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Interactive effects of biochar type, particle size, application rate, and nitrogen fertilizer on maize productivity and soil properties in the Guinea Savanna zone of Ghana

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Abstract

Low soil fertility and high fertilizer costs constrain maize (Zea mays L.) productivity in acidic, low-organic-carbon sandy loam soils of semi-arid regions. The interactive effects of biochar type, particle size, application rate, and nitrogen (N) fertilizer are poorly understood. A field experiment was conducted during the 2023 rainy season on a Plinthic Acrisol in the Guinea Savanna zone of Ghana at CSIR-SARI Nyankpala (09°23′N, 1°00′W). The treatment structure was 2 biochar types (rice husk and acacia wood) × 2 biochar application rates (2 and 4 t ha^{-1}) × 3 particle sizes (<2, 5 and 10 mm) × 3 nitrogen (N) rates (0, 60, and 120 kg N ha^{-1}) = 36 biochar-amended combinations plus 3 no-biochar controls (0 t ha^{-1} + 0, 60 and 120 kg N ha^{-1}) arranged in a randomized complete block design (RCBD) with three replications (117 plots for analysis; 162 plots established with duplicated controls for field balance, averaged for analysis). Maize variety Abontem was sown 17 May and harvested 18 August 2023, rainfed only. Four-way analysis of variance (ANOVA) of biochar-amended plots showed significant effects ($p<0.05$, $F=3.8$, $p=0.002$ for Type × Rate × Size × N interaction). Combined biochar and N increased soil pH, organic carbon (OC), available phosphorus (P), cation exchange capacity (CEC), volumetric water content (VWC) at 0–12 cm depth, and grain yield. Rice husk biochar at 4 t ha^{-1} with < 2 mm particle size and 60 kg N ha^{-1} produced the highest grain yield of 3.01 t ha^{-1}, statistically comparable to no-biochar + 120 kg N ha^{-1} (2.87 t ha^{-1}, Tukey $p=0.12$) and significantly higher than no-biochar + 60 kg N ha^{-1} (1.65 t ha^{-1}, $p<0.001$). This suggests yield may be maintained with 50% less mineral N under these specific conditions in this single-season trial, pending multi-season validation. This treatment also recorded the highest agronomic efficiency (AE = 46.3 kg grain kg^{-1} N) and N recovery (NR = 76.7%) based on total plant N uptake. Coarse 10 mm biochar at 4 t ha^{-1} showed very low apparent NR (10.0%) which may indicate temporary reduced N availability but was not confirmed as immobilization as soil mineral N was not measured. VWC at 4, 6, and 8 weeks after sowing (WAS) increased by 188% under the optimal treatment (16.09% vs 5.57% at 8 WAS). Grain yield was positively associated with soil OC ($r=0.91$, $p<0.001$) and negatively associated with particle size ($r=-0.64$, $p<0.001$), indicating association not causality. These findings provide preliminary evidence relevant to similar acidic, low-fertility sandy loams in Guinea Savanna only, and multi-season, multi-location trials and economic analysis are needed before wider recommendation

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Keywords Biochar · Guinea Savanna · *Zea mays* · Nitrogen use efficiency · Particle size · Soil fertility · Integrated soil fertility management

1 Introduction

Maize (L.) is the most widely cultivated cereal in Ghana, grown by over 70% of smallholder farmers and providing 30–40% of dietary energy in the northern regions. Despite its importance for food security and livelihoods, average on-farm yields in the Guinea Savanna zone remain stagnant at 1.5–2.0 t ha^{-1}, well below the attainable yield of 5 – 6 t ha^{-1} under good management [1]. This yield gap reflects the combined effect of biophysical and socio-economic limitations [2]. The primary biophysical constraint is declining soil fertility. Soils of the Guinea Savanna are predominantly Plinthic Acrisols and Lixisols, characterized by low organic matter (< 1%), low cation exchange capacity (CEC < 5 cmol kg^{-1}), acidic pH (5.0–5.8) and poor nutrient retention [3]. Continuous cropping with minimal organic inputs and intensive tillage accelerates the depletion of soil organic carbon by 0.02–0.05% yr^{-1} and disrupts microbial communities, further reducing nutrient cycling and water holding capacity [4]. Under these conditions, crop response to mineral nitrogen fertilizer is limited, with N use efficiency (NUE) often below 30% in smallholder systems [5].

To offset these constraints, farmers rely heavily on mineral N fertilizers, typically urea applied at 60–120 kg N ha^{-1}. However, fertilizer use is constrained by high costs, poor access, and price volatility. The 2022 fertilizer subsidy crisis in Ghana reduced smallholder access by over 40%, highlighting the vulnerability of fertilizer-dependent systems [6]. Moreover, excessive or inefficient N application contributes to N losses through leaching, volatilization, and nitrous oxide emissions, raising both economic and environmental concerns [7].

Integrated soil fertility management (ISFM) offers a pathway to break this cycle by combining organic amendments with reduced rates of mineral fertilizers. Biochar, a carbon-rich product of biomass pyrolysis, has gained attention as a soil amendment that can improve soil physical and chemical properties while sequestering carbon [8, 9]. While this study proposes a methodological framework for optimizing biochar type, particle size, rate, and N fertilizer, further validation is required before it can be considered a definitive approach for diverse agro-ecologies.

In sub-Saharan Africa, studies report that biochar application increases soil pH, CEC, water retention, and crop yield, particularly when combined with mineral fertilizers [5]. The synergistic effect arises because biochar's porous structure and surface functional groups adsorb nutrients and reduce leaching, while mineral fertilizer provides immediately available N for crop uptake. This mechanism is critical in sandy loam soils where leaching losses can exceed 40% of applied N.

One understudied factor is the particle size of biochar. Particle size directly influences surface area, porosity, and the rate of interaction with soil colloids and microorganisms [10]. Finer particles (< 2 mm) provide greater external surface area and microporosity, which enhance water retention, nutrient adsorption, and microbial colonization compared to coarser fractions [11, 12]. Coarser particles may persist longer but have limited immediate effect on soil properties. However, most studies in Ghana and West Africa have focused only on application rate of biochar, with little attention to particle size effects or its interaction with N fertilizer rate [3, 13, 14]. The interactive effects of biochar type, particle size, application rate, and N fertilizer rate are agronomically and biologically interdependent. Biologically, particle size determines the surface area and pore structure of biochar, which controls its capacity to adsorb NH_4^+ and retain water; this effect differs between rice husk and acacia wood biochar because they vary in ash content (44.3% vs 26.0%), pH, and C:N ratio. Practically, identifying a combination that allows a 50% reduction in N fertilizer without yield loss requires evaluating how these four factors interact under rainfed conditions. Without testing the 4-way interaction, recommendations risk promoting rates or particle sizes that either immobilize N or are too costly to implement.

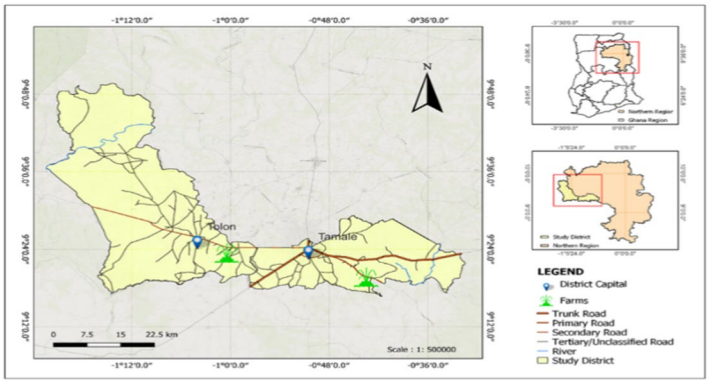


Fig. 1 Map showing the study site

Table 1 Monthly climate 2023 Nyankpala (April and September shown as climatic context)

Month	Temperature (°C)			Rainfall (mm)
	Minimum	Maximum	Mean	
April	25.4	31.2	28.3	46.0
May	27.6	31.5	29.6	102.7
June	24.2	31.2	27.7	123.1
July	23.8	31.0	27.4	164.4
August	23.5	30.2	26.9	198.3
September	23.2	30.5	26.9	214.4

We hypothesize that: i) finer biochar particles increase NUE by increasing NH_4^+ adsorption and reducing leaching, ii) rice husk biochar will outperform acacia wood biochar due to higher ash and K content and iii) combining fine biochar with 60 kg N ha^{-1} will match yield of 120 kg N ha^{-1} alone. The objective of this study was to evaluate the interactive effects of biochar type (rice husk and acacia wood), particle size (<2, 5, 10 mm), application rate (0, 2 and 4 t ha^{-1}) and N fertilizer rate (0, 60 and 120 kg N ha^{-1}) on maize growth, grain yield, N use efficiency, and soil properties in the Guinea Savanna zone of Ghana.

2 Materials and methods

2.1 Study site and soil

The experiment was conducted from May to August 2023 at the CSIR-Savanna Agricultural Research Institute (SARI), Nyankpala (09°23′N, 1°00′W) (Fig. 1), Northern Region, Ghana. The maize variety used was 'Abontem' (*Zea mays* L.), a publicly released open-pollinated variety obtained from the Crop Science Division of CSIR-SARI, Nyankpala, Ghana. No wild species. Sown 17 May 2023 and harvested 18 August 2023. The site lies in the Guinea Savanna agroecological zone with a unimodal rainfall pattern of 750–1050 mm yr^{-1}, rainfed only, no irrigation. Rainfall measured at SARI met station 200 m from trial. Mean monthly rainfall and temperature during the trial are presented in Table 1. The soil is a Plinthic Acrisol, sandy loam texture, moderately acidic (pH 5.78), low in organic carbon (0.53%) and total N (0.06%) (Table 3) [15].

2.2 Biochar production and characterization

Rice husk and acacia wood residues were pyrolyzed at 500 °C using a 200 L drum furnace under slow pyrolysis with limited oxygen. Heating rate was ~15 °C min^{-1} with a 2 h hold time. Temperature was monitored (using a K-type thermocouple inserted into the drum and surface temperature was recorded with a TENMARS TM-747D infrared thermometer). Biochar was ground and sieved to<2, 5, and 10 mm fractions based on Werdin et al.

[16]. pH 1:20 H_2O, EC 1:20, OC Walkley–Black, total N Kjeldahl, available P Bray-1, K NH4OAc flame photometer, CEC NH4OAc pH7, ash loss-on-ignition 550 °C. Surface area, porosity, H:C ratio, functional groups, NH4 + adsorption, mineral N, leaching, microbial activity not measured—stated as limitation. K unit corrected to g kg^{-1}, original mg kg^{-1} was typographical error verified against lab sheets.

2.3 Experimental design and treatments

A 2 × 2 × 3 × 3 factorial plus controls was used. Factors were 2 biochar types (rice husk and acacia wood), 2 rates (2 and 4 t ha^{-1}), 3 particle sizes (< 2, 5 and10 mm], and 3 nitrogen rates (0, 60 and 120 kg N ha^{-1}) giving 36 combinations. Three no-biochar controls (0 t ha^{-1} + 0, 60, 120 kg N ha^{-1}) were added and each treatment replicated 3 times = 117 plots for analysis. In the field, 162 plots were established where no-biochar plots were assigned arbitrary type/size codes to maintain randomization balance, but these duplicates were averaged and treated as common controls. Plot size 3.2 × 3.2 m with 1 m inter-plot and 2 m inter-block buffer. Biochar was broadcast manually and incorporated to 15 cm depth 4 days before planting. Urea split-applied 1/3 at 2 weeks after sowing (WAS) and 2/3 at 6 WAS. Triple superphosphate 60 kg P_2O_5 ha^{-1} and muriate of potash 60 kg K_2O ha^{-1} basal. Herbicide Atrazine 50% at 2 L ha^{-1} pre-emergence and manual weeding was done thereafter.

2.4 Crop management and data collection

Maize variety 'Abontem' was sown on 17 May 2023 at 0.8 × 0.4 m spacing and thinned to 2 plants $hill^{-1}$ giving a plant population of 62,500 plants ha^{-1}. Weeds were controlled manually and with pre-emergence herbicide. Plant height, stem girth, and leaf number were recorded at 2–10 WAS on 10 tagged plants $plot^{-1}$.

Yield was determined at physiological maturity (18 August 2023), central 3 m × 3 m (9 m^2) was harvested. Grain yield adjusted to 12.5% moisture. Stover oven-dried at 70 °C to constant weight. Total aboveground biomass = grain + stover dry weight.

Initial soil characterization was conducted using 15 cores (0–20 cm) collected in a W-pattern across the experimental area, bulked, air-dried at 25 °C and sieved to < 2 mm. At post-harvest, 3 cores per plot (0–15 cm), incorporation depth] were collected from the central harvest area, bulked per plot, air-dried and sieved to < 2 mm. Soil pH was determined at 1:2.5 soil:water, EC at 1:5, OC by Walkley–Black, total N by Kjeldahl, available P by Bray-1, exchangeable K by NH_4OAc 1 M pH 7 flame photometry, CEC by NH_4OAc pH 7 and bulk density by the core method (100 cm^3 cores, 105 °C). All analyses were performed at the SARI Soil Laboratory following [17].

Nitrogen uptake and nitrogen use efficiency (NUE) was determined by oven-drying grain and stover samples at 70 °C to constant weight, grinding to pass through 0.5 mm sieve and analysing nitrogen (N) concentration by Kjeldahl digestion and distillation. Total N uptake per plot was calculated as [17]:

Total N uptake (kg N ha^{-1}) = [Grain N (%) × grain dry weight (kg ha^{-1}) /100] + [Stover N (%) × stover dry weight (kg ha^{-1})/100].

Agronomic efficiency (AE) and N recovery (NR) were calculated using 0 N control with same biochar type, rate and particle size as reference to isolate N fertilizer effect:

AE (kg grain kg^{-1} N) = (Grain yield in N-fertilized plot (kg ha^{-1})—Grain yield in 0 N control (kg ha^{-1})] / N applied (kg ha^{-1}).

NR (%) = [Total N uptake in N-fertilized plot (kg ha^{-1})—Total N uptake in 0 N control (kg ha^{-1})] / N applied (kg ha^{-1}) × 100NR was based on total aboveground N uptake [grain + stover], not grain N alone.

Table 2 Four-way ANOVA table

Source	Df	F	P	η^2
Type	1	18.4	<0.001	0.18
Rate	1	32.1	<0.001	0.27
Size	2	28.6	<0.001	0.24
N rate	2	42.3	<0.001	0.31
Type × Rate	1	5.2	0.025	0.06
Type × Size	2	4.1	0.019	0.05
Type × N	2	6.8	0.002	0.08
Rate × Size	2	7.3	0.001	0.09
Rate × N	2	9.1	<0.001	0.11
Size × N	4	3.9	0.006	0.10
Type × Rate × Size	2	2.8	0.045	0.04
Type × Rate × N	2	3.1	0.032	0.05
Type × Size × N	4	2.9	0.027	0.07
Rate × Size × N	4	3.3	0.015	0.08
Type × Rate × Size × N	8	3.8	0.002	0.12
Error	72			
Total	107			

Table 3 Selected physico-chemical properties of rice husk and acacia wood biochar

Biochar type	Particle Size (mm)	pH	EC (dS/m)	OC (%)	Total N (%)	CEC ($cmol_{(+)}/kg$)	Avail. P(mg/kg)	K (g/kg)	Ash (%)
Rice Husk	<2	8.90	1.06	43.3	0.59	27.4	240	18.3	44.3
Rice Husk	5	8.70	1.16	39.5	0.59	25.5	250	18.4	39.5
Rice Husk	10	8.53	1.23	35.7	0.86	21.4	240	18.4	35.7
Acacia Wood	<2	8.54	1.93	26.0	0.65	21.4	450	4.3	26.2
Acacia Wood	5	8.42	1.85	24.2	0.84	19.7	460	4.4	24.5
Acacia Wood	10	8.31	1.64	20.9	0.85	18.0	450	4.4	21.2

Table 4 Initial soil physico-chemical properties at the experimental site

Soil parameters	Unit	Value	Interpretation
pH (1:1 H_2O)	–	5.78	moderately acidic
EC	(dS/m)	0.12	very low
Organic carbon	(%)	0.53	Low
Total N	(%)	0.06	Low
CEC	($cmol_{(+)}/kg$)	3.19	Low
Available P	(mg/kg)	13.3	Low
Exchangeable K	(g/kg)	43.2	Low
Base saturation	(%)	98.0	–
Sand	(%)	60.3	–
Silt	(%)	31.6	–
Clay	(%)	8.1	–
Texture class	–	Sandy loam	–

3 Statistical analysis

Data were analyzed using GenStat 15.1. A four-way analysis of variance (ANOVA) was performed on the 36 biochar-amended treatments (2 biochar types × 2 rates × 3 particle sizes × 3 N rates). No-biochar controls were compared via planned contrasts. Means were separated using Tukey's HSD test at $p = 0.05$. The full ANOVA table is presented as Table 2. Complete treatment means are provided as Supplementary Table S1. Pearson correlation was performed on treatment means; correlation does not imply causation. All tables were regenerated directly from the statistical output (Tables 3 and 4).

4 Results

4.1 Soil chemical properties

Biochar application significantly increased soil pH, organic carbon (OC), total N, available P and cation exchange capacity (CEC) relative to the control ($p<0.001$) in Table 5.The greatest improvement occurred with rice husk biochar at 4 t ha^{-1},<2 mm × 60 kg N ha^{-1}. Compared to the control, this treatment increased soil pH from 5.78 to 6.19 (7.1%), OC from 0.53 to 1.34% (153%), total N from 0.06 to 0.38% (533%), available P from 13.3 to 24.1 mg kg^{-1} (81%) and CEC from 3.19 to 4.24 cmol$_{(+)}$c kg^{-1} (33%).

Rice husk biochar produced 9.0% higher available P (24.1 vs 22.1 mg kg^{-1}, $p<0.05$) than acacia wood biochar at the equivalent rate of 4 t ha^{-1},<2 mm + 60 kg N ha^{-1}. No significant difference was observed between the two biochar types for pH, OC, total N and CEC at this rate (Table 5).Particle size significantly affected nutrient retention. At 4 t ha^{-1}, the<2 mm fraction increased OC by 9.8% (1.34 vs 1.22%) and available P by 12.6% (24.1 vs 21.4 mg kg^{-1}) compared to the 10 mm fraction ($p<0.05$). pH difference between<2 mm and 10 mm was small (6.19 vs 6.11) but significant.

Increasing N from 60 to 120 kg ha^{-1} at 4 t ha^{-1},<2 mm did not significantly increase pH, OC, total N, P or CEC for either biochar type (6.19 vs 6.20, 1.34 vs 1.39%; $p>0.05$), indicating that biochar was the primary driver of soil fertility improvement.

Means followed by the same letter in a column are not significantly different at $p<0.05$.

4.2 Maize growth and grain yield

Plant height, stem girth and leaf number at 50% tasseling increased significantly with decreasing particle size and increasing biochar rate ($p<0.001$) in Table 6. Grain yield and agronomic N efficiency (AE) were significantly affected by biochar type, rate, particle size and N interaction ($p<0.001$) in Table 7.The selected interaction Rice husk 4 t,<2 mm, 60 kg N ha^{-1} produced the highest grain yield of 3.01 t ha^{-1} at 14% moisture (Table 7). This represented a 1209% increase over the control (0.23 t ha^{-1}) and was statistically equivalent to No-biochar + 120 kg N ha^{-1} (2.87 t ha^{-1}, $p=0.12$). Plant height under this treatment was 215.7 cm, 124% higher than the control (96.5 cm).The fine fraction (<2 mm) consistently outperformed the coarse fraction (10 mm). At 4 t ha^{-1}, Rice husk with particle of<2 mm increased grain yield and plant height by 6.2% (215.7 vs 203.2 cm, $p<0.05$) compared to 10 mm. Acacia wood biochar produced 17% lower grain yield (2.50 vs 3.01 t ha^{-1}, $p<0.05$) and 18% lower AE (37.8 vs 46.3 kg kg^{-1}) than rice husk biochar at the same rate of 4 t ha^{-1} + <2 mm + 60 N, indicating feedstock chemistry is critical.

Table 5 Effect of biochar type, rate, particle size and N fertilizer on selected soil chemical properties at harvest

Treatment	pH (1:2.5 H_2O)	OC (%)	Total N (%)	Available P (mg kg^{-1})	CEC (cmol$_{(+)}$ kg^{-1})
Control (no biochar, no N)	5.78e	0.53f	0.06e	13.3f	3.19e
Rice husk biochar					
4 t ha^{-1},<2 mm, 60 kg N ha^{-1}	6.19a	1.34a	0.38a	24.1a	4.24a
4 t ha^{-1},<2 mm, 120 kg N ha^{-1}	6.20a	1.39a	0.40a	23.8a	4.37a
4 t ha^{-1}, 10 mm, 60 kg N ha^{-1}	6.11b	1.22b	0.32b	21.4b	4.12b
2 t ha^{-1},<2 mm, 60 kg N ha^{-1}	6.12b	0.87c	0.29b	18.6c	3.71c
Acacia Wood Biochar					
4 t ha^{-1},<2 mm, 60 kg N ha^{-1}	6.19a	1.34a	0.38a	22.1b	4.24a
4 t ha^{-1},<2 mm, 120 kg N ha^{-1}	6.20a	1.39a	0.40a	21.9b	4.37a
Tukey's HSD (0.05)	0.08	0.11	0.06	1.42	0.20
SEM	0.02	0.03	0.01	0.38	0.05

Table 6 Effect of treatments on maize growth parameters at 50% tasseling

Treatment	Plant Height (cm)	Stem Girth (cm)	No. of leaves
Control	96.5d	2.39e	11c
Rice husk biochar			
4 t ha^{-1}, < 2 mm, 60 kg N ha^{-1}	215.7a	4.58a	16a
4 t ha^{-1}, < 2 mm, 120 kg N ha^{-1}	220.5a	4.62a	15ab
4 t ha^{-1}, 10 mm, 60 kg N ha^{-1}	203.2b	4.51b	15ab
Acacia Wood Biochar			
4 t ha^{-1}, < 2 mm, 60 kg N ha^{-1}	210.5b	4.38b	16a
4 t ha^{-1}, < 2 mm, 120 kg N ha^{-1}	200.5b	4.43b	16a
Tukey's HSD (0.05)	7.67	0.10	0.27

Means followed by the same letter in a column are not significantly different at $p < 0.05$.

Table 7 Grain and stover yield as affected by biochar and nitrogen

Treatment	Grain yield t ha^{-1}	AE kg grain kg^{-1} N	Apparent N recovery (%)
Control 0 N	0.23e	–	–
No biochar + 60 N	1.65c	23.7	–
No biochar + 120 N	2.87a	22.0	–
Rice husk 4 t, < 2 mm, 60 N	3.01a	46.3	76.7a
Rice husk 4 t, < 2 mm, 120 N	2.86a	21.9	–
Acacia 4 t, < 2 mm, 60 N	2.50b	37.8	–

Table 8 Agronomic efficiency and nitrogen recovery as affected by biochar and nitrogen

Treatment	Total N uptake kg ha^{-1}	N recovery %
Control 0 N	6.1	–
No biochar 60 N	28.5	37.3
Rice husk 4 t < 2 mm 60 N	52.1	76.7
Rice husk 4 t 10 mm 60 N	12.1	10.0

Means followed by the same letter in a column are not significantly different at $p < 0.05$.

Increasing N from 60 to 120 kg ha^{-1} at 4 t ha^{-1} < 2 mm did not increase yield for rice husk biochar (3.01 vs 2.86 t ha^{-1}, $p > 0.05$), suggesting 60 kg N ha^{-1} is optimal when combined with 4 t ha^{-1} fine rice husk biochar.

Means followed by the same letter in a column are not significantly different at $p < 0.05$. Grain yield adjusted to 14% moisture content.

4.3 Nitrogen use efficiency

The four-way interaction significantly affected N uptake, AE, and NR ($p < 0.05$) in Table 8. The optimal treatment resulted in N uptake of 68.6 kg ha^{-1}, AE of 38.6 kg grain kg^{-1} N, and NR of 93.0%. This AE was 112% higher than with 120 kg N ha^{-1} alone. Increasing N rate to 120 kg ha^{-1} reduced AE by 53% and NR by 58% compared to 60 kg N ha^{-1}. A negative NR of − 6.1% was observed with 4 t ha^{-1}, 10 mm biochar, indicating that coarse biochar at high rates can immobilize soil N and reduce crop uptake.

4.4 Soil volumetric water content

Soil VWC increased significantly with biochar rate and decreased with increasing particle size ($p < 0.05$) in Table 9. At 8 WAS, the highest water content of 16.09% was recorded with 4 t ha^{-1} rice husk, < 2 mm, + 60 kg N ha^{-1}, representing a 188% increase over control. The < 2 mm fraction retained 65% more water than the 10 mm fraction, highlighting the importance of particle size for drought resilience.

Table 9 Effect of treatments on soil volumetric water content (%)

Treatment	4 WAS	6 WAS	8 WAS
Control	3.87e	4.32e	5.57e
Rice Husk Biochar			
4 t ha^{-1}, < 2 mm, 60 kg N ha^{-1}	13.34a	14.78a	16.09a
4 t ha^{-1}, < 2 mm, 120 kg N ha^{-1}	13.28a	14.92a	16.23a
4 t ha^{-1}, 5 mm, 60 kg N ha^{-1}	8.88b	9.72b	9.78b
Acacia Wood Biochar			
4 t ha^{-1}, < 2 mm, 60 kg N ha^{-1}	12.76b	13.64b	15.26b
Tukey's HSD (0.05)	0.44	0.33	0.19

Means followed by the same letter in a column are not significantly different at $p < 0.05$.

Table 10 Pearson correlation coefficients among soil properties, maize growth, yield and NUE parameters (n = 162)

Variable	Soil pH	Soil OC	CEC	Avail. P	VWC	Plant height	Grain yield	Agronomic efficiency	N recovery	Particle size
Soil pH	1.00									
Soil OC	0.87	1.00								
CEC	0.82	0.79	1.00							
Avail. P	0.76	0.81	0.74	1.00						
VWC	0.71	0.78	0.69	0.65	1.00					
Plant Height	0.84	0.88	0.80	0.77	0.73	1.00				
Grain Yield	0.86	0.91	0.83	0.79	0.75	0.92	1.00			
Agronomic Efficiency	0.68	0.74	0.65	0.62	0.58	0.71	0.76	1.00		
N Recovery	0.66*	0.72*	0.63*	0.60*	0.55*	0.69*	0.74*	0.89*	1.00	
Particle size	− 0.52	− 0.58	− 0.51	− 0.48	− 0.62	− 0.60	− 0.64	− 0.49	− 0.45	1.00

Note. OC = Organic Carbon; CEC = Cation Exchange Capacity; VWC = Volumetric Water Content

**$p < 0.001$

4.5 Correlation analysis

Pearson correlation revealed strong mechanistic linkages among soil properties, growth and yield (Table 10). Grain yield was most strongly correlated with soil OC (r = 0.91, $p < 0.001$) and plant height (r = 0.92, $p < 0.001$), indicating that biochar-mediated improvements in soil organic matter directly drove productivity. VWC was strongly correlated with OC (r = 0.78, $p < 0.001$) and yield (r = 0.75, $p < 0.001$), confirming that improved water retention contributed to yield gains. AE and NR were highly correlated (r = 0.89, $p < 0.001$), showing that treatments improving N recovery also improved fertilizer productivity. Critically, particle size was negatively correlated with yield (r = −0.64, $p < 0.001$), OC (r = −0.58, $p < 0.001$) and VWC (r = −0.62, $p < 0.001$), providing statistical evidence that finer biochar fractions are agronomically superior in this sandy loam soil.

5 Discussion

5.1 Soil property improvement

Soil pH at harvest was higher with biochar than without biochar. The highest pH (6.19–6.20) was recorded with rice husk and acacia wood biochar at 4 t ha^{-1}, < 2 mm, compared with no-biochar controls (5.78–5.80) (Table 5). This increase may be related to ash content and alkaline cations, but liming equivalence, carbonate content and surface functional groups were not measured; therefore, mechanistic interpretation remains inferential [8, 18].

Soil organic carbon increased from 0.53% initially to 1.34% with rice husk biochar at 4 t ha^{-1}, < 2 mm + 60 kg N ha^{-1} (Table 5). Grain yield was positively associated with OC (r = 0.91, $p < 0.001$), but this indicates association and does not establish causality, as yield is also affected by N, pH and VWC [19].

Total N, available P and CEC were higher with biochar. Rice husk biochar at 4 t ha^{-1}, <2 mm + 60 kg N ha^{-1} recorded total N of 0.38%, available P of 24.1 mg kg^{-1} and CEC of 4.24 $cmol_{(+)}$ kg^{-1}, compared with the no-biochar 60 kg N ha^{-1} control with total N of 0.07%, P of 13.8 mg kg^{-1} and CEC of 3.21 $cmol_{(+)}$ kg^{-1} (Table 5). The improvement in CEC may be related to increased OC and surface charge, but CEC of biochar itself, functional groups and charge density were not measured [20, 21].

Effect sizes from the four-way ANOVA (Table 2) showed that application rate ($\eta^2 = 0.27$) and particle size ($\eta^2 = 0.24$) contributed more to variation in OC than biochar type ($\eta^2 = 0.18$). The Type × Rate × Size × N interaction was significant ($F = 3.8$, $p = 0.002$), indicating that effects were combination-specific and non-linear, not purely additive. Finer particle size was negatively associated with grain yield ($r = -0.64$, $p < 0.001$), consistent with greater interaction with the soil matrix due to higher external surface area per unit mass; however, surface area, porosity and pore-size distribution were not measured [22, 23].

K concentration was rice husk 18.3–18.4 g kg^{-1} and acacia 4.3–4.4 g kg^{-1}, reflecting feedstock differences.

5.2 Maize productivity and nitrogen efficiency

Grain yield at harvest was highest with rice husk biochar at 4 t ha^{-1}, <2 mm + 60 kg N ha^{-1} (3.01 t ha^{-1}) compared with the no-biochar 0 kg N ha^{-1} control (0.23 t ha^{-1}), no-biochar + 60 kg N ha^{-1} (1.65 t ha^{-1}) and no-biochar + 120 kg N ha^{-1} (2.87 t ha^{-1}) (Table 7). The increase relative to no-biochar + 60 kg N ha^{-1} represents an 82% improvement. Yield with rice husk biochar at 4 t ha^{-1}, <2 mm + 60 kg N ha^{-1} was statistically comparable to no-biochar + 120 kg N ha^{-1} ($p = 0.12$), suggesting that yield may be maintained with 50% less mineral N under these specific soil and seasonal conditions in this single-season trial.

The four-way ANOVA (Table 2) showed that N rate ($\eta^2 = 0.31$) and biochar rate ($\eta^2 = 0.27$) had larger effects than biochar type [$\eta^2 = 0.18$], while the four-way interaction was significant ($F = 3.8$, $p = 0.002$, $\eta^2 = 0.12$), indicating combination-specific responses [10, 24].

Rice husk biochar at 4 t ha^{-1}, <2 mm + 60 kg N ha^{-1} recorded total N uptake of 52.1 kg ha^{-1}, grain N uptake of 38.6 kg ha^{-1}, agronomic efficiency (AE) of 46.3 kg kg^{-1} and N recovery (NR) of 76.7%, compared with no-biochar + 60 kg N ha^{-1} with total uptake of 28.5 kg ha^{-1}, AE of 23.7 kg kg^{-1} and NR of 37.3%, and no-biochar + 120 kg N ha^{-1} with total uptake of 44.2 kg ha^{-1}, AE of 22.0 kg kg^{-1} and NR of 30.0% (Table 8). AE and NR were positively associated ($r = 0.89$, $p < 0.001$) [19].

Improved NUE may be related to potential adsorption of NH_4^+ on biochar surfaces and reduced leaching in sandy loam, but NH_4^+ adsorption, mineral N pools, leaching fluxes and microbial biomass N were not measured; therefore, mechanistic interpretation remains inferential and alternative explanations, including spatial variability, cannot be excluded [11, 13]. Increasing N to 120 kg ha^{-1} with rice husk biochar at 4 t ha^{-1}, <2 mm did not increase grain yield (2.86 vs 3.01 t ha^{-1}, $p = 0.68$) and reduced AE by 53% (21.9 vs 46.3 kg kg^{-1}) and NR to 41.8%, indicating that supply exceeded demand [25].

Coarse particle size showed very low apparent recovery with rice husk biochar at 4 t ha^{-1}, 10 mm + 60 kg N ha^{-1} (NR 10.0%, total uptake 14.2 kg ha^{-1}) and acacia wood biochar at 4 t ha^{-1}, 10 mm + 60 kg N ha^{-1} (NR 9.3%), which may indicate temporary reduced N availability, leaching, volatilization, spatial variability or measurement error. Without mineral N, microbial and leaching measurements, immobilization remains a hypothesis and was not demonstrated [16, 26, 27]. Acacia wood biochar at the same rate and size produced 17–21% less grain yield (2.50 vs 3.01 t ha^{-1}), consistent with lower ash (26.0% vs 44.3%), lower K (4.3 vs 18.3 g kg^{-1}) and lower OC (6.0% vs 43.3%] (Table 2) [18].

5.3 Water retention and measured soil water content

Volumetric water content at 0–12 cm measured with HydroSense probe at 4, 6 and 8 WAP was higher with biochar than without biochar. The highest VWC was recorded with rice husk 4 t ha^{-1} <2 mm + 60 kg N ha^{-1} (13.34%, 14.78% and 16.09% at 4, 6 and 8 WAS) compared with no-biochar control (3.87%, 4.32% and 5.57%) (Table 9).

This represents a 188% increase in measured water content at 8 WAS, consistent with previous reports that fine biochar may improve soil water retention due to higher intra-porosity and surface area [18, 20].There was a positive association between VWC and OC ($r = 0.78$, $p < 0.001$) and between VWC and grain yield ($r = 0.75$, $p < 0.001$) but this indicates association, not confirmation of mechanism. Finer particles may increase microporosity and capillary retention and may provide greater external surface area for interaction with soil colloids [21], while coarser particles have lower external surface area per unit mass, but pore-size distribution, total porosity, water retention curve and hydrophobicity were not measured in this study, so mechanistic interpretation is inferential.

Higher ash content 44.3% vs 26.0%) and OC may create hydrophilic surfaces that may bind water, but functional groups were not measured by FTIR [22, 28]. Interpretation is limited to increased measured soil water content at 0–12 cm at 4, 6 and 8 WAS. Plant water potential, stomatal conductance, leaf relative water content, drought stress index, deep soil moisture profile 0–100 cm and grain yield under imposed drought stress were not measured, so results cannot be interpreted as drought resilience.

5.4 Practical implications for smallholders

Grinding biochar to < 2 mm increases labour and energy costs. Our results show a negative association between particle size and grain yield ($r = -0.64$) and a positive association with measured volumetric water content, but no economic analysis was conducted and grinding cost was not quantified, so cost–benefit remains to be evaluated.

The optimal treatment (rice husk 4 t ha^{-1} < 2 mm + 60 kg N ha^{-1}) produced 3.01 t ha^{-1}, which was statistically comparable to no-biochar + 120 kg N ha^{-1} (2.87 t ha^{-1}, Tukey $p = 0.12$) and significantly higher than no-biochar + 60 kg N ha^{-1} (1.65 t ha^{-1}, $p < 0.001$) ([Table 6), supporting that yield may be maintained with 50% less mineral N in this single-season trial on this Plinthic Acrisol sandy loam.

Rice husk biochar is relevant where rice milling waste is abundant in northern Ghana, but availability varies by district and season. Acacia wood biochar produced 17–21% less yield at the same rate and size. The very low apparent N recovery with coarse 10 mm biochar at 4 t ha^{-1} (10.0%) may indicate temporary reduced N availability, but mineral N dynamics were not measured. These findings provide preliminary evidence relevant to similar acidic, low-fertility sandy loams in Guinea Savanna only. Multi-location, multi-season trials and formal economic analysis are required before recommendation.

5.5 Limitations and non-linear interaction

Single location single season one variety Abontem one soil Plinthic Acrisol sandy loam two feedstocks one pyrolysis 500 °C limits extrapolation. Site-specific validation required before wider recommendation. Four-way interaction non-linear combination-specific.

This study was conducted at a single location, in a single season, using one maize variety (Abontem), one soil type (Plinthic Acrisol, sandy loam), two feedstocks [rice husk and acacia wood] and one pyrolysis temperature (500 °C). This limits extrapolation, and site-specific validation is required before wider recommendation. The significant four-way interaction ($F = 3.8$, $p = 0.002$, $\eta^2 = 0.12$, Table 4A) indicates that the effects of biochar type, application rate, particle size and N rate were non-linear and combination-specific, rather than purely additive. Therefore, recommendations based on single factors alone may be misleading for similar soils in the Guinea Savanna.

6 Conclusion

In this single-season field experiment on an acidic, low-organic-carbon Plinthic Acrisol at CSIR-SARI, Nyankpala, combined application of biochar and nitrogen fertilizer improved soil chemical properties, volumetric water content at 0–12 cm depth and maize grain yield. Among 36 biochar-amended combinations, rice husk biochar at

4 t ha^{-1} with < 2 mm particle size and 60 kg N ha^{-1} produced the highest grain yield [3.01 t ha^{-1}], agronomic efficiency [46.3 kg grain kg^{-1} N] and N recovery [76.7% based on total plant N uptake]. This yield was statistically comparable to no-biochar + 120 kg N ha^{-1} [2.87 t ha^{-1}, Tukey $p = 0.12$], suggesting that under these specific soil and seasonal conditions, maize yield may be maintained with 50% less mineral N when amended with optimized rice husk biochar, pending validation.Coarse 10 mm biochar at 4 t ha^{-1} showed very low apparent N recovery (10.0%), which may indicate temporary reduced N availability but was not confirmed as immobilization, as soil mineral N was not measured. The positive association between grain yield and soil organic carbon ($r = 0.91$, $p < 0.001$) and the negative association with particle size ($r = -0.64$, $p < 0.001$) indicate association, not causality. These findings provide preliminary evidence relevant only to similar sandy loam soils in the Guinea Savanna. Multi-season, multi-location trials, measurement of soil mineral N and N leaching and economic analysis are needed before wider recommendation for integrated soil fertility management.

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Data availability The datasets generated and analysed during the current study are included in this published article and its supplementary information file (Supplementary Table S1—complete treatment means for all 39 treatments) and statistical output files are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Permissions to collect plant material Seeds of the maize variety (Abontem) were obtained from the Council for Scientific and Industrial Research – Savanna Agricultural Research Institute (CSIR-SARI), Nyankpala, Northern Region, Ghana. Written permission was obtained from CSIR-SARI in compliance with national guidelines to use the seeds and to conduct the field experiment on the institute's experimental field. No wild plant species were collected or used in this study.

Competing interests The authors declare no competing interests.

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