinforcing the agronomic relevance of the treatments tested.

4. DISCUSSION

This study demonstrated that the application of the *pre-Terra Preta* – a soil amendment composed of biochar, local biomass, and topsoil – significantly enhanced the vegetative growth of *Pennisetum purpureum* cv. Mott on marginal land in South Kalimantan. The highest leaf number, tiller count, and plant height were observed under *pre-Terra Preta* (60% biochar) at 30 t ha^{-1}. These improvements were closely associated with increased soil organic carbon, available phosphorus, cation exchange capacity (CEC), and a shift toward neutral pH.

Table 5. Average growth (number of leaves, number of tillers, and plant height, mean± SE) *P. purpureum* cv. Mott based on *pre-Terra Preta* application and composition

Treatment	Number of leaves		Number of tillers		Plant height	
Non-*pre-Terra Preta*						
- Application 10 t ha^{-1}	6.043 ± 0.537	i	1.989 ± 0.071	g	41.439 ± 0.484	f
- Application 20 t ha^{-1}	6.760 ± 0,181	hi	2.122 ± 0.074	g	45.767 ± 0.697	e
- Application 30 t ha^{-1}	7.937 ± 0.140	fg	2.484 ± 0.027	f	51.302 ± 0.902	d
Pre-Terra Preta (biochar 20%)						
- Application 10 t ha^{-1}	7.753 ± 0.397	gh	2.427 ± 0.091	f	43.574 ± 1.991	ef
- Application 20 t ha^{-1}	8.963 ± 0.518	def	2.883 ± 0.064	de	49.976 ± 0.875	d
- Application 30 t ha^{-1}	9.797 ± 0.489	cde	3.132 ± 0.089	c	55.310 ± 0.524	c
Pre-Terra Preta (biochar 40%)						
- Application 10 t ha^{-1}	8.800 ± 0.188	efg	2.863 ± 0.018	e	51.438 ± 0.378	d
- Application 20 t ha^{-1}	10.033 ± 0.102	cd	3.108 ± 0.092	cd	55.343 ± 0.171	c
- Application 30 t ha^{-1}	11.240 ± 0.419	b	3.401 ± 0.122	b	58.714 ± 0.465	b
Pre-Terra Preta (biochar 60%)						
- Application 10 t ha^{-1}	9.817 ± 0.249	cde	2.997 ± 0.011	cde	54.525 ± 0.756	c
- Application 20 t ha^{-1}	10.810 ± 0.364	bc	3.401 ± 0.101	b	59.821 ± 0.331	ab
- Application 30 t ha^{-1}	12.900 ± 0.459	a	3.791 ± 0.050	a	61.875 ± 0.622	a

Remarks: Different letters in each treatment indicate significant differences based on DMRT further test at 5% level ($p < 0.05$). Comparisons were made between each level of composition against the control (k1, 0% biochar)

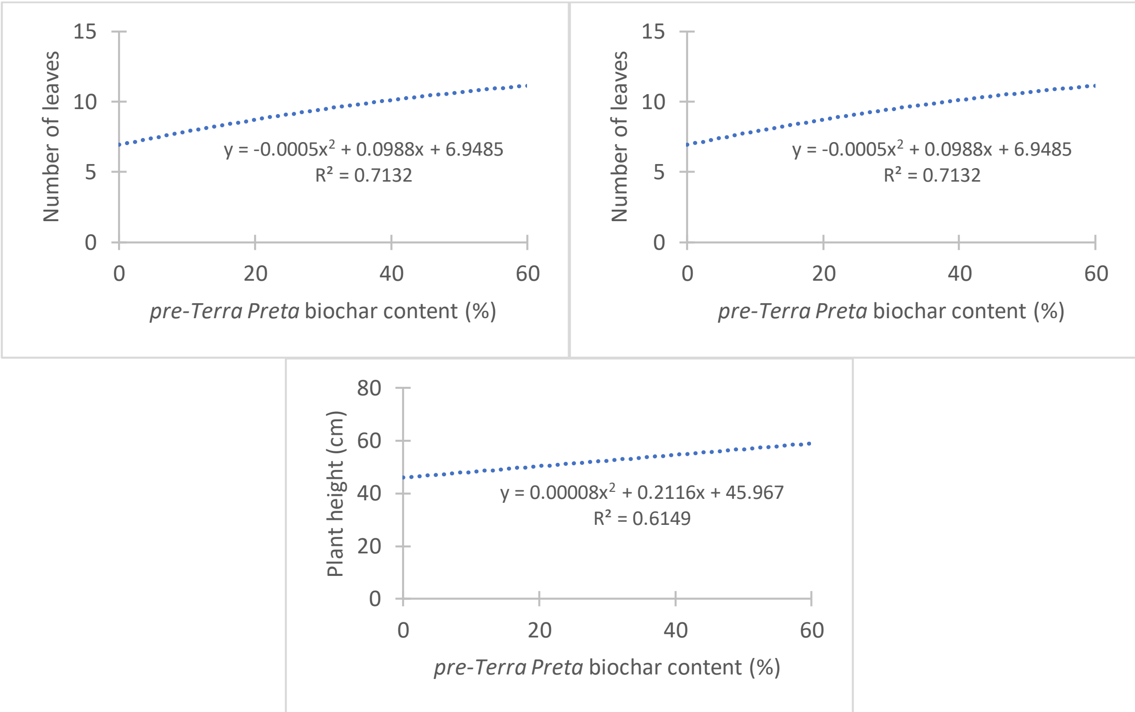

Figure 5. Effect of *pre-Terra Preta* biochar content (%) on the growth of *Pennisetum purpureum* cv. Mott (leaf number, tiller number, dan plant height; mean ± SE)

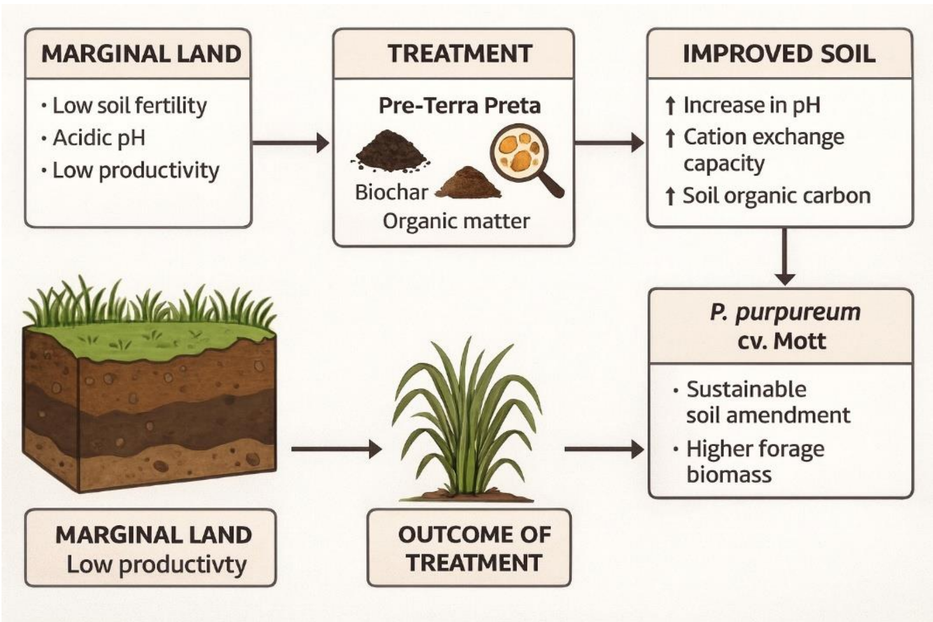

Figure 6. Schematic representation of soil enhancement strategies for marginal land using *pre-Terra Preta*

The findings align with previous studies confirming biochar's potential to improve soil fertility and crop performance in tropical agroecosystems (FAO, 2021; Gu & Yang, 2022; Li et al., 2023; Reza et al., 2020; Singh Yadav et al., 2023). As roots expand more freely and access nutrients efficiently, plants exhibit increased leaf formation, tillering, and stem elongation. Enhanced macroaggregate formation and aggregate stability foster a more favorable rhizosphere environment, thereby contributing to the observed improvements in aboveground biomass accumulation.

Biochar applications significantly improved soil physical properties, particularly porosity and water retention capacity. Its porous structure and high surface area facilitated better aeration and moisture availability, which are essential for root expansion and sustained growth *of Pennisetum purpureum* cv. Mott. Enhanced cation exchange capacity (CEC) due to biochar's functional groups also contributed to improved nutrient retention and reduced nutrient leaching (Acharya et al., 2024; Murtaza et al., 2023).

These improvements in CEC supported the retention of essential cations such as ammonium (NH_4^+) and potassium (K^+), which are vital for leaf formation, tillering, and stem elongation. Together, these soil enhancements strengthen overall soil functional capacity and long-term plant performance, support higher biomass accumulation and vegetative performance. Additionally, biochar stimulated enzymatic activities such as urease and dehydrogenase, which play key roles in nitrogen cycling and microbial respiration (Ali et al., 2025). However, the effectiveness of biochar may vary depending on feedstock type, pyrolysis conditions, and soil characteristics, highlighting the importance of local adaptation in amendment strategies (Acharya et al., 2024; Nepal et al., 2023; Tang et al., 2023; Zhu et al., 2025).

Enhanced transformation kinetics of potassium (K), which is vital for plant physiology, also explains the observed vegetative. Biochar application increases the availability of water-soluble, exchangeable, and non-exchangeable forms of K, supporting stem elongation and tillering (Xia et al., 2022; Xu et al., 2023). Nutrient retention in the soil matrix was further supported by biochar's porous structure and high surface area, which minimized leaching and maintained nutrient availability in the rhizosphere (Brtnicky et al., 2023; Llovet et al., 2023).

On the microbiological side, biochar creates microhabitats that favor the growth of soil microorganisms. Increased microbial activity contributed to organic matter decomposition and phosphorus, which are essential for sustained plant growth (Fritz et al., 2022; Martínez-Gómez et al., 2022; Singh et al., 2022). The synergy between biochar and local biomass, especially animal manure, enhances microbial stimulation and nutrient uptake efficiency. While manure supplied provides macronutrients such as N and P, biochar maintains the availability of these nutrients in the root zone, improves soil structure, and enhances plant tolerance to environmental stress (Chen et al., 2023; Mustafa et al., 2022; Obayomi et al., 2023).

Although available iron (Fe) and exchangeable aluminum (Exch. Al) concentrations increased after *pre-Terra Preta* application, their levels remained below toxicity thresholds and did not induce physiological stress in *Pennisetum purpureum* cv. Mott. The observed increase may reflect enhanced nutrient mobility, the significant rise in soil pH – from 5.60 to 6.29 – due to biochar's alkaline nature helped buffer soil acidity and reduce the solubility of toxic metal ions (de Lima et al., 2022). This pH shift created a more favorable environment for root development and nutrient uptake. These findings confirm that *pre-Terra Preta* application is safe and effective for rehabilitating acidic marginal soils, even when Fe and Al levels fluctuate within acceptable ranges (Obayomi et al., 2023).

Increased soil organic carbon due to high biochar carbon content promotes increased microbial activity and soil aggregate quality (Ahmad Bhat et al., 2022; Nepal et al., 2023). Phosphorus availability also increases due to interactions between biochar and soil P dynamics, which enhance the Phyto mobilization of this nutrient (Anjum et al., 2022).

The application of *pre-Terra Preta* aligns with sustainable agriculture principles by utilizing locally available organic waste and reducing dependence on synthetic inputs. Its ability to improve soil structure, enhance nutrient cycling, and increase water retention contributes to long-term soil health and resilience against climate variability. By rehabilitating degraded marginal lands, this approach supports food security while minimizing environmental degradation. Furthermore, the stable carbon content of biochar contributes to long-term carbon sequestration, positioning *pre-Terra Preta* as a nature-based solution that integrates productivity with ecological restoration (Amelung et al., 2020; FAO, 2021, 2023; Lal, 2020).

Beyond agronomic benefits, the *pre-Terra Preta* model offers socio-economic advantages by empowering smallholder farmers to utilize locally available organic materials—such as animal manure and sawdust—that are often underutilized or discarded. This approach reduces dependence on costly chemical inputs and promotes circular resource use within farming communities. With a participatory implementation model, *pre-Terra Preta* can be integrated into community-based agricultural systems, enhancing local resilience and adaptive capacity to environmental changes. By fostering knowledge-sharing and collective action, this technology supports inclusive development and strengthens the social fabric of rural livelihoods (Bezner Kerr et al., 2023; Kumar & Choudhury, 2024).

Overall, the findings of this study affirm that *pre-Terra Preta* application can transform marginal soils into productive substrates by improving soil structure, nutrient retention, and biological activity. These improvements collectively support the vegetative performance of *Pennisetum purpureum* cv. Mott and demonstrate the potential of locally adapted soil amendments to rehabilitate degraded tropical landscapes. The integration of agronomic, ecological, and socio-economic benefits positions *pre-Terra Preta* as a promising model for sustainable land management in regions facing similar constraints.

While this study focuses on vegetative growth parameters, ongoing analyses of biomass yield and forage quality are expected to further clarity the agronomic potential of *pre-Terra Preta* in tropical forage systems. This study marks the beginning of a broader research trajectory, with upcoming analyses focusing on biomass yield and nutritional quality to complement the vegetative growth findings.

5. CONCLUSION

This study demonstrated that the application of *pre-Terra Preta* – a soil amendment composed of biochar, fermented biomass, and local soil – significantly improved the physical and chemical properties of marginal land in South Kalimantan. These improvements supported the vegetative growth of *Pennisetum purpureum* cv. Mott, as evidenced by increased leaf number, tiller count, and plant height. As land degradation intensifies across tropical regions, the *pre-Terra Preta* model presents a replicable and scalable strategy for restoring soil health, improving forage productivity, and strengthening community resilience in smallholder farming systems.

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Author's Declaration of AI Assistance

Generative AI tools (such as ChatGPT by OpenAI) were used solely to enhance the clarity and readability of the manuscript through language editing. No AI tools were used in data analysis, interpretation, or scientific reasoning.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Acharya, B. S., Dodla, S., Wang, J. J., Pavuluri, K., Darapuneni, M., Dattamudi, S., . . . Kharel, G. (2024). Biochar impacts on soil water dynamics: knowns, unknowns, and research directions. *Biochar*, *6*(1), 34. https://doi.org/10.1007/s42773-024-00323-4

Ahmad Bhat, S., Kuriqi, A., Dar, M. U. D., Bhat, O., Sammen, S. S., Towfiqul Islam, A. R. M., . . . Heddam, S. (2022). Application of Biochar for Improving Physical, Chemical, and Hydrological Soil Properties: A Systematic Review. *Sustainability*, *14*(17), 11104. https://doi.org/10.3390/su141711104

Ali, A., Jabeen, N., Chachar, Z., Chachar, S., Ahmed, S., Ahmed, N., . . . Yang, Z. (2025). The role of biochar in enhancing soil health & interactions with rhizosphere properties and enzyme activities in organic fertilizer substitution [Review]. *Frontiers in Plant Science*, *Volume 16 - 2025*. https://doi.org/10.3389/fpls.2025.1595208

Amelung, W., Bossio, D., de Vries, W., Kögel-Knabner, I., Lehmann, J., Amundson, R., . . . Chabbi, A. (2020). Towards a global-scale soil climate mitigation strategy. *Nat Commun*, *11*(1), 5427. https://doi.org/10.1038/s41467-020-18887-7

Anda, M., Diah Purwantari, N., Yulistiani, D., Sajimin, Suryani, E., Husnain, & Agus, F. (2022). Reclamation of post-tin mining areas using forages: A strategy based on soil mineralogy, chemical properties and particle size of the refused materials. *CATENA*, *213*, 106140. https://doi.org/10.1016/j.catena.2022.106140

Anjum, Z., Min, Q., Riaz, L., Waqar-Un-Nisa, Qadeer, S., & Saleem, A. R. (2022). Employment of Cannabis sativa biochar to improve soil nutrient pool and metal immobilization [Original Research]. *Frontiers in Environmental Science*, *Volume 10 - 2022*. https://doi.org/10.3389/fenvs.2022.1011820

Bezner Kerr, R., Postigo, J. C., Smith, P., Cowie, A., Singh, P. K., Rivera-Ferre, M., . . . Neufeldt, H. (2023). Agroecology as a transformative approach to tackle climatic, food, and ecosystemic crises. *Current Opinion in Environmental Sustainability*, *62*, 101275. https://doi.org/10.1016/j.cosust.2023.101275

Brtnicky, M., Mustafa, A., Hammerschmiedt, T., Kintl, A., Trakal, L., Beesley, L., . . . Holatko, J. (2023). Pre-activated biochar by fertilizers mitigates nutrient leaching and stimulates soil microbial activity. *Chemical and Biological Technologies in Agriculture*, *10*(1), 57. https://doi.org/10.1186/s40538-023-00430-7

BSN. (2024). Spesifikasi informasi geospasial: Survei dan pemetaan tanah semidetail skala 1:50.000. SNI 8473:2024. [Geospatial Information Specification: Semi-detailed Soil Survey and Mapping at a 1:50,000 Scale].

Burland, A., & von Cossel, M. (2023). Towards Managing Biodiversity of European Marginal Agricultural Land for Biodiversity-Friendly Biomass Production. *Agronomy*, *13*(6), 1651. https://doi.org/10.3390/agronomy13061651

Chen, J., Yu, J., Li, Z., Zhou, J., & Zhan, L. (2023). Ameliorating Effects of Biochar, Sheep Manure and Chicken Manure on Acidified Purple Soil. *Agronomy*, *13*(4), 1142. https://doi.org/10.3390/agronomy13041142

Csikós, N., & Tóth, G. (2023). Concepts of agricultural marginal lands and their utilisation: A review. *Agricultural Systems*, *204*, 103560. https://doi.org/10.1016/j.agsy.2022.103560

de Lima, A. F. L., Campos, M. C. C., Martins, T. S., Silva, G. A., Brito, W. B. M., dos Santos, L. A. C., . . . da Cunha, J. M. (2022). Soil chemical attributes in areas under conversion from forest to pasture in southern Brazilian Amazon. *Scientific Reports*, *12*(1), 22555. https://doi.org/10.1038/s41598-022-25406-9

FAO. (2021). *The State of the World's Land and Water Resources for Food and Agriculture – Systems at breaking point. Synthesis report 2021.* Food and Agriculture Organization of the United Nations. https://doi.org/10.4060/cb7654en

FAO. (2023). *Sustainable Development Goals. Guidelines for the Use of the SDG Logo, Including the Colour Wheel and 17 Icons*. United Nations Department of Global Communications. https://unsdg.un.org/resources/guidelines-use-sdg-logo-including-colour-wheel-and-17-icons

Fritz, A.-L., Jannoura, R., Beuschel, R., Steiner, C., Buerkert, A., & Joergensen, R. G. (2022). The combined application of nitrogen and biochar reduced microbial carbon limitation in irrigated soils of West African urban horticulture. *Chemical and Biological Technologies in Agriculture*, *9*(1), 48. https://doi.org/10.1186/s40538-022-00312-4

Gu, J., & Yang, J. (2022). Nitrogen (N) transformation in paddy rice field: Its effect on N uptake and relation to improved N management. *Crop and Environment*, *1*(1), 7-14. https://doi.org/10.1016/j.crope.2022.03.003

Holatko, J., Bielska, L., Hammerschmiedt, T., Kucerik, J., Mustafa, A., Radziemska, M., . . . Brtnicky, M. (2022). Cattle Manure Fermented with Biochar and Humic Substances Improve the Crop Biomass, Microbiological Properties and Nutrient Status of Soil. *Agronomy*, *12*(2), 368. https://doi.org/10.3390/agronomy12020368

Iacomino, G., Idbella, M., di Costanzo, L., Amoroso, G., Allevato, E., Abd-ElGawad, A. M., & Bonanomi, G. (2024). Biochar aging, soil microbiota and chemistry of charcoal kilns in Mediterranean forests. *Biochar*, *6*(1), 82. https://doi.org/10.1007/s42773-024-00378-3

IUSS Working Group WRB. (2022). *World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps.* (4th ed.). International Union of Soil Sciences (IUSS), Vienna, Austria. https://files.isric.org/public/documents/WRB_fourth_edition_2022-12-18.pdf

Kern, J., Giani, L., Teixeira, W., Lanza, G., & Glaser, B. (2019). What can we learn from ancient fertile anthropic soil (Amazonian Dark Earths, shell mounds, Plaggen soil) for soil carbon sequestration? *CATENA*, *172*, 104-112. https://doi.org/10.1016/j.catena.2018.08.008

KLHK. (2024). *Laporan Kinerja Ditjen Pengelolaan Daerah Aliran Sungai dan Rehabilitasi Hutan tahun 2023* [Performance Report of the Directorate General of Watershed Management and Forest Rehabilitation for 2023] https://pdasrh.kehutanan.go.id/newsdetail.php?id=420-Laporan-Kinerja-Ditjen-Pengelolaan-Daerah-Aliran-Sungai-dan-Rehabilitasi-Hutan-tahun-2023

Kumar, P., & Choudhury, D. (2024). Chapter 21 - Role of indigenous knowledge in agricultural soil reclamation without disturbing other ecosystems. In P. Kumar, A. L. Srivastav, V. Chaudhary, E. D. van Hullebusch, & R. Busquets (Eds.), *Bioremediation of Emerging Contaminants from Soils* (pp. 465-488). Elsevier. https://doi.org/10.1016/B978-0-443-13993-2.00021-9

Kurniawan, W., Ramdani, A., Bain, A., Bachtiar, T., & Wahyono, T. (2022). Influences of manure and biochar on biomass yield and nutrient value of Pennisetum purpureum cv. Mott grown on post-nickel-mining soil. *JAPS: Journal of Animal & Plant Sciences*, *32*(5). https://doi.org/10.36899/JAPS.2022.5.0537

Lal, R. (2020). Regenerative agriculture for food and climate. *Journal of Soil and Water Conservation*, *75*(5), 123A-124A. https://doi.org/10.2489/jswc.2020.0620A

Li, Y., Feng, G., & Tewolde, H. (2023). Biochar derived from papermill factories improves soil physical and hydraulic properties in no-till cotton fields. *Biochar*, *5*(1), 35. https://doi.org/10.1007/s42773-023-00235-9

Llovet, A., Vidal-Durà, A., Alcañiz, J. M., Ribas, A., & Domene, X. (2023). Biochar addition to organo-mineral fertilisers delays nutrient leaching and enhances barley nutrient content. *Archives of Agronomy and Soil Science*, *69*(13), 2537-2551. https://doi.org/10.1080/03650340.2022.2161092

Martínez-Gómez, Á., Poveda, J., & Escobar, C. (2022). Overview of the use of biochar from main cereals to stimulate plant growth [Review]. *Frontiers in Plant Science*, *Volume 13 - 2022*. https://doi.org/10.3389/fpls.2022.912264

Mawalla, D., & Gülser, C. (2023). İmpacts of biochar on tropical soil quality: A review. *International Symposium on Soil Science & Plant Nutrition*, 92-97. https://doi.org/10.5281/zenodo.11084425

Melo, L. C. A., & Sánchez-Monedero, M. Á. (2024). How biochar-based fertilizers and biochar compost affect nutrient cycling and crop productivity. *Nutrient Cycling in Agroecosystems*, *128*(3), 411-414. https://doi.org/10.1007/s10705-024-10358-5

Murtaza, G., Ahmed, Z., Eldin, S. M., Ali, B., Bawazeer, S., Usman, M., . . . Tariq, A. (2023). Biochar-Soil-Plant interactions: A cross talk for sustainable agriculture under changing climate [Review]. *Frontiers in Environmental Science*, *Volume 11 - 2023*. https://doi.org/10.3389/fenvs.2023.1059449

Mustafa, A., Holatko, J., Hammerschmiedt, T., Kucerik, J., Baltazar, T., Kintl, A., . . . Brtnicky, M. (2022). Unveiling the Impacts of Biochar, Manure and Their Optimal Combinations on Microbiological Soil Health Indicators and Lettuce Biomass. *Agronomy*, *12*(10), 2307. https://doi.org/10.3390/agronomy12102307

Neina, D., & Agyarko-Mintah, E. (2023). The Terra Preta Model soil for sustainable sedentary yam production in West Africa. *Heliyon*, *9*(5), e15896. https://doi.org/10.1016/j.heliyon.2023.e15896

Nepal, J., Ahmad, W., Munsif, F., Khan, A., & Zou, Z. (2023). Advances and prospects of biochar in improving soil fertility, biochemical quality, and environmental applications [Review]. *Frontiers in Environmental Science*, *Volume 11 - 2023*. https://doi.org/10.3389/fenvs.2023.1114752

Obayomi, O., Taggart, C. B., Zeng, S., Sefcik, K., Willis, B., Muir, J. P., . . . Brady, J. A. (2023). Dairy Manure-Derived Biochar in Soil Enhances Nutrient Metabolism and Soil Fertility, Altering the Soil Prokaryote Community. *Agronomy*, *13*(6), 1512. https://doi.org/10.3390/agronomy13061512

Ollila, K., & Kotavaara, O. (2023). Measuring Accessibility and Optimising Logistics of Marginal Land Grass Biomass in the Case of Northern Ostrobothnia, Finland. *European Countryside*, *15*(4), 542-562. https://doi.org/10.2478/euco-2023-0029

Orozco-Ortiz, J. M., Peña-Venegas, C. P., Bauke, S. L., Borgemeister, C., Mörchen, R., Lehndorff, E., & Amelung, W. (2021). Terra Preta Properties in Northwestern Amazonia (Colombia). *Sustainability*, *13*(13), 7088. https://doi.org/10.3390/su13137088

Reza, M. S., Afroze, S., Bakar, M. S. A., Saidur, R., Aslfattahi, N., Taweekun, J., & Azad, A. K. (2020). Biochar characterization of invasive Pennisetum purpureum grass: effect of pyrolysis temperature. *Biochar*, *2*(2), 239-251. https://doi.org/10.1007/s42773-020-00048-0

Sazali, N., Kettner, M., & Salim, N. (2025). Save the Planet 2.0: A Mini Review of Improving Agricultural Soil with Terra Preta. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, *126*(2), 226-236. https://doi.org/10.37934/arfmts.126.2.226236

Singh, H., Northup, B. K., Rice, C. W., & Prasad, P. V. V. (2022). Biochar applications influence soil physical and chemical properties, microbial diversity, and crop productivity: a meta-analysis. *Biochar*, *4*(1), 8. https://doi.org/10.1007/s42773-022-00138-1

Singh Yadav, S. P., Bhandari, S., Bhatta, D., Poudel, A., Bhattarai, S., Yadav, P., . . . Oli, B. (2023). Biochar application: A sustainable approach to improve soil health. *Journal of Agriculture and Food Research*, *11*, 100498. https://doi.org/10.1016/j.jafr.2023.100498

Suwardi. (2025). *82 Persen Daratan Indonesia Lahan Marginal, Inovasi Teknologi Tanah Jadi Kunci Pemulihan*. https://www.ipb.ac.id/News/Index/2025/08/Prof-Suwardi-82-Persen-Daratan-Indonesia-Lahan-Marginal-Inovasi-Teknologi-Tanah-Jadi-Kunci-Pemulihan/

Tang, E., Liao, W., & Thomas, S. C. (2023). Optimizing Biochar Particle Size for Plant Growth and Mitigation of Soil Salinization. *Agronomy*, *13*(5), 1394. https://doi.org/10.3390/agronomy13051394

Xia, H., Liu, B., Riaz, M., Li, Y., Wang, X., Wang, J., & Jiang, C. (2022). 30-Month Pot Experiment: Biochar Alters Soil Potassium Forms, Soil Properties and Soil Fungal Diversity and Composition in Acidic Soil of Southern China. *Plants*, *11*(24), 3442. https://doi.org/10.3390/plants11243442

Xu, P., Gao, Y., Cui, Z., Wu, B., Yan, B., Wang, Y., . . . Xue, W. (2023). Research Progress on Effects of Biochar on Soil Environment and Crop Nutrient Absorption and Utilization. *Sustainability*, *15*(6), 4861. https://doi.org/10.3390/su15064861

Yang, Y., Hobbie, S. E., Hernandez, R. R., Fargione, J., Grodsky, S. M., Tilman, D., . . . Chen, W.-Q. (2020). Restoring Abandoned Farmland to Mitigate Climate Change on a Full Earth. *One Earth*, *3*(2), 176-186. https://doi.org/10.1016/j.oneear.2020.07.019

Zhu, Z., Zhang, Y., Tao, W., Zhang, X., Xu, Z., & Xu, C. (2025). The Biological Effects of Biochar on Soil's Physical and Chemical Characteristics: A Review. *Sustainability*, *17*(5), 2214. https://doi.org/10.3390/su17052214