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Soil fertility and plantain productivity enhancement using potassium-rich biochar and wood-ash source

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ABSTRACT

Soil fertility depletion in Nigeria has spurred the search for effective soil fertilization strategies to support optimal plantain productivity. This study assessed wood-ash (WA) and biochar (BC) as natural potassium (K) fertilizer sources to enhance soil fertility and the performance of 'agbagba' plantain (*Musa paradisiaca* L.). The study evaluated the combined and separate effects of BC and WA fertilization on soil properties, plantain growth and yield, sucker multiplication, phenology, and proximate composition. Treatments included single applications of 2 kg WA or 2 kg BC, combined applications of 2 kg WA + 2 kg BC or 1 kg WA + 1 kg BC, and an unfertilized control. Approximately 200 kg/ha of NPK 20:10:10 fertilizer was incorporated into all treatments and the control as a nitrogen supplement. The study revealed that WA and BC, applied individually or in combination, act as natural K fertilizers, increasing soil available K by over 298%. This improvement fostered a strong interaction between the soil amendments and plant growth-promoting rhizobacteria (PGPR), promoting the production of beneficial plant hormones like cytokinin and auxin. The resulting increases in leaf and sucker counts, leaf area, chlorophyll content, relative water content, early flowering and maturity, bunch and cluster weights, number of clusters per bunch, and fingers per cluster, alongside finger length and diameter, were attributed to improved soil availability of K, calcium, magnesium, phosphorus, organic matter/carbon, porosity, and pH, and a decrease in soil bulk density. The effects on soil and plantain productivity were greater with WA than BC, and with combined fertilization compared to sole fertilization. Furthermore, both sole and combined treatments showed a greater positive impact on the ratoon crop compared to the parent crop.

Keywords: Yield; Metabolic Energy value; Cytokinin; Ratoon; Sucker; Carbohydrate; Chlorophyll, Protein; Leaf Area

1. INTRODUCTION

In West and Central Africa, plantains (*Musa paradisiaca* L.) are a staple food, providing at least 10% of the daily calorie intake for over 70 million people (IITA

Report, 2000). They are also the third most consumed carbohydrate in Nigeria, following cassava and yam (Akinyemi et al., 2010). The parthenocarpic fruit of plantain is notable for its rich nutritional content, providing the body with appreciable amounts of potassium (K), magnesium (Mg), and vitamins A, B6, and C (Adepoju et al., 2012). However, factors such as excessive local consumption and, more importantly, soil fertility depletion have limited plantain production in southwest Nigeria (Adebisi et al., 2020). Soil fertility depletion poses a serious threat to Nigeria's agricultural productivity and food security, stemming from unsustainable, intensified land use (Vanlauwe et al., 2010), high nutrient leaching (Akinrinade and Obigbesan, 2000), topsoil erosion (Sanchez, 2002), and low nitrogen (N), organic matter (OM), and organic carbon (OC) content (Obisesan, 2000). These issues result in low water and nutrient holding capacities (Mafongoya et al., 2006), compounded by practices such as bush burning, overgrazing, and soil acidification. The reliance on chemical fertilizers for soil replenishment has become unsustainable due to high costs, scarcity, and adverse effects such as soil acidification, nutrient imbalance, and pollution, as detailed by Kwayep et al., (2017). Consequently, organic fertilizers are increasingly favored as a viable alternative because of their consistent availability, affordability, ease of production, and eco-friendly characteristics.

Although local farmers in Nigeria have adopted various conventional agronomic methods involving both separate and combined fertilization with organic and inorganic fertilizers, the annual yield of heavy-feeding crops such as plantain remains sub-maximal to this day. Suggestively, the use of alternative fertilizer sources, particularly those rich in K like wood-ash (WA) and biochar (BC), could provide a solution for plantain farmers, as soil-available K significantly determines the productivity of crops in the humid tropics (Aba and Baiyeri, 2015; Sun et al., 2025). Biochar is a carbon-rich, solid by-product of the thermochemical pyrolysis of biomass materials, such as wood, sawdust, cocoa pods, banana peels, rice husks, wheat straw, corn cobs, farmyard manures, sewage sludge, and municipal waste, at high temperatures (350-900°C) in a low-oxygen environment. This carbon-rich organic product effectively amends degraded soils (Lu et al., 2012) by improving soil physicochemical properties, such as soil fertility (Graber et al., 2010), OM and OC content, and water retention (Laird et al., 2010; Ogunwole et al., 2023). Additionally, it lowers soil compaction (Laird et al., 2010) and reduces the need for synthetic fertilizers (Van Zwieten et al., 2010). Biochar is rich in plant-essential cations, and has been applied to modulate drought stress and enhance plant yield and productivity (Deenik and Cooney, 2016; Ogunwole et al., 2023). However, the effectiveness of BC as a fertilizer varies with pyrolysis temperature, biomass type, and soil type. Therefore, this study assessed the potential of WA and BC, alone and combined, as natural K fertilizers to improve plantain productivity.

Wood-ash from the complete combustion of wood is a nutrient-rich alternative to expensive chemical fertilizers, containing essential elements like K, calcium (Ca), phosphorus (P), Mg, aluminum (Al), and iron (Fe) (Gill et al., 2015). It is the oldest form of K source (Bang-Andreasen et al., 2021), and improves soil quality by raising pH, enhancing available K, and boosting microbial activity upon incorporation into the soil.

Because WA has a N deficiency, it is a minor component of overall soil fertility management. Therefore, applying WA as a fertilizer always requires supplementing it with inorganic options, such as NPK, NP, or N fertilizers, or sometimes with organic materials like poultry, rabbit, goat, sheep manure, or cow dung, to supply sufficient N to crops (Quimet and Moore, 2015). Although previous studies noted the long-term benefits of WA and BC fertilization, including fertilizer savings (Moilanen et al., 2002; Gill et al., 2015), few alternative agronomic management practices combining these materials for plantain crops exist. This study, therefore, aims to evaluate the separate and combined application of WA and BC as natural K fertilizers to enhance soil fertility and plantain performance. The study holistically assessed the impact of these separate and combined fertilization on soil physicochemical properties and nutrient availability, as well as on plantain growth, photosynthetic pigments, relative water content, sucker proliferation, days to flowering and maturity, and nutritive value.

2. MATERIALS AND METHODS

2.1. Study Location

The study site was a five-year fallow half-acre of land at the back of the Biochemistry and Microbiology building, Wesley University, Ondo, Nigeria (7°6′30″ N and 4°49′0″ E).

2.2. Analysis of Soil, Biochar, and Wood-ash

After clearing the site in May 2022, composite soil samples were collected from ten different spots at a depth of 0–10 cm. The samples were air-dried on a laboratory bench at room temperature and then crushed and sieved to pass through a 2 mm mesh. Two bags of commercial charcoal were purchased locally. One bag was crushed into a powder, designated as biochar (BC), and sieved using a <5 mm mesh. The other bag was incinerated in a local charcoal pot to produce wood-ash (WA), which was sieved using a 2 mm mesh. Key properties of the BC and WA were analyzed using standard procedures outlined by the International Institute of Tropical Agriculture (IITA, 1982) and the American Society for Testing and Materials (ASTM D1762-84).

Soil particle size was determined using the Bouyoucos hydrometer method (Sheldrick and Wang, 1993). Bulk density (Bd) was measured using the cylinder method (FAO, 2023), and total porosity was calculated from the Bd and particle density. Soil organic matter (SOM) was determined using the loss-on-ignition (LOI) method, and OC was quantified using the Walkley-Black titration method. Soil moisture content was measured by drying samples at 105 °C for 24 hours. Soil pH and electrical conductivity (EC) were measured in a 1:2 soil:water suspension with a digital pH meter and a conductivity meter, respectively (Van Reeuwijk, 1992).

After extraction with ammonium acetate (pH 7.0), exchangeable K+ was quantified with a flame photometer, and Ca^{2+} and Mg^{2+} were determined using an atomic absorption spectrometer (AAS). Total N was determined using the micro-Kjeldahl method, as described by the Association of Official Chemists (AOAC, 1990). Soil available P was extracted using the Bray-1 method and quantified spectrophotometrically at 882 nm, a method that produces a blue color. All laboratory studies were conducted in triplicates. Table 1 presents the physical and chemical properties of the soil, BC, and WA.

2.3. Planting Material and Pre-planting Operations

The planting material consisted of four-week-old suckers from the plantain cultivar *Musa paradisiaca* var. agbagba. This variety was selected for its short life cycle, high productivity, consumer demand, and nutritive value. A total of 125 uniform suckers were inspected for damage from nematodes and weevils, and any remaining debris was removed from the roots and pseudostem. The suckers then underwent mechanical scarification, which involved removing approximately three-quarters of the outer leaf sheaths to expose the lateral dormant buds. Following this, the suckers were surface-sterilized by soaking in 70% ethanol for 15 minutes, followed by a 1-hour soak in 40% Jik (1.5% sodium hypochlorite). Finally, the suckers were rinsed five times with distilled water and air-dried at room temperature for 48 hours to heal any injuries and prevent pest infestation before planting.

2.4. Experimental Design and Treatments Application.

The field trial began with planting sterilized suckers in holes measuring 40 cm × 40 cm × 40 cm (length × width × depth), one per hole. A 3m x 3m interspace was established, both between and along the rows. The experiment was a randomized complete block design set up on a half-acre of land with five sub-plots. The four treatments applied on the planting date were: fertilization with 2 kg wood-ash (WA), fertilization with 2 kg biochar (BC), combined fertilization with 1 kg each of WA and BC (WA+BC), and combined fertilization with 2 kg each of WA and BC (WA2+BC2), while the unfertilized soil (0 kg WA and/or BC) served as control. All treatments were placed in a shallow hole dug approximately 10 cm away from the root of each sucker and then watered to field capacity to minimize dust losses. Each sub-plot consisted 15 suckers, giving a total of 75 plantain stands on the cultivated land. Six weeks after planting (6 WAP), NPK 20:10:10 fertilizer was applied at the rate of 240 kg/ha to each treatment and control group. This chemical fertilizer served to supplement the soil N-pool and prevent N immobilization caused by soil microbial activity. Regular and necessary agronomic management and practices, such as weeding, pruning of dead and diseased leaves, and de-suckering to allow just one ratoon crop to succeed the parent/mother plantain, were performed throughout the experiment.

2.5. Soil and Plantain Data Collection and Analysis

Twelve weeks after planting (12 WAP), composite soil were carefully sampled from the rhizosphere region (8-12 cm from the root) of six plantain crops in each subplot using a steel cone sampler at a 0-10 cm depth, without damaging the root. A total of three collections were made at eight-week intervals; afterward, the means were calculated. The procedures and analysis for physical and chemical properties of the soil were the same as described above. Primary data collection on plantain commenced at 14 WAP. A total of five different measurements were taken on six randomly selected crops per subplot at eight-week intervals. Afterwards, the means were calculated. With a measuring tape, pseudostem height and diameter were measured from the base to the V-junction of the last two unfurled leaves, and at 10 cm from the plant's base, respectively. The leaf and sucker per plant were counted, and the days from planting to flowering and harvesting were noted. Leaf area was determined using the formula:

$$Leaf\ Area\ (cm2)\ = Leaf\ Length\ (cm) \times Leaf\ Width\ (cm) \times 0.8 \qquad \ldots\ldots\ldots\ldots(1)$$

Where 0.83 is a leaf area factor

Photosynthetic pigment analysis began when a small fraction of the third youngest, fully open leaf was excised from five plantain stands selected from each sub-plot. A total of five collections at eight-week intervals. Approximately 0.5 g of this leaf tissue was crushed and extracted in 0.5 mL 80% acetone. The solution was centrifuged at 10,000 rpm for 5 minutes, and the absorbance of the supernatant was read at 664, 647, and 470 nm. Chlorophyll a, b, chlorophyll a+b, and carotenoid in the sample were calculated using Lichtenthaler's (1987) formulae and expressed as μM g^{-1} fresh weight. Similarly a small fraction of a physiologically active leaf (as described for chlorophyll above) was used for quantifying the leaf relative water content (RWC). Twenty 0.5 cm discs were excised from each sample using a cork borer, and their weights were immediately determined with an analytical balance Then, the leaf discs were placed in plastic tubes containing 10 mL of distilled water. The content was put in a refrigerator for 24 hours. After saturation, the discs were blotted dry with tissue paper, and their turgid weights were recorded. Finally, the dry weight of the leaf discs was determined by oven-drying at 70°C for 24 hours, and the RWC was calculated as follows:

$$Relative\ Water\ Content\ (\%) = \frac{Fresh\ Weight - Dry\ Weight}{Turgid\ Weight - Dry\ Weight} \times 100 \quad \text{……………………..(2)}$$

Yield and its components were determined ten weeks post-fruiting initiation. From each treatment, five plants were sampled from each subplot. The harvested bunches were weighed to obtain the yield index. The number of clusters per bunch and fingers per cluster were counted. Finger length was measured along the concave side, and the diameter at the center of individual fruits from the second hand of the bunch was recorded to determine circumference. Total yield per cycle was calculated using the formula:

$$Total\ Yield\ (t/ha) = Bunch\ Weight\ \times Number\ of\ Harvestable\ Plantain\ \times 0.2 \quad \text{..(3)}$$

Where 0.202 is the correction factor for half acre of land area use

2.6. Proximate Composition Analysis

Plantain fruits were deemed mature when their peels displayed at least 50% yellow coloration or showed increased xanthophyll content. The sampled fruits were immediately rinsed, peeled to expose the pulp, and its fresh moisture content was determined. The remaining pulp was sliced, sun-dried for two weeks to ensure proper drying, and to prevent the loss of volatile secondary metabolites. After drying, samples were homogenized, sieved through a 0.5 mm mesh, and their crude lipid content quantified using Soxhlet extraction (Pearson, 1976). Ash, crude protein, and crude fiber contents were determined according to AOAC guidelines (1990). Carbohydrate content was calculated by subtracting the sum of protein, fat, ash, and fiber from 100g of dry matter (AOAC, 1990). The metabolic energy value was determined using the Atwater factor (FAO, 2003). All proximate content measurements were performed in six replicates.

Statistical Analyses

Statistical analyses were conducted using the General Linear Model (GLM) procedure in SPSS version 16.0. A Tukey's Honestly Significant Difference (HSD) post-hoc test was used to separate the means that showed significant differences at a 95% confidence level.

3. RESULTS

3.1. Pre-field Chemical and Physical Properties of Soil, Biochar and Wood-Ash

The pre-field analysis showed the soil was a moderately acidic loamy sand, deficient in OM, OC, N, K, Ca, and Mg, with a marginal P level (Table 1). In contrast, WA and BC had lower bulk densities but higher levels of OM, OC, pH, K, Ca, Mg, and P. The relative abundance of nutrients in both BC and WA, in decreasing order, was: Ca >> K >> Mg >> P >> N (Table 1).

3.2. Impacts of Biochar and Wood-ash on Soil Properties

The combined application of WA and BC, particularly the WA2+BC2 treatment, significantly reduced soil bulk density (Bd) and increased soil porosity (Table 2). Specifically, the WA2+BC2 treatment showed the largest Bd reduction (23.88%) and the greatest porosity increase (22.95%), while the WA-only fertilization had the least impact on these properties. All fertilized soils showed improvements in other soil properties, including soil pH, electrical conductivity (EC), moisture content, water retention capacity (WHC), organic matter (OM), organic carbon (OC), and exchangeable cations (K+, Ca2+, and Mg2+), compared to untreated soil (Table

2). The BC treatment resulted in notable increases for specific components: K+ (298.8%), OM (210.7%), OC (210.0%), Ca2+ (122.2%), P (103.0%), Mg2+ (30.4%), total N (25.0%), WHC (14.8%), moisture content (7.5%), and pH (5.1%). In contrast, the WA treatment led to more substantial increases in K+ (349.4%), Ca2+ (483.3%), P (126.0%), Mg2+ (151.9%), and total N (15.9%), but resulted in smaller gains for OM (62.7%), OC (60.0%), WHC (2.0%), moisture content (5.2%), and pH (9.3%). Applying a 1 kg mixture of WA and BC (WA+BC) improved soil properties significantly, increasing K+ by 414.4%, OM by 180.0%, OC by 179.2%, Ca2+ by 527.0%, P by 149.0%, Mg2+ by 193.9%, total N by 31.8%, WHC by 16.9%, moisture content by 8.7%, and pH by 16.6%. The 2 kg application (WA2+BC2) yielded even greater enhancements, with increases of 513.1% for K+, 256.2% for OM, 254.8% for OC, 693.7% for Ca2+, 165.0% for P, 253.0% for Mg2+, 68.2% for total N, 19.1% for WHC, 11.1% for moisture content, and 25.1% for pH. These results demonstrate that the combined application of WA and BC substantially enhanced all measured soil properties compared to either individual fertilization, with the benefits increasing proportionally to the application rate (dose-dependent).

Table 1: Pre-planting physical and chemical properties of soil, biochar and wood-ash

Medium and Soil Amendments	Sand	Clay	Silt	OM	OC	%N	MC	WHC	Ash	BD	pH	EC	K	Ca	Mg	P
	%									g/cm^{3}		dS/m	mg/kg			
Soil	84.6	2.5	12.9	5.09	2.96	0.73	30.93	31.40	nd	1.36	5.21	0.63	1.77	2.36	2.01	7.12
Biochar	na	na	na	107.28	62.3	0.66	20.9	5.71	8.79	0.47	8.23	0.42	22.42	52.3	16.4	2.31
Wood-Ash	na	na	na	20.41	11.84	0.09	0.8	2.03	94.4	0.35	10.1	0.09	14.12	111.5	11.9	4.72

Legend: BD: Bulk density, EC: Electrical conductivity, MC: Moisture content, WHC: Water retention capacity, OM: Organic Matter, OC: Organic Carbon, %N: Percentage Nitrogen, K: Potassium, Ca: Calcium, Mg: Magnesium, P: Phosphorus

Table 2: Impacts of Separate and Combined Fertilization with Wood-Ash and Biochar on Physical and Chemical Properties of Soil

Treatments	Bulk Density	pH	EC	Moisture Content	WRC	Organic Matter	Organic Carbon	Total Nitrogen	Exch. K^{+}	Exch. Ca^{2+}	Exch. Mg^{2+}	Avail. P
	g/cm^{3}		dS/m	%					mg/kg			
CONTROL	1.34+0.1^{a}	5.25+0.0^{g}	0.59+0.0^{d}	31.36+0.9^{e}	31.34+0.2^{e}	4.29+0.2^{f}	2.50+0.1^{f}	0.44+0.1^{d}	1.60+0.1^{f}	5.04+0.2^{f}	1.81+0.0^{e}	1.05+0.0^{b}
BC	1.06+0.0^{b}	5.52+0.1^{ef}	0.69+0.0^{abc}	33.70+0.4^{bc}	35.99+0.2^{c}	13.33+0.3^{bc}	7.75+0.3^{bc}	0.55+0.0^{bcd}	7.19+0.5^{cd}	11.2+0.9^{e}	2.36+0.0^{d}	2.01+0.1^{a}
WA	1.0+0.1^{b}	6.57+0.1^{a}	0.65+0.0^{bcd}	33.00+0.6^{cd}	31.98+0.1^{d}	6.89+0.3^{e}	4.01+0.4^{e}	0.51+0.1^{cd}	6.38+0.5^{de}	31.6+1.9^{c}	5.32+0.3^{b}	1.78+0.0^{b}
WA+BC	1.02+0.1^{b}	5.74+0.1^{de}	0.68+0.0^{abc}	34.08+0.1^{abc}	36.62+0.1^{b}	12.01+0.4^{cd}	6.98+0.5^{cd}	0.58+0.1^{bcd}	8.23+0.4^{bc}	29.4+0.6^{cd}	4.56+0.2^{c}	2.24+0.6^{a}
WA2+BC2	1.00+0.1^{b}	6.12+0.0^{bc}	0.74+0.0^{a}	34.85+0.1^{a}	37.32+0.1^{a}	15.28+0.3^{a}	8.87+0.3^{a}	0.74+0.0^{a}	9.81+0.3^{a}	40.0+1.3^{a}	6.39+0.3^{a}	2.40+0.0^{a}
F-value	1.438	68.988	11.661	24.222	619.638	152.515	155.353	9.958	104.660	378.863	198.823	23.564

* The values represent the mean + standard deviation of six replicates of each sample collected 18 months after application. Mean values with the same superscript across the same column are not significantly different at *P*<0.05. Control: Application of 0 kg of WA and/or BC; BC: application of 2 kg of BC; WA: application of 2 kg of WA; WA+BC: combined application of 1kg each of BC and WA; WA2+BC2: combined application of 2 kg each of BC and WA.

Table 3: Changes in Growth Indices, Sucker Proliferation, and Days to Flowering and Maturity of Plantain as influenced by Separate and Combined Fertilization with Wood-Ash and Biochar

Treatments	Pseudostem Height m		Pseudostem Diameter m		Number of Leaves		Days to Flowering		Days to Harvesting		Number of Suckers	
	Parent	Ratoon	Parent	Ratoon	Parent	Ratoon	Parent	Ratoon	Parent	Ratoon	Parent	Ratoon
CONTROL	1.56+0.1^{a}	2.05+0.2^{f}	60.40+9.6^{a}	68.20+2.4^{e}	9.43+0.4^{b}	10.20+0.6^{e}	387.0+7.8^{a}	384.3+8.1^{a}	459.0+8.9^{a}	457.7+11.9^{a}	3.33+0.6^{d}	4.0+1.0^{e}
BC	1.67+0.3^{a}	2.28+0.0^{ef}	62.50+1.0^{a}	71.63+0.9^{cd}	10.13+0.3^{b}	12.47+0.6^{cd}	380.3+6.0^{a}	353.7+7.5^{bc}	453.0+5.3^{a}	425.3+5.0^{bc}	5.00+1.0^{bcd}	8.7+0.6^{cd}
WA	1.77+0.1^{a}	2.49+0.0^{cde}	64.47+0.8^{a}	73.33+0.8^{bcd}	10.47+0.2^{b}	13.10+0.5^{bcd}	378.0+6.6^{a}	361.3+6.0^{ab}	453.3+3.5^{a}	431.7+8.3^{abc}	6.33+0.6^{abc}	9.3+0.6^{bcd}
WA+BC	1.72+0.0^{a}	2.60+0.1^{bcd}	63.33+0.8^{a}	73.57+1.0^{bcd}	10.40+0.1^{b}	13.80+0.5^{abc}	376.3+6.8^{a}	345.0+5.6^{bcd}	450.0+4.4^{a}	414.3+8.7^{bcd}	5.67+1.2^{bc}	9.3+0.6^{bcd}
WA2+BC2	1.89+0.1^{a}	3.15+0.2^{a}	65.67+0.4^{a}	77.20+1.4^{a}	10.90+0.7^{a}	14.90+0.3^{a}	373.3+4.9^{a}	307.0+9.2^{e}	446.3+3.2^{a}	378.0+4.6^{e}	8.00+0.0^{a}	12.3+0.6^{a}
F-value	1.728	34.568	0.686	16.383	2.052	25.960	2.449	21.248	3.385	19.846	9.900	32.788

* The values represent the mean + standard deviation of six replicates of each sample of Pseudostem Height, Diameter and Leaf Count and mean + standard deviation of fifteen replicates of samples for sucker count, and Days to Flowering and Harvesting collected at eight-week intervals from application date.

* Mean values with the same superscript across the same column are not significantly different at *P*<0.05. Control: Application of 0 kg of WA and/or BC; BC: application of 2 kg of BC; WA: application of 2 kg of WA; WA+BC: combined application of 1kg each of BC and WA; WA2+BC2: combined application of 2 kg each of BC and WA.

3.3. Growth and Physiological Attributes of Plantain as Affected by Separate and Combined Fertilization with Biochar and Wood-ash

Compared to the control, both WA applied alone and the combinations of WA with 1 kg (WA+BC) and 2 kg (WA2+BC2) of BC significantly promoted ratoon crop height, diameter, leaf, and sucker counts. In contrast, BC alone significantly increased only pseudostem diameter, leaf, and sucker counts, with a transient increase in ratoon crop height (Table 3). For parent crops, WA alone and the WA+BC and WA2+BC2 combinations showed a positive effect on sucker counts, while only the WA2+BC2 treatment promoted parent crop leaf count (Table 3). Plantain phenology indices, specifically days to flowering (DTF) and days to maturity (DTH), also decreased significantly in fertilized ratoon crops compared to unfertilized crops (Table 3). In summary, the combined applications of WA and BC were generally more effective than individual treatments for both sucker counts, and growth and phenology indices, and WA fertilization was more effective than BC fertilization (Table 3).

The impact of all treatments on plantain physiology was assessed by measuring leaf area, photosynthetic pigment content, and relative water content (Table 4). Leaf area (LA) was higher in all fertilized crops compared to unfertilized ones. Fertilization with combined WA and BC elicited a 38.5%–59.1% LA increase in the parent crop and a 48.3%–65.6% LA increase in the ratoon crop (Table 4). In contrast, BC and WA fertilization alone resulted in a 22.6% and 29.8% LA increase, respectively, in the ratoon crop. Similarly, photosynthetic pigment dynamics showed higher levels of chlorophyll a and chlorophyll a+b in fertilized crops compared to unfertilized ones (Figure 4). The trend of relative abundance for both parent and ratoon crops was: WA2+BC2 >> WA+BC >> WA >> BC >> control. Fertilization with BC and WA significantly enhanced chlorophyll b accumulation, with BC being more effective than WA (Table 4). Additionally, carotenoid content was slightly higher in fertilized crops than in unfertilized crops. Application of BC alone, as well as combined fertilization with WA and BC (WA+BC and WA2+BC2), significantly improved the leaf relative water content (RWC) in both parent and ratoon crops (Table 4). The highest increase was observed for the WA2+BC2 treatment, while WA fertilization elicited the least increase. Leaf RWC was generally higher in ratoon than parent crops, though a post-hoc test revealed no significant mean difference ($p<0.05$) among the treatments for either crop type (Table 4).

Table 4: Change in Photosynthetic Pigments and Relative Water Contents of Plantain as influenced by Sole and Combined Application of Wood-Ash and Biochar

Treatments	Leaf Area (m^2)		Chlorophyll a (μM g^{-1} FW)		Chlorophyll b (μM g^{-1} FW)		Chlorophyll a+b (μM g^{-1} FW)		Carotenoids (μM g^{-1} FW)		Relative Water Content (%)	
	Parent	Ratoon	Parent	Ratoon	Parent	Ratoon	Parent	Ratoon	Parent	Ratoon	Parent (× 10)	Ratoon (× 10)
CONTROL	$1.59+0.2^{b}$	$1.95+0.2^{d}$	$4.83+0.3^{d}$	$5.15+0.3^{d}$	$2.04+0.2^{c}$	$2.55+0.3^{c}$	$6.86+0.3^{d}$	$7.70+0.4^{d}$	$2.74+0.3^{c}$	$3.23+0.2^{b}$	$7.84+0.2^{c}$	$7.95+0.3^{c}$
BC	$1.75+0.2^{ab}$	$2.385+0.2^{cd}$	$5.00+0.4^{cd}$	$5.56+0.5^{cd}$	$2.41+0.1^{ab}$	$2.73+0.3^{bc}$	$7.42+0.4^{c}$	$8.28+0.5^{c}$	$3.52+0.2^{b}$	$3.44+0.1^{ab}$	$8.32+0.3^{bc}$	$8.59+0.2^{b}$
WA	$1.82+0.1^{ab}$	$2.525+0.1^{bc}$	$5.27+0.3^{bc}$	$5.84+0.4^{c}$	$2.55+0.2^{ab}$	$2.70+0.2^{c}$	$7.82+0.3^{b}$	$8.53+0.4^{c}$	$3.17+0.3^{bc}$	$3.36+0.2^{bc}$	$8.06+0.3^{c}$	$8.23+0.3^{c}$
WA+BC	$2.21+0.1^{a}$	$2.885+0.3^{ab}$	$5.53+0.4^{ab}$	$6.26+0.4^{b}$	$2.57+0.3^{ab}$	$2.9+0.2^{b}$	$8.09+0.2^{b}$	$9.16+0.^{b}$	$3.75+0.3^{ab}$	$3.59+0.1^{a}$	$8.64+0.4^{b}$	$8.78+0.4^{b}$
WA2+BC2	$2.53+0.2^{a}$	$3.22+0.2^{a}$	$5.88+0.4^{a}$	$6.75+0.3^{a}$	$2.70+0.2^{a}$	$3.22+0.3^{a}$	$8.58+0.4^{a}$	$9.97+0.5^{a}$	$3.79+0.2^{a}$	$3.63+0.1^{a}$	$8.99+0.3^{a}$	$9.12+0.2^{a}$

* The values represent the mean + standard deviation of five replicates of each sample collected at eight-week intervals for five weeks. Mean values with the same superscript across the same column are not significantly different at $P<0.05$. Control: Application of 0 kg of WA and/or BC; BC: application of 2 kg of BC; WA: application of 2 kg of WA; WA+BC: combined application of 1kg each of BC and WA; WA2+BC2: combined application of 2 kg each of BC and WA.

3.4. Impacts of Separate and Combined Application of Biochar and Wood-ash on Yield and Yield Components of Plantain

Of the treatments investigated, only the combined application of 2 kg of BC and WA (WA2+BC2), significantly increased the number of harvested parent crops compared to unfertilized crops (Table 5). Conversely, application of 2 kg of BC alone, and in combination with 2 kg of WA (WA2+BC2), as well as application of 1 kg each of BC and WA (WA+BC), significantly improved the number of harvested ratoon crops, the ratoon crop yield index, and the cluster weight of ratoon crop (Table 5). The positive effects on these ratoon yield indices were found to be more significant with combined treatments than with BC alone (Table 5). Fertilization with WA alone, and the combination of 2 kg each of WA and BC (WA2+BC2), also significantly improved the parent crop's yield index and cluster weight (Table 5). The cluster per bunch count of the parent crop was significantly increased by 42.5% with the sole application of WA (Table 6). A greater increase of 67.5% was observed with the combined application of 2 kg each of WA and BC (WA2+BC2). In contrast, the cluster per bunch count of the ratoon crop was significantly increased by 79.07% exclusively through the combined application of 2 kg each of WA and BC (WA2+BC2). The application of 2 kg of each of WA and BC (WA2+BC2) significantly increased the parent crop's finger per cluster count, finger length, and diameter by 33.35%, 21.43%, and 35.23%, respectively. Under the same treatment, the ratoon crop showed substantial increases of 92.42%, 38.53%, and 59.26% for these parameters compared to the unfertilized control (Table 6). In contrast, the 1 kg application of WA and BC (WA+BC) only enhanced the ratoon crop's finger per cluster count, finger length, and diameter by 45.27%, 22.46%, and 39.92%, respectively (Table 6).

Table 5: Effects of Separate and Combined Fertilization with Biochar and Wood-Ash on Yield indices of Plantain

Treatment	No of Plants Harvested		Bunch Weight (kg)		Clusters Weight (kg)		Total Yield (kg/ha)	
	Parent	Ratoon	Parent	Ratoon	Parent	Ratoon	Parent	Ratoon
CONTROL	15.33+3.2^{b}	16.33+1.5^{e}	5.21+0.4^{b}	5.28+0.3^{d}	4.94+0.4^{b}	5.22+0.2^{e}	16.19+4.0^{c}	17.47+2.5^{e}
BC	17.00+1.7^{ab}	19.33+0.6^{abc}	5.51+0.2^{ab}	6.18+0.3^{bc}	5.25+0.0^{ab}	6.18+0.2^{cd}	18.88+1.5^{abc}	24.16+2.0^{cd}
WA	19.33+0.6^{ab}	18.00+1.0^{cde}	5.61+0.0^{a}	6.32+0.5^{bc}	5.40+0.0^{a}	6.57+0.1^{abc}	21.92+0.6^{ab}	22.95+1.7^{cd}
WA+BC	18.33+1.5^{ab}	20.00+0.0^{ab}	5.56+0.1^{ab}	6.62+0.3^{abc}	5.33+0.0^{ab}	6.62+0.1^{abc}	20.59+1.4^{abc}	26.74+1.2^{bc}
WA2+BC2	20.33+0.6^{a}	21.00+0.0^{a}	5.65+0.1^{a}	7.30+0.2^{a}	5.47+0.1^{a}	6.97+0.1^{a}	23.19+0.8^{a}	30.97+1.0^{a}
F-value	4.238	16.692	2.698	13.114	3.930	29.866	5.842	25.610

* The values represent the mean + standard deviation from twelve replicates. $P<0.05$. Mean values with the same superscript across the same column are not significantly different at $P<0.05$. Control: Application of 0 kg of WA and/or BC; BC: application of 2 kg of BC; WA: application of 2 kg of WA; WA+BC: combined application of 1kg each of BC and WA; WA2+BC2: combined application of 2 kg each of BC and WA.

Table 6: Effects of Separate and Combined Fertilization with Biochar and Wood-Ash on Yield Components of Plantain

Treatment	Clusters per Bunch Count		Fingers per Cluster Count		Fingers Length (cm)		Fingers Diameter (cm)	
	Parent	Ratoon	Parent	Ratoon	Parent	Ratoon	Parent	Ratoon
CONTROL	4.0+0.0^{d}	4.3+0.6^{d}	17.00+3.6^{a}	17.67+1.5^{e}	20.07+1.6^{b}	22.40+0.9^{e}	8.43+0.5^{b}	9.67+0.2^{e}
BC	4.7+0.6^{bcd}	5.3+0.6^{bcd}	18.67+3.1^{a}	22.33+1.5^{d}	20.40+1.0^{ab}	23.83+1.1^{de}	9.33+0.5^{ab}	10.67+0.2^{de}
WA	5.7+0.6^{abc}	6.0+1.0^{abcd}	21.33+1.5^{a}	24.33+1.2^{cd}	22.27+1.2^{ab}	26.30+0.9^{cd}	10.07+0.4^{ab}	12.37+0.5^{c}
WA+BC	5.0+1.0^{bcd}	6.0+1.0^{abcd}	19.33+2.5^{a}	25.67+1.5^{bcd}	21.77+1.0^{ab}	27.43+0.9^{bc}	9.93+0.6^{ab}	13.53+0.6^{b}
WA2+BC2	6.7+0.6^{a}	7.7+0.6^{a}	22.67+0.6^{a}	34.00+2.0^{a}	24.37+1.7^{a}	31.03+0.6^{a}	11.40+0.5^{a}	15.40+0.5^{a}
F-value	8.071	7.864	2.187	34.547	3.132	23.000	3.720	87.966

* The values represent the mean + standard deviation from twelve replicates. $P<0.05$. Mean values with the same superscript across the same column are not significantly different at $P<0.05$. Control: Application of 0 kg of WA and/or BC; BC: application of 2 kg of BC; WA: application of 2 kg of WA; WA+BC: combined application of 1kg each of BC and WA; WA2+BC2: combined application of 2 kg each of BC and WA.

Table 7: Proximal Components and Metabolic Energy Value of Plantain (Ratoon) as Influenced by Separate and Combined Fertilization with Biochar and Wood-Ash

Treatment	Moisture	Ash Content	Crude Fibre	Protein	Lipid Content	Carbohydrate	Energy Value
				%			**(kcal/g)**
CONTROL	16.37+1.3^{c}	1.44+0.1^{a}	1.01+0.2^{c}	3.09+1.2^{a}	0.57+0.4^{c}	77.52+2.8^{a}	327.57+9.9^{a}
BC	23.03+2.1^{abc}	1.56+0.1^{a}	1.30+0.2^{c}	3.72+1.1^{a}	1.02+0.2^{bc}	69.37+1.8^{ab}	301.54+5.8^{bcde}
WA	20.30+2.6^{abc}	1.75+0.1^{a}	1.46+0.5^{abc}	3.91+1.0^{a}	1.30+0.6^{abc}	71.28+3.8^{ab}	312.46+14.0^{abc}
WA+BC	24.10+1.3^{ab}	1.84+0.1^{a}	1.47+0.2^{ab}	4.08+0.6^{a}	1.42+0.2^{abc}	67.09+4.0^{b}	297.46+15.0^{cde}
WA2+BC2	26.17+2.9^{a}	2.09+0.1^{a}	1.92+0.2^{a}	4.72+0.8^{a}	2.04+0.4^{a}	63.06+1.0^{b}	289.48+6.0^{e}
F-value	5.514	2.583	10.041	0.920	6.202	4.606	12.162

* The values represent the mean + standard deviation of six replicates collected for ratoon crop. $P<0.05$. Mean values with the same superscript across the same column are not significantly different at $P<0.05$. Control: Application of 0 kg of WA and/or BC; BC: application of 2 kg of BC; WA: application of 2 kg of WA; WA+BC: combined application of 1kg each of BC and WA; WA2+BC2: combined application of 2 kg each of BC and WA.

3.5. Proximate Composition of Plantain as Affected by Separate and Combined Application of Biochar and Wood-ash

Table 7 presents the graph of proximal components for the ratoon crop. While the means of protein and ash content in plantain pulp showed no significant differences across treatments, moisture and fiber content were significantly higher in treatments involving combined WA and BC fertilization (WA+BC and WA2+BC2) compared to unfertilized crops. In contrast, carbohydrate content in plantain pulp was transiently lower with sole BC and WA fertilization. Furthermore, carbohydrate content was significantly reduced by 10.43 kcal/100g (13.45%) with the combined application of 1 kg WA and BC (WA+BC), and by 14.46 kcal/100g (14.82%) with the application of 2 kg WA and BC (WA2+BC2), respectively. Consequently, the metabolic energy (caloric value) of the fruit was significantly reduced by 30.11 kcal/100g (9.19%) and 38.09 kcal/100g (11.63%) with these respective treatments (Table 7). Notably, WA fertilization was more effective than BC fertilization in increasing the carbohydrate, protein, lipid, fiber, and ash content in plantain pulp, thereby yielding plantain with a higher metabolic energy value. The measured proximal components also increased with higher amendment doses, and combined fertilization with WA and BC resulted in a higher caloric value compared to individual fertilization.

4. DISCUSSION

4.1. Change in Soil Physicochemical Properties as influenced by Separate and Combined Application of Biochar and Wood-ash Amendments

Soil fertility depletion is a serious challenge in Nigeria, necessitating the search for soil amendments to support the optimum productivity of heavy-feeder crops, such as plantain, in the country. Aba and Baiyeri, (2015) described plantain as a heavy-feeder crop that requires a combined application of 200 to 400 kg N and 300-600 kg K_2O/ha per annum for optimum performance in the humid tropics. Wood-ash and BC are local by-products obtained from the combustion of agricultural residues. The easy production method for BC and WA, which requires basic skills and little technicality with no sophisticated equipment, coupled with their nutrient-rich characteristics (e.g., high water retention and high capacity for adsorption of heavy metals and other soil contaminants), as noted by Stankowski et al. (2021), can offer a sustainable solution. This offers a long-anticipated, reliable fertilizer-saving strategy, thereby reducing the over-dependence of small-scale farmers on chemical fertilizers.

This study demonstrated that the application of BC and WA, individually or combined, led to significant improvements in soil properties, including reduced soil compaction, increased porosity, pH, electrical conductivity (EC), moisture content, water-holding capacity (WHC), OM, and OC, as well as enhanced levels of exchangeable K, P, Ca, and Mg. These findings suggest that BC and WA possess beneficial fertilizer properties, making them suitable for improving soil health and fertility. These results agree with the findings of previous researchers who reported reduced soil compaction (Omondi et al., 2016), and improved porosity (Zackrisson et al., 1996) for water and nutrient retention upon fertilization with BC. Mechanistically, by modulating soil pH, structure, and nutrient availability, WA increased the population and activity of beneficial soil bacteria, such as Nitrospira and the MND1 genera, which stimulate nitrification (the conversion of ammonia and nitrites to nitrates) (Prasedya et al., 2022; Wang et al., 2024). Similarly, activity of bacterial genera such as RB41 and TRA3-20 was found to increase significantly in WA amended soil (Nicomrat et al., 2008; Stone et al., 2021). The authors further emphasized that the genera RB41 and TRA3-20 are heterotrophic bacteria. These genera of bacteria utilize OC derived from decomposed compounds such as those found in WA, to obtain energy and carbon for oxidizing ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}) in a process that promotes growth and cellular functions of plants. Therefore, the transient increase in soil N from the combined application of WA and BC is likely due to WA's enhancement of specific bacterial genera like Nitrospina and MND1, which increased their abundance and activity, coupled with BC providing an ideal microbial environment with optimal pH, water, and nutrients.

4.2. Plantain's Growth, Yield, Sucker Proliferation, Phenology, and Proximate Composition as Affected by Separate and Combined Fertilization with Biochar and Wood-ash

The general improvement in soil fertility discussed above had a profound effect on plantain growth, yield, proximate composition, and sucker count. Interestingly, combined fertilization with WA and BC significantly enhanced plantain growth and yield compared to individual fertilization, a result consistent with the findings of Bieser and Thomas, (2019) and Gagnon and Ziadi, (2020). Notable also is the fact that both sole and combined fertilization with WA and BC significantly affected ratoon crops compared to parent crops. By harnessing the power of plant growth hormones such as auxins, cytokinins, gibberellins, and abscisic acid, produced by plant growth-promoting bacteria (PGPB) (Mintah 2018; Zhu et al., 2023), WA and BC fertilization either as individual or together, improved the root system development, uptake and mobilization of water and nutrients, and increase the rate of apical and lateral meristems division in plantain. The colonization of PGPB, due to favourable microclimate available in the macro and micro-pores of BC, coupled with WA's capacity to attract bacterial genera like Nitrospina, MND1, TRA3-20, RB41, was expected, is the most potent driver of the observed surge in plantain performance. These PGPB enhance cytokinin synthesis and activity, which in turn support auxin-mediated cytokinin distribution, ultimately fostering optimal plantain growth and productivity. The root-produced trans-zeatin riboside (T-ZR), a form of cytokinin, appeared to play a critical role in proliferating the axillary buds outgrowth on plantain corms, leading to increased sucker count. The association between the PGPB and amendments, increased the root-synthesized T-ZR and shoot-produced auxin in plantain, resulting in an increased activity of lateral cells, dormancy breaking, axillary bud development, and the subsequent plantlets development in plantain. Mintah, (2018) found that elevated levels of root-produced T-ZR in plantain treated with coconut water, led to a greater number of sucker plantlets. Shimizu-Sato and Mori, (2001) and Wang et al. (2024) explained that root-derived cytokinin controls axillary bud outgrowth while shoot-apex-derived auxin facilitates efficient mobilization of cytokinin in plants. The combined action of cytokinin and auxin appeared to suppress the apical meristem while simultaneously stimulating lateral cell activity, which resulted in a larger pseudostem diameter.

As hypothesized, the co-location of OC and plant nutrients within BC's macro- and micro-pores, combine with its high intrinsic K, promoted PGPB colonization. This, in turn, increased cytokinin levels, enhanced N fixation and nutrient solubilization, and improved nutrient cycling, as evident in a greater pseudostem diameter, increased leaf and sucker (Zou et al., 2024), larger leaf area, higher photosynthetic pigment content, better relative water content, and earlier flowering and maturity in plantain.

Phyto-ash, long recognized by early researchers as a source of K fertilization, functions as a soil amendment that improves microbial activity, soil pH, and available K when incorporated into the soil (Perez-Crusado et al., 2011; Bang-Andreasen et al., 2021). Other researchers have identified abundant available K and soil pH modulation from phyto-ash fertilization as major drivers of microbial communities, and they have noted that endogenous auxin synthesis and activity regulate leaf photosynthesis and carbon supply, and ensure a source/sink balance by modulating it's polar transport from shoots to roots (Song et al., 2015; Li et al., 2022; Wang et al., 2024). Therefore, the observed increases in the growth and yield indices of WA-treated ratoon crops, compared to the untreated crop, can be attributed to the increased level of exchangeable K^+ in the growth medium. The significant increase in plantain leaf production and area suggests a greater photosynthetic surface, critical for overall growth and crop yield. This result aligns with findings by Wang et al. (2024), who observed that increased available K and soil pH modification from phyto-ash boosted soil bacterial communities, which in turn enhanced tobacco plant growth (as evidenced by increased leaf and root biomass). Perez-Crusado et al. (2011) reported similar results for a young Castanea × Coudercii plantation after the application of wood-bark ash. In addition, Wang et al., (2024) found that phyto-ash treatment in tobacco plants enhanced auxin synthesis and polar transport, which shifted auxin distribution. This altered distribution, in turn, stimulated the development of first and second lateral roots and leaves, ultimately increasing the CO_2 assimilation rate.

Notably, the crude lipid content in 'agbagba' plantain pulp was generally low across all treatments, with no statistically significant differences observed between them. Ash content, a measure of a plant's essential mineral richness, transiently increased in the pulp from both sole and combined fertilization with WA and BC. This increase is expected to not only boost nutritional element levels but also support the body's acid-base balance. This result conforms with the finding of Akinrinade et al. (2022), who reported no significant changes in the ash content of plantain treated with crop residues.

Dietary proteins are notable for their role in tissue building and repair. This study found that the application of WA and BC, either alone or combined, resulted in a modest increase in plantain protein content. This nutritional benefit could potentially lead to improved palatability, enhanced immune function, better cell growth and division, and a possible reduction in protein energy malnutrition in children (Akinsola et al., 2018). The amount and quality of protein in fruit is a function of the crop's ability to uptake N from the soil or applied fertilizers (Worthington, 2001). Therefore, a transient increase in pulp crude protein content corroborates the transient contribution of WA and BC fertilization to the soil N pool, as reported earlier in this study (Table 2). Wood biomass typically loses a significant amount of volatile N during pyrolysis to BC and incineration to WA applied in this study (Table 2). Consequently, the high soil N levels observed in treatments with combined WA and BC fertilization did not translate to higher plantain protein content, confirming sub-optimal and inadequate N availability in all treated groups for protein synthesis.

Carbohydrates are a major energy source for muscle growth, brain function, and other organ functions, providing 40-80% of total dietary energy (Rugota, 2021). In this study, plantain fertilization with WA and BC resulted in a slight reduction in carbohydrate content, though the resulting values were comparable to those found by Adeniji et al. (2007), and higher than those reported by Oyeyinka and Afolayan (2019) and Akinsola et al. (2021) for the same variety. Aligning with the Institute of Medicine's recommendation of 130 grams of carbohydrates daily for brain and muscle function, these findings suggest that plantain treated with WA and BC could offer sufficient carbohydrates for a moderately active adult. However, the combined WA and BC application significantly reduced carbohydrate content in the pulp, likely due to increased enzymatic hydrolysis. This conversion of carbohydrates to glucose before visible ripening may have been enhanced by the pulp's high moisture content, a condition that Nguyen et al. (2021) found supports rapid enzymatic activity in potatoes and vegetables. The study's findings are consistent with Akinrinade et al. (2021), who observed decreased carbohydrate content in plantain var. agbagba on cocoa pod BC-amended soil.

The metabolic energy value (MEv) of untreated plantain pulp, measured at 327.6 kcal/100g, was observed to be transiently higher than that from sole fertilization with WA and BC, which ranged from 301-319 kcal/100g. Furthermore, it was significantly greater than the MEv resulting from combined BC and WA fertilization, which fell within the range of 289.5-297.5 kcal/100g. Generally, a high MEv is characteristic of the ‘agbagba’ variety, as reported by Oluwajuyitan et al. (2021). Although a significant reduction in the MEv of plantain was caused by combined BC and WA fertilization, the resulting energy levels are still considered potentially adequate for an energy-rich, protein-sparing diet. For example, a similar energy range was documented by Akinsola et al. (2021), who determined that plantain pulp with a value of 293.2 kcal/100g can serve as a good energy source. Similarly, Adepoju et al. (2012) demonstrated that a

100g portion of plantain products can contribute between 6.3-15.3% of the energy, 5.9-30.2% of protein, 7.8-16% of Ca, 9.2-23.3% of Fe, 28.5-33.7% of zinc towards the recommended daily allowances (RDAs) for consumers.

5. CONCLUSION

Although wood-ash (WA) and biochar (BC) are nitrogen-deficient, making them minor components of overall soil fertility management, this study found they effectively substitute for potassium (K) fertilizers. The amendments significantly increased soil exchangeable K+ by 298.8% with WA and 349.4% with BC. The beneficial effects on soil properties stemmed from strong interactions between the amendments and plant growth-promoting rhizobacteria (PGPR). This interaction promoted the synthesis and movement of cytokinin and auxin, plant hormones essential for growth. Consequently, WA and BC enhanced key plantain characteristics by delivering high K content and synergistic interactions with PGPR. This led to increased leaf and sucker counts, larger leaf areas, higher photosynthetic pigment content, and improved water content. It also resulted in earlier flowering and maturity, increased bunch and cluster weights, and more, larger fingers per cluster. WA fertilization was more effective than BC alone, and the effect of combined WA and BC treatments was significantly higher than either amendment used individually. Furthermore, WA and BC application showed a greater positive impact on ratoon (second-generation) crops than on parent crops.

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Author’s Contribution
This work was carried out in collaboration among all authors. Authors AAO conceived the study and participated in its design and coordination. Author SOA performed the statistical analysis and writing of the final manuscript. Authors ODO and VSS carried out the field measurement, all agronomic practices and managed the literature search. All the authors read and approved the final manuscript.

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Data availability
All data associated with this work are present in the paper.

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