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Combined biochar and perlite amendments improve soil physicochemical properties and cassava yield in tropical sandy soil

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Research Article

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Combined biochar and perlite amendments improve soil physicochemical properties and cassava yield in tropical sandy soil

Abstract

Coarse-textured tropical soils frequently lose water and nutrients rapidly, creating simultaneous physical and chemical constraints on crop production. This study tested whether biochar and expanded perlite, applied separately or in combination, could improve soil water availability, nutrient-related properties, and cassava (*Manihot esculenta* Crantz) productivity under field conditions. Seven amendment treatments were evaluated over 300 days in a randomized complete block design with three replications. Repeated measurements of soil pH, available water capacity (AWC), cation exchange capacity (CEC), exchangeable nutrients, and available phosphorus were analyzed with linear mixed-effects models, while fresh root yield was assessed at harvest. Among the treatments, the high-rate perlite-biochar combination (6,250 + 6,250 kg ha^{-1}; PBH10) produced the most consistent overall response. PBH10 maintained greater AWC than the untreated control and was associated with higher soil pH and greater concentrations of exchangeable Ca, K, Mg, and available P. CEC varied over time, as indicated by a significant treatment × time response. The same combined treatment produced the highest fresh root yield (20.28 ± 0.43 Mg ha^{-1}), 57.17% above the control. Overall, the field results indicate that combining biochar with perlite can simultaneously alleviate water- and nutrient-related limitations of tropical sandy soil and may provide a practical amendment option for cassava production on coarse-textured agricultural land.

Keywords: Available water capacity; Cation exchange capacity; Nutrient availability; Root-zone water retention; *Manihot esculenta*

1. Introduction

Coarse-textured soils in tropical regions present a combined water and fertility challenge for crop production. They occur extensively in areas such as Southeast Asia and Africa and are often associated with sandstone-derived or other sandy parent materials. Their high sand content, small clay fraction, and low organic matter generally produce weak aggregation and limited storage of both water and plant nutrients, thereby constraining soil functioning and increasing susceptibility to degradation (Bünemann et al., 2018). In cropped fields, rapid drainage can shorten the period during which water remains available to roots, while low cation exchange capacity reduces the soil's ability to

retain nutrient cations. As a result, applied nutrients may be used inefficiently or move below the active root zone, especially where rainfall is variable and drainage is rapid. Nutrient losses under free-draining cultivation have likewise been observed when nutrient supply exceeds crop uptake (Gallardo et al., 2025). Management strategies for tropical sandy soils therefore need to address water storage and nutrient retention together rather than treating them as separate limitations.

Amendments with contrasting physical and chemical functions may offer one way to address these coupled constraints. Biochar is a carbon-rich product of biomass pyrolysis under oxygen-limited conditions and can alter the chemical environment of coarse-textured soils by contributing exchange sites, surface area, alkalinity, and nutrient-retention capacity (Major et al., 2010). Its porous structure may also influence soil water storage, although the magnitude of this response varies with feedstock, pyrolysis conditions, application rate, and soil texture (Zhu et al., 2024a). Perlite provides a different set of properties. Heating hydrated volcanic glass produces a lightweight, highly porous expanded material with favorable air-water characteristics (Bar-Tal et al., 2019; Lim et al., 2021; Silber et al., 2010). In coarse-textured soils and growing media, perlite can modify pore space, aeration, and the distribution of water in the root zone (Silber et al., 2010). Because expanded perlite is relatively inert, however, its direct contribution to nutrient buffering and exchange is smaller than that of chemically active or organic amendments (Huang et al., 2025; Yang et al., 2023). These contrasting properties suggest a complementary role: biochar can contribute mainly to nutrient-related chemical functions, whereas perlite can contribute mainly to root-zone physical conditions and water storage.

Despite substantial research on biochar and on perlite individually, their joint use as soil amendments has been examined much less frequently, particularly in field-grown crops on tropical sandy soils (Huang et al., 2025; Yang et al., 2023; Zhu et al., 2024a). This gap is relevant because coarse-textured soils commonly exhibit water and nutrient limitations at the same time. An amendment system that combines the nutrient-retention and exchange-related properties of biochar with the pore-related physical properties of perlite could therefore provide a more balanced improvement than either material alone. Evidence from field experiments is still limited, however, and it remains unclear whether simultaneous changes in water availability and soil fertility are large enough to translate into higher crop productivity, especially for cassava in tropical sandy environments.

Accordingly, this study compared biochar, perlite, and combined biochar-perlite treatments under field conditions to determine their effects on soil water availability, cation exchange capacity, nutrient status, and cassava

yield. Soil pH, available water capacity, CEC, and major nutrient indicators were followed through the 300-day experiment, and fresh root yield was measured at harvest. The study was designed to determine whether combining amendments with different functional properties could provide a practical strategy for improving both root-zone conditions and crop performance in tropical sandy soil.

2. Materials and methods

2.1. Study area and soil characteristics

The field trial was established on the Pheniat foothill plain in Lop Buri Province, Thailand, along the marginal zone of the Lop Buri Basin (Fig. 1). The experimental site is located at UTM Zone 47P, 692,344 E and 1,664,397 N. Climatic conditions in this part of central Thailand are tropical, with distinct wet and dry seasons. The field lies near Khao Pheniat, where sandstone-derived parent materials have strongly influenced soil development. Agriculture is the dominant land use in the surrounding foothill area, and the soils are generally coarse textured, with rapid drainage, low water-holding capacity, and limited ability to retain nutrients.

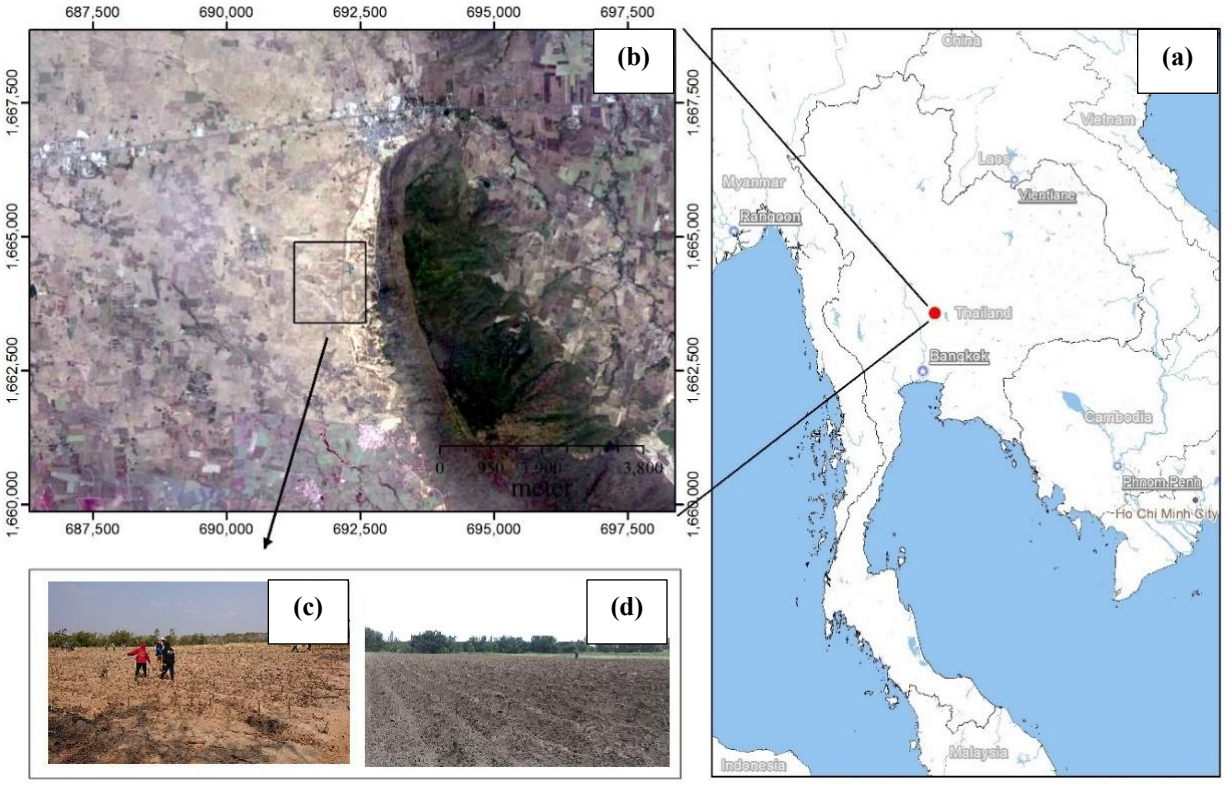


Fig. 1. Location and general characteristics of the experimental site. (a) Regional location of the study area in Thailand. (b) Satellite image showing the experimental field situated in a foothill plain dominated by sandy parent materials. (c–d) Field views of the experimental plots illustrating the coarse-textured soil conditions prior to treatment application.

Baseline soil conditions were characterized before the amendments were applied. Composite samples collected across the experimental field showed that the soil contained 86.4% sand and only 4.1% clay and was therefore classified as loamy sand under the USDA soil textural classification (Table 1). Initial bulk density was 1.58 ± 0.15 g cm^{-3}, and total porosity was 41.00 ± 2.60%. These measurements confirm that the site represents a coarse-textured soil with limited capacity to store plant-available water in the root zone. Its low nutrient-retention potential also provided an appropriate field setting for testing whether biochar and perlite could improve soil water availability, nutrient exchange, and crop performance.

Table 1 Soil Properties before the experiment

Property	Unit	Value
Sand	%	86.40
Silt	%	9.50
Clay	%	4.10
Texture class	-	Loamy sand
Bulk density	g cm^{-3}	1.58 ± 0.15
Total porosity	%	41.00 ± 2.60
Soil pH	-	6.32 ± 0.06
Electrical Conductivity (EC)	µS cm^{-1}	57.34 ± 6.11
The cation exchange capacity (CEC)	cmol kg^{-1}	4.50 ± 0.42
Exchangeable Ca	mg kg^{-1}	261.98 ± 16.09
Exchangeable K	mg kg^{-1}	24.66 ± 3.42
Exchangeable Mg	mg kg^{-1}	44.92 ± 1.32
Available P	mg kg^{-1}	23.92 ± 2.91
Soil organic matter	%	0.20 ± 0.00
Volumetric water content	%	5.31 ± 0.16

2.2. Preparation of soil amendments

2.2.1 Biochar production

Biochar was prepared from maize (corn) residues using a hybrid gasification-pyrolysis unit with an internal combustion core developed through a research project at the Kasetsart University Research Station. Before thermal conversion, the residues were mechanically shredded to lengths below 5 cm. Pyrolysis proceeded under oxygen-limited conditions at temperatures exceeding 400 °C for approximately 2.0-2.5 h until stable char had formed. The product was then allowed to cool naturally to room temperature. No additional crushing or sieving was performed, so the final biochar particle size reflected the dimensions of the prepared feedstock. The material was kept dry before field use to limit moisture uptake and contamination.

2.2.2 Perlite material preparation

Perlite originated from Niyomchai Subdistrict, Sa Bot District, Lop Buri Province, Thailand, and was expanded by heat treatment at the Kasetsart University Research Station, Lop Buri Campus. Raw material was heated to approximately 800 °C to promote expansion and develop the porous structure required for soil amendment use. After cooling naturally to room temperature, the expanded material was passed through a sieve to retain particles smaller than 3 mm. The prepared perlite was stored under dry conditions until field application.

2.3. Characterization of amendment properties

2.3.1 Biochar properties

Before field application, the biochar was characterized for chemical composition, elemental content, surface features, and pore-related properties. Measurements included pH, electrical conductivity (EC), cation exchange capacity (CEC), major nutrients, and carbon, nitrogen, and sulfur. Biochar pH and EC were measured in a 1:1 (w/v) suspension of biochar and distilled deionized water using a Sartorius DOCU-pH+ meter; EC values were expressed as $\mu S\ cm^{-1}$. CEC was measured by ammonium acetate (NH_4OAc) extraction at pH 7.0 and reported as $cmol(+)\ kg^{-1}$. Total C, N, and S were quantified by dry combustion with a LECO CHNS-932 elemental analyzer equipped with a VTF-900 furnace module, and the C/N ratio was calculated from the measured carbon and nitrogen concentrations. Following acid digestion, K, Ca, Mg, and P were quantified by inductively coupled plasma mass spectrometry (ICP-MS) and expressed as $mg\ kg^{-1}$.

Biochar surface morphology was examined by scanning electron microscopy (SEM; Hitachi S-4100 FE-SEM). Samples were dried and coated with a thin gold layer before observation. Images collected at 2,500× magnification were used to visualize micrometer-scale pores and surface features.

Nitrogen adsorption measurements were used to characterize the biochar pore system by the Brunauer-Emmett-Teller (BET) approach. Prior to analysis, samples were dried and degassed at 80 °C for 24 h. A Quantachrome Autosorb-1C surface area and pore analyzer was then used to derive specific surface area, mean pore diameter, and total pore volume from the adsorption data.

2.3.2 Perlite properties

Expanded perlite was characterized before field use with emphasis on mineral composition and pore-related properties. Major oxide composition was determined by wavelength-dispersive X-ray fluorescence spectrometry (WDXRF; Thermo Scientific ARL PERFORM'X). The perlite was finely ground, formed into pressed pellets, and analyzed by XRF, after which the major components were reported as oxide percentages.

Perlite specific surface area, average pore diameter, and total pore volume were also assessed by nitrogen adsorption using the Brunauer-Emmett-Teller (BET) method. Measurements were carried out with the same Quantachrome Autosorb-1C surface area and pore analyzer used for the biochar characterization.

2.4. Experimental design

The field trial followed a randomized complete block design (RCBD) comprising seven treatments with three replicate blocks, for a total of 21 plots. Individual plots were 6 × 6 m (36 m²). Cassava (*Manihot esculenta* Crantz) was planted at 1 × 1 m spacing and managed uniformly across treatments with respect to weed control and routine field maintenance. Groundwater was delivered through a drip-irrigation system. Before planting, all plots received one application of 15-15-15 compound fertilizer at 30 kg rai^{-1} (187.5 kg ha^{-1}). Apart from the amendments assigned to each treatment, no other soil amendment was added. The crop was harvested 300 days after planting, when fresh root yield was measured.

The seven treatments comprised an unamended control, two biochar rates, two perlite rates, and two treatments combining the two materials. Biochar-only and perlite-only treatments were applied at 3,125 or 6,250 kg ha^{-1}. In the combined treatments, each material was supplied at equal rates of 3,125 + 3,125 kg ha^{-1} or 6,250 + 6,250

kg ha⁻¹. Plot-level application amounts were calculated from the 36 m² plot area and the designated field rates (Table 2). Planting ridges approximately 30 cm high were formed with a four-wheel tractor before crop establishment. Each amendment was broadcast uniformly along the planting rows and incorporated manually into the soil before cassava was planted. A single batch of each amendment material was used throughout the experiment to limit between-treatment variation in material properties.

Table 2 Types, application rates, and actual amounts of soil amendments

Treatment	Soil amendment	Application rate (kg ha^{-1})	Actual amount per plot (kg plot^{-1})
Control	No amendment	–	–
BCH05	Biochar	3,125	11.25
BCH10	Biochar	6,250	22.50
PER05	Perlite	3,125	11.25
PER10	Perlite	6,250	22.50
PBH05	Perlite + Biochar	3,125 + 3,125	11.25 + 11.25
PBH10	Perlite + Biochar	6,250 + 6,250	22.50 + 22.50

2.5. Soil sampling and analyses

Soil was sampled from every plot at 60, 120, 180, 240, and 300 days after amendment application. At each sampling date, five cores were taken from the 0-10 cm depth at predetermined positions within the plot - one from each corner and one from the center - using a soil core sampler. These five disturbed cores were pooled to obtain one composite sample for chemical analysis. Composite samples were air-dried, gently crushed, and passed through a 2-mm sieve. In addition, three undisturbed cores were collected separately from each plot for measurement of available water capacity (AWC) with a pressure plate apparatus.

For chemical analyses, soil pH and electrical conductivity (EC) were measured in a 1:1 (w/v) soil-to-distilled deionized water suspension. Soil organic matter was determined by the Walkley-Black procedure, while CEC was measured by ammonium acetate (NH_4OAc) extraction at pH 7.0. Exchangeable Ca, K, and Mg were extracted with NH_4OAc and quantified by inductively coupled plasma mass spectrometry (ICP-MS). Available P was obtained by Bray II extraction and was also quantified by ICP-MS.

Soil water retention was evaluated as available water capacity (AWC) using a pressure plate apparatus in accordance with ASTM D6836. Samples were saturated before measurement, and gravimetric water contents were determined at matric potentials of 33 kPa for field capacity (FC) and 1,500 kPa for the permanent wilting point (PWP). AWC was calculated as FC minus PWP and reported on a gravimetric basis (% w/w).

2.6. Crop Yield Analysis

Fresh root yield was determined once, at harvest 300 days after planting. Storage roots from each plot were collected and weighed immediately, whereas stems and leaves were excluded from the yield measurement. Recorded fresh weight per plot was converted to Mg ha^{-1} using the harvested plot area, and these values were used to compare crop productivity among amendment treatments.

2.7. Statistical Analysis

Statistical significance was evaluated at $p < 0.05$. Repeated measurements of soil physicochemical properties were analyzed with linear mixed-effects models (LMMs). Treatment, sampling time, and the treatment × time interaction were specified as fixed effects, and plot was included as a random effect to account for repeated observations from the same experimental unit. Where significant effects occurred, estimated marginal means (EMMs) were compared pairwise using Tukey adjustment.

Because cassava yield was measured only at harvest, it was analyzed separately from the repeated soil measurements. For the RCBD yield analysis, treatment was specified as a fixed effect and block as a random effect in a linear mixed-effects model. The seven treatment levels were C, BCH05, BCH10, PER05, PER10, PBH05, and PBH10. Model adequacy was assessed from residual normality and homogeneity of variance. When the treatment effect was significant, EMMs were compared among treatments using Tukey-adjusted pairwise tests at $p < 0.05$.

3. Results

3.1. Properties of Biochar and Perlite

Biochar and expanded perlite were characterized with different sets of measurements because the two amendments differ markedly in composition and function. The principal chemical and physical characteristics are presented in Table 3. The biochar was neutral to slightly alkaline and had a comparatively high cation exchange capacity, together with substantial carbon and potassium contents. These properties indicate that the material could provide both exchange surfaces and plant nutrients after incorporation into soil. Its porous character was also evident in the SEM images, which showed irregular micrometer-scale openings across the particle surfaces (Fig. 2). Nitrogen-adsorption analysis further confirmed a measurable specific surface area and pore volume.

198 **Table 3** Properties of biochar and perlite

Properties	Value
Biochar	
pH	7.55
EC(μS cm^{-1})	163.00
Cation exchange capacity (cmol(+) kg^{-1})	55.08
Total calcium (mg kg^{-1})	503.00
Total potassium (mg kg^{-1})	20589.00
Total magnesium (mg kg^{-1})	1902.00
Plant-available phosphorus (mg kg^{-1})	692.00
Carbon (%)	54.66
Nitrogen (%)	1.33
Sulfur (%)	0.09
Carbon-to-nitrogen ratio (C/N ratio)	41.20
BET surface area (m^2 g^{-1})	88.66
Pore volume (mL g^{-1})	0.07
Average pore (Å)	27.03
Perlite	
Bulk density (kg m^{-3})	97.5
Specific gravity	2.38
SiO_2 (%)	68.63
Al_2O_3 (%)	15.36

199

200 Expanded perlite showed a contrasting profile. Its low bulk density and the predominance of SiO2 and Al2O3
201 were consistent with a lightweight, expanded siliceous mineral. Thus, the two amendments offered different functional
202 attributes before application: biochar was characterized mainly by carbon, nutrients, and exchange capacity, whereas
203 perlite was characterized mainly by its low density, mineral composition, and pore-related physical properties.

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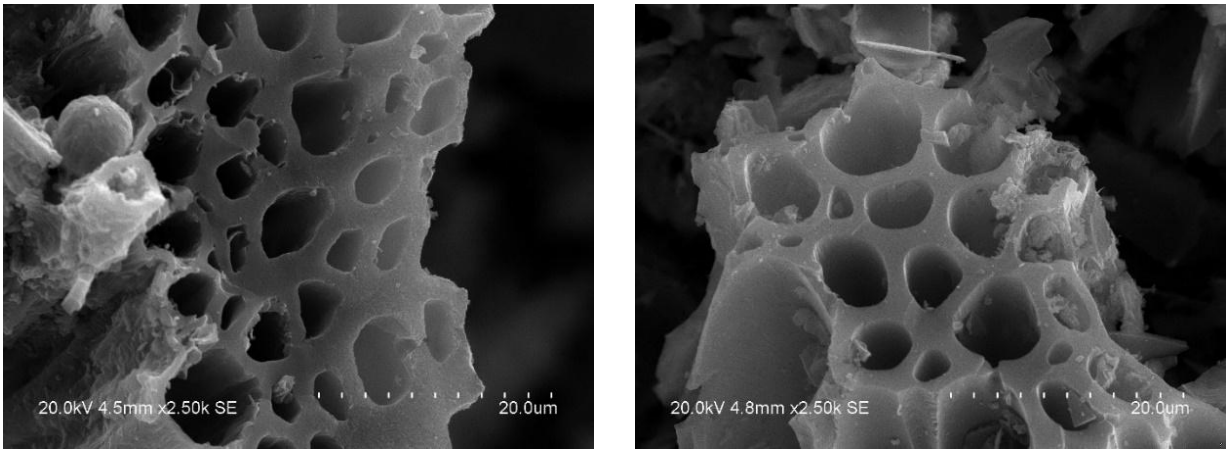
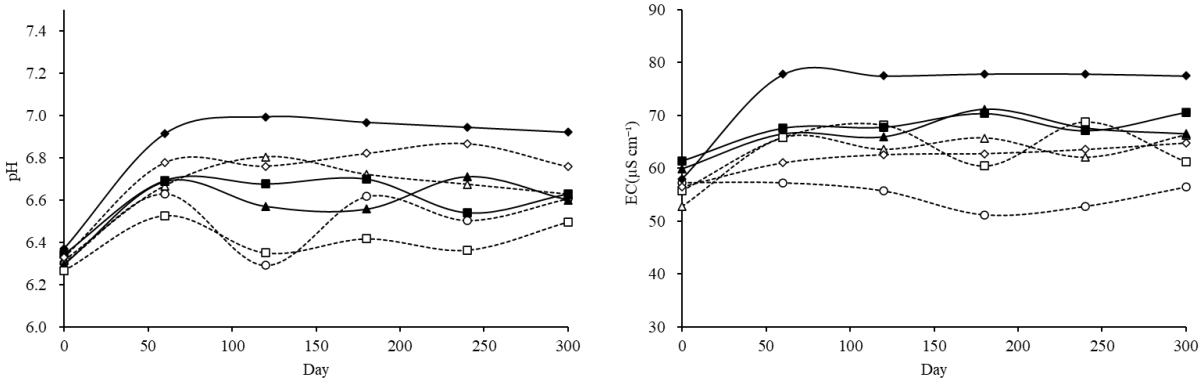


Fig. 2. SEM micrographs of the biochar surface at 2,500× magnification.

3.2. Effects of soil amendments on soil physicochemical properties

Changes in soil fertility indicators were evident across the 300-day sampling period (Fig. 3). Relative to the untreated control, amended plots generally maintained higher soil pH and greater concentrations of exchangeable Ca, K, Mg, and available P. The clearest and most persistent response occurred under the high-rate combined treatment (PBH10), although several other high-rate treatments also produced values above the control at individual sampling times. Endpoint values at 300 days are summarized in Table 4, showing that the amendments altered multiple aspects of soil chemical condition during the field trial.



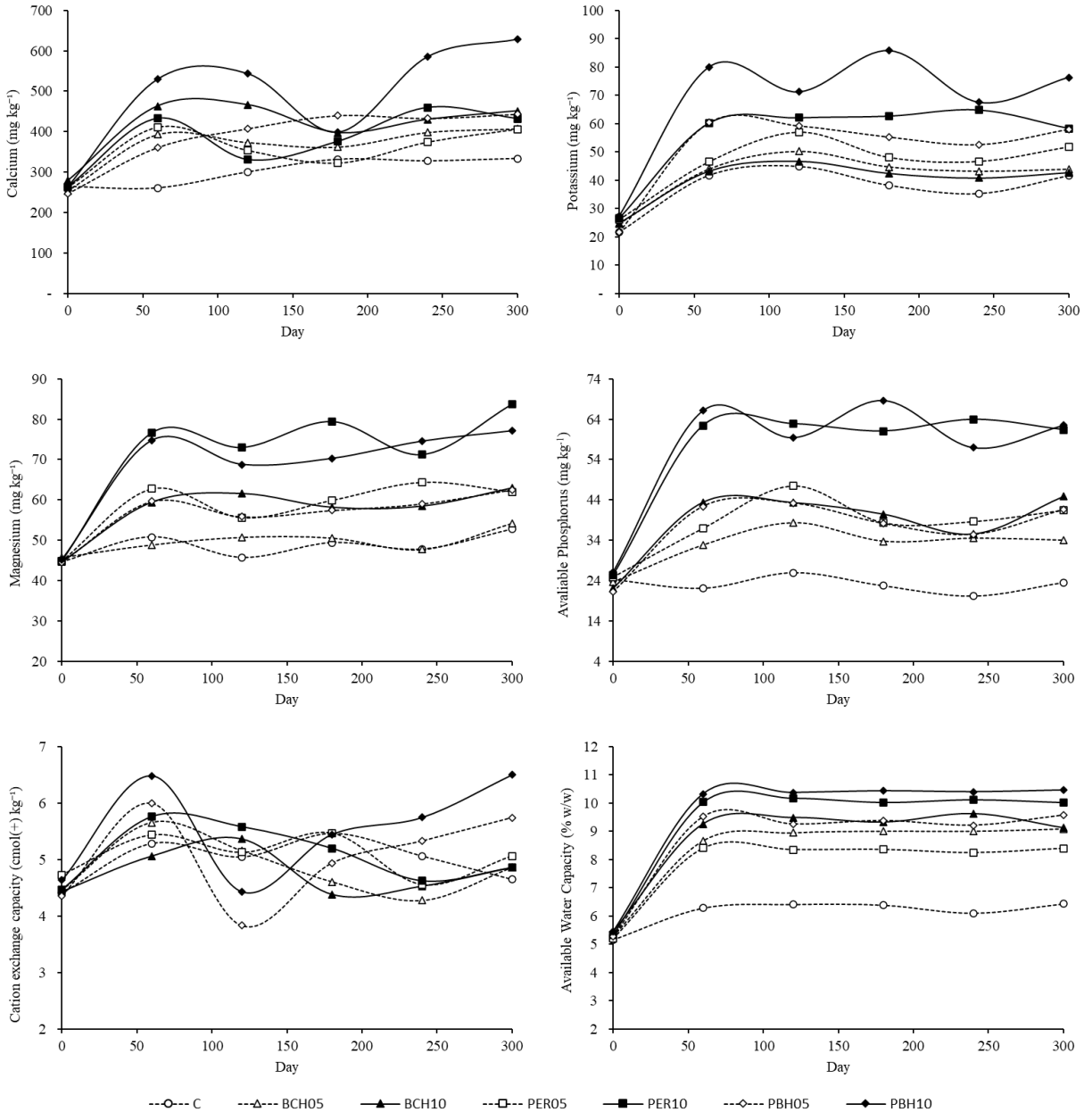


Fig. 3. Temporal changes in soil properties under different soil management treatments over the 300-day experimental period.

3.3. Effects of soil amendments on available water capacity and cation exchange capacity

Available water capacity (AWC) responded more consistently to amendment treatment than cation exchange capacity (CEC) (Fig. 3; Tables 4 and 5). The control remained the lowest-AWC treatment across the observation period, while all amended soils retained more plant-available water. The combined treatments were particularly

effective, and PBH10 maintained values close to 10% w/w after amendment application and was among the highest treatments at most sampling dates. The mixed-effects analysis identified a strong treatment effect for AWC ($p < 0.0001$), whereas neither time nor the treatment x time interaction was significant (Table 5). This pattern indicates that the observed AWC differences were primarily associated with amendment treatment rather than with changes among sampling dates.

CEC behaved differently. Neither the overall treatment effect nor the overall time effect was significant, whereas the treatment x time interaction was highly significant ($p < 0.0001$; Table 5). Accordingly, differences in CEC were not stable across the full experimental period but varied according to the treatment at a particular sampling date. Some amended plots exceeded the control at specific times, but the response was less uniform than that observed for AWC.

240 **Table 4** Soil properties at the end of the experiment (300 days)

Variables	Treatment						
	Control	BCH05	BCH10	PER05	PER10	PBH05	PBH10
pH	6.61 ± 0.17	6.63 ± 0.14	6.60 ± 0.23	6.50 ± 0.19	6.63 ± 0.15	6.76 ± 0.07	6.92 ± 0.10
EC (μS cm^{-1})	56.44 ± 8.52	66.32 ± 2.98	66.50 ± 4.89	61.19 ± 5.96	70.58 ± 4.76	64.80 ± 1.02	77.49 ± 1.53
CEC (cmol kg^{-1})	4.65 ± 0.49	4.86 ± 0.66	4.86 ± 0.39	5.06 ± 0.43	4.86 ± 0.71	5.74 ± 0.06	6.50 ± 0.14
Ca (mg kg^{-1})	333.68 ± 9.80	407.11 ± 16.09	451.44 ± 48.10	406.47 ± 58.42	432.35 ± 101.24	443.86 ± 10.50	628.84 ± 38.72
K (mg kg^{-1})	41.55 ± 1.32	43.96 ± 6.43	42.72 ± 8.21	51.81 ± 8.20	58.31 ± 3.52	58.00 ± 1.30	76.36 ± 7.15
Mg (mg kg^{-1})	52.71 ± 2.18	54.13 ± 3.77	62.96 ± 8.43	62.04 ± 20.03	83.81 ± 4.37	62.53 ± 2.43	77.09 ± 4.63
P (mg kg^{-1})	23.52 ± 0.28	34.02 ± 7.82	44.83 ± 1.21	41.48 ± 9.03	61.40 ± 8.08	41.60 ± 2.10	62.48 ± 9.87
AWC (% w/w)	6.76 ± 0.28	9.09 ± 0.33	9.12 ± 0.21	8.40 ± 0.08	10.02 ± 1.05	9.57 ± 0.48	10.46 ± 0.16

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Table 5 Analysis of variance (ANOVA) results from the linear mixed-effects model for soil properties measured over the 300-day experimental period.

Variable	Fixed effect	Numerator df	p-value	Significance
pH	Treatment	6	< 0.0001	***
pH	Time	4	0.0102	*
pH	Treatment × Time	24	0.1630	ns
EC	Treatment	6	< 0.0001	***
EC	Time	4	0.8629	ns
EC	Treatment × Time	24	0.0569	ns
CEC	Treatment	6	0.1956	ns
CEC	Time	4	0.9705	ns
CEC	Treatment × Time	24	< 0.0001	***
Ca	Treatment	6	< 0.0001	***
Ca	Time	4	0.7576	ns
Ca	Treatment × Time	24	0.1209	ns
K	Treatment	6	< 0.0001	***
K	Time	4	0.9993	ns
K	Treatment × Time	24	0.0061	**
Mg	Treatment	6	< 0.0001	***
Mg	Time	4	0.5376	ns
Mg	Treatment × Time	24	0.0460	*
P	Treatment	6	< 0.0001	***
P	Time	4	0.4873	ns
P	Treatment × Time	24	0.7414	ns
AWC	Treatment	6	< 0.0001	***
AWC	Time	4	0.5540	ns
AWC	Treatment × Time	24	0.0884	ns

3.4. Crop yield response to soil amendments

Fresh cassava root yield varied significantly among treatments ($p < 0.001$; Fig. 4). PBH10 produced the greatest yield, 72.3 ± 1.53 kg plot^{-1} or 20.28 ± 0.43 Mg ha^{-1}, which was 57.17% higher than the untreated control. Tukey-adjusted comparisons placed PBH10 in a significantly higher group than every other treatment. PER10 and PBH05 comprised the next highest group, BCH10 and PER05 produced intermediate yields, and BCH05 did not differ from the control in the lowest-yield group.

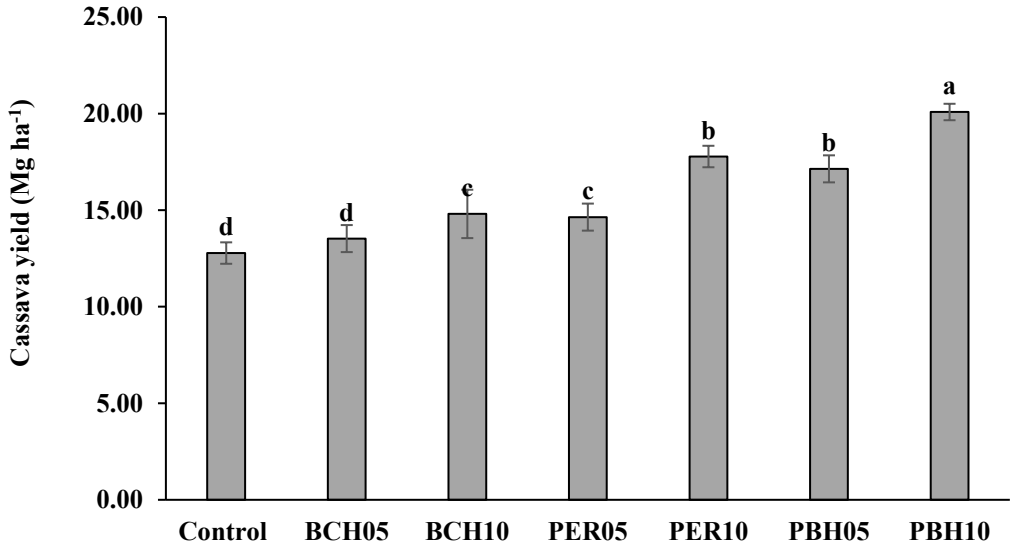


Fig. 4. Different letters denote significant treatment differences based on Tukey-adjusted pairwise comparisons of estimated marginal means.

4. Discussion

4.1. Amendment properties and their relevance to tropical sandy soil improvement

The contrasting characteristics of the two amendments provide a basis for interpreting their different roles after incorporation into the sandy soil. Biochar combined a relatively high CEC with high carbon and potassium contents and a visibly porous surface, features that are relevant to nutrient retention and chemical fertility. Previous syntheses have likewise reported increases in pH, exchange capacity, organic carbon, and nutrient cycling following biochar addition, with responses often being pronounced in coarse-textured soils (Singh et al., 2022; Bekchanova et al., 2024). Expanded perlite, by comparison, was a low-density siliceous material dominated by silica and alumina. Its largely inert chemistry suggests a smaller direct contribution to nutrient exchange, while its lightweight and porous structure is more closely associated with modification of pore space, aeration, and water distribution (Silber et al., 2010; Yang et al., 2023).

These complementary characteristics are relevant to tropical sandy soils because water limitation and weak nutrient retention commonly occur together. In such soils, an amendment that improves only chemical fertility may leave the physical limitation unresolved, whereas a purely physical amendment may contribute little to nutrient supply

or exchange. The combined biochar-perlite treatment was therefore expected to influence both components of the root-zone environment, providing a plausible basis for the broader soil responses observed in this field experiment.

4.2. Improvement of soil water retention and nutrient availability under biochar–perlite amendment

Among the measured soil variables, AWC showed the most stable treatment response. The unamended soil retained comparatively little plant-available water, while each amendment increased AWC to some extent and the strongest response occurred under PBH10. This finding is consistent with the known sensitivity of sandy soils to rapid drainage through large pores. Biochar can alter water retention through its internal porosity, surface area, and effects on pore-size distribution, as reported for coarse-textured soils in previous studies (Alghamdi et al., 2020; Blanco-Canqui, 2017; Omondi et al., 2016). Perlite can also modify the physical environment of the root zone by increasing pore space and affecting the balance between air and readily available water (Acuña et al., 2013). The high AWC measured under the combined treatment therefore supports a complementary physical contribution from the two amendments, although the present experiment did not directly partition their individual effects on pore architecture.

The chemical indicators showed a related but more variable response. Exchangeable Ca, K, and Mg and available P were generally greater in amended soils, with PBH10 showing the strongest overall nutrient profile. Biochar provides a plausible chemical contribution because its nutrient content, surface area, and exchange sites can promote retention of nutrient cations and reduce losses from coarse-textured soils (Dorosh et al., 2025; Li et al., 2025). Perlite itself is comparatively inert, but changes in root-zone water distribution may influence nutrient movement and residence time in a porous soil matrix, as has been observed in mineral-based cultivation systems (Gallardo et al., 2025). The higher available P at the larger amendment rates may reflect a combination of P supplied by biochar and subsequent adsorption or redistribution reactions, including Ca-associated processes (Ma et al., 2025; Tian et al., 2025; Tilahun et al., 2025). Because leaching fluxes and adsorption reactions were not measured directly, these mechanisms should be regarded as plausible interpretations rather than demonstrated causal pathways.

4.3. Linkages between soil property changes and cassava yield response

The yield pattern paralleled the broader improvement in soil condition. PBH10 produced 20.28 ± 0.43 Mg ha^{-1} of fresh cassava roots, a 57.17% increase over the control, and the same treatment also maintained the highest or near-highest AWC together with elevated concentrations of several plant nutrients. The correspondence among these

298 responses suggests that the yield advantage was associated with simultaneous improvement in water availability and
299 nutrient status rather than with a single measured soil property.

300 This integrated response is particularly relevant in coarse-textured tropical soils, where rapid water loss and low
301 nutrient-holding capacity can constrain cassava at the same time. PER10 increased AWC and maintained relatively
302 favorable nutrient levels, yet its yield remained below that of PBH10. The comparison indicates that improving
303 physical conditions alone was not sufficient to reproduce the full yield response of the combined amendment. A more
304 plausible explanation is that perlite contributed primarily to the physical water environment while biochar added
305 chemical functions related to nutrient supply and exchange. Comparable studies of biochar and mixed-amendment
306 systems have also linked crop responses to concurrent changes in several soil properties rather than to nutrient addition
307 alone (Tilahun et al., 2025; Adekiya et al., 2022; Wang et al., 2025).

308 The experiment was not designed to resolve plant physiological, microbiological, or molecular mechanisms.
309 Root architecture, microbial communities, enzyme activity, and the continuity of nutrient supply were not measured.
310 Consequently, mechanisms involving these processes, although supported by previous studies (Ding et al., 2025; Gül
311 et al., 2013; Zhu et al., 2024b), cannot be claimed as direct evidence from this dataset. Within the limits of the
312 measurements made, the most defensible interpretation is that PBH10 created a more favorable combination of soil
313 water and nutrient conditions that was accompanied by higher cassava yield.

314

315 *4.4. Practical implications and limitations*

316 A practical contribution of this study is that the response was demonstrated under field conditions rather than
317 solely in pots or controlled substrates. Applying biochar and perlite together at 6,250 kg ha^{-1} of each material improved
318 both water-related and nutrient-related soil indicators and was accompanied by a clear increase in cassava yield. For
319 coarse-textured agricultural soils, where rapid drainage, weak nutrient retention, and low inherent fertility occur
320 simultaneously, this field evidence provides a basis for considering combined amendments as a management option
321 rather than treating each constraint independently.

322 From an applied perspective, the results favor a function-based approach to amendment selection. Perlite appears
323 to have contributed mainly through modification of the physical root-zone environment, especially water retention,
324 whereas biochar supplied nutrients and exchange-related chemical functions. The superior performance of the
325 combined high-rate treatment suggests that addressing both sets of limitations together may be more effective than

focusing on only one. This interpretation is consistent with studies of soil and substrate management in which plant performance reflects the combined effects of physical structure, nutrient dynamics, and material stability rather than a single property such as pH or EC (Yang & Lin, 2025).

Several limitations define the scope of these conclusions. The trial covered one cassava growing cycle, so persistence of the response across years and contrasting rainfall regimes remains unknown. Root traits, microbial activity, nutrient leaching, and detailed adsorption processes were also outside the measurements made in this experiment. The observed field responses therefore support agronomic and soil-level interpretations but do not establish specific biological or physicochemical mechanisms. Future work should test the longevity of the amendment effects, identify economically realistic rates, and evaluate performance across additional sandy soils, rainfall conditions, and crop-management systems.

5. Conclusion

Under the conditions of this 300-day field experiment, combining biochar and perlite produced the strongest overall improvement in the studied tropical sandy soil. PBH10 increased available water capacity, maintained a favorable nutrient profile, and achieved the highest cassava fresh root yield (20.28 ± 0.43 Mg ha^{-1}), 57.17% above the untreated control. The results are consistent with complementary amendment functions: biochar contributed nutrient and exchange-related properties, while perlite contributed mainly to the physical water environment of the root zone. CEC did not show a uniform main treatment response and instead varied with treatment over time, indicating that not all soil properties responded in the same manner. Taken together, the findings support combined biochar-perlite application as a promising field-scale strategy for improving water and nutrient constraints in tropical sandy soil, while longer-term and multi-environment studies are still needed to determine persistence, economic feasibility, and transferability.

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