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Integrating Biochar, Compost, and Chemical Fertilizer Improves Maize Yield and Soil Health in the Guinea Savanna: Evidence from Two Cropping Seasons in Northern Ghana

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ABSTRACT

Maize production by smallholder farmers in sub-Saharan Africa is constrained by declining soil fertility due to low input use and poor nutrient management. This study evaluated the individual and combined effects of biochar, compost, and chemical fertilizer on maize growth, yield, and soil chemical properties during the 2023 and 2024 cropping seasons in Northern Ghana. A randomized complete block design was used with six treatments: control, biochar alone (B), compost alone (C), chemical fertilizer (CF), biochar + compost (½ B + ½ C), and biochar + compost + chemical fertilizer (½ B + ½ C + ½ CF). Data were analyzed using analysis of variance (ANOVA), and treatment means were separated using the least significant difference (LSD) test at a 5% probability level. The biochar + compost + chemical fertilizer (½ B + ½ C + ½ CF) treatment significantly increased maize grain yield by 105.7% in 2023 and 127.4% in 2024 compared to the control. Soil organic carbon, nitrogen, and phosphorus improved by 115.8%, 685%, and 40.2%, respectively, under this integrated treatment. The SPAD chlorophyll index, cob number, seed weight, and harvest index also increased significantly. Grain yield correlated strongly with soil pH (r = 0.88*), electrical conductivity (r = 0.94***), organic carbon (r = 0.84***), and phosphorus (r = 0.86***). The results demonstrate that integrating biochar, compost, and mineral fertilizer enhances maize productivity and soil fertility, while biochar addition contributes to increased soil carbon storage in semi-arid, low-input systems of West Africa.**

Keywords: Biochar, Compost, Guinea Savanna, Integrated nutrient management, Maize productivity, Soil chemical properties.

1. INTRODUCTION

Maize (*Zea mays* L.) is one of the most important cereal crops globally, serving as a major source of food, feed, and income for millions of smallholder farmers, particularly in sub-Saharan Africa (SSA) (Shiferaw et al., 2011; FAO, 2021). In Ghana, maize is a cornerstone of food security and rural livelihoods, especially in the Guinea Savanna agro-ecological zone, where it is cultivated largely under rainfed conditions (Badu-Apraku et al., 2012). Despite its significance, maize productivity in SSA, including Ghana, remains far below its potential due to chronic soil fertility decline, erratic rainfall, and poor soil health (Vanlauwe et al., 2010; Agyeman et al., 2020). The soils of the Guinea Savanna are inherently fragile, dominated by highly weathered Ferric Lixisols characterized by low organic matter, poor nutrient retention, and rapid decomposition under continuous cultivation (Saaka et al., 2021). To address nutrient deficiencies, smallholder farmers often apply mineral fertilizers, particularly nitrogen (N) and phosphorus (P), which are critical for maize growth. For instance, optimum maize production in the Guinea Savanna typically requires 60–90 kg N ha^{-1}, 40–60 kg P_2O_5 ha^{-1}, and 40–60 kg K_2O under smallholder conditions (MoFA, 2019; FAO, 2021). However, average maize yields in this zone remain low, typically ranging from 1.5 to 2.0 t ha^{-1} (MoFA, 2019; Agyeman et al., 2020). While mineral fertilizers have been shown to increase yields in the short term, their exclusive use often results in soil acidification, declining organic matter, low fertilizer use efficiency, and high production costs (Adjei-Nsiah & Bagamsah, 2012; Abdulai et al., 2023). Moreover, global price volatility and supply chain disruptions have highlighted the vulnerability of input-dependent systems.

These challenges underscore the need for sustainable approaches that improve both crop yields and soil health. Integrated Soil Fertility Management (ISFM), which strategically combines organic and inorganic nutrient sources, has gained global recognition as a pathway to enhance productivity, restore soil fertility, and strengthen resilience (Vanlauwe et al., 2015; Chivenge et al., 2021). Among organic amendments, biochar and compost are widely studied. Biochar, a carbon-rich product of biomass pyrolysis, improves soil cation exchange capacity, pH buffering, and water retention, while also providing habitat for beneficial microorganisms (Lehmann & Joseph, 2015; Jeffery et al., 2017). Mechanistically, biochar tends to increase soil pH by neutralizing acidity through the release of basic cations (Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}) and surface functional groups, thereby creating a more favorable environment for nutrient availability. Its porous structure also contributes to higher electrical conductivity (EC) by retaining exchangeable ions in the soil solution (Glaser et al., 2002). Furthermore, the high carbon content of biochar enhances soil organic carbon stocks, improves aggregation, and stabilizes native soil organic matter, while its relatively low N content promotes nitrogen retention and reduces volatilization losses (Lehmann & Joseph, 2015; Woolf et al., 2010; Laird et al., 2010; Agegnehu et al., 2016). In addition, biochar surfaces can adsorb phosphate ions, reduce fixation, and gradually increase available phosphorus for plant uptake (Lehmann & Joseph, 2015; Liu et al., 2018). Compost, on the other hand, supplies readily available nutrients such as N, P, and K through mineralization, enhances microbial activity, and contributes to long-term organic matter buildup (Sohi et al., 2010; Agegnehu et al., 2016). The microbial activity stimulated by compost accelerates organic matter turnover, thereby improving total nitrogen and available phosphorus levels, while also contributing to higher EC and cation exchange capacity. When applied together with mineral fertilizers, biochar and compost have been shown to synergistically improve nutrient availability, reduce leaching losses, and enhance nutrient use efficiency (Glaser et al., 2002; Liu et al., 2018; Adekiya et al., 2020). Despite global advances, the application of ISFM in the Guinea Savanna of Ghana remains limited. Previous studies have often considered compost or biochar in isolation—*Yawson et al.* (2016) found that compost alone improved soil N and P but had limited residual yield effects, while *Asare-Bediako et al.* (2020) reported that biochar enhanced soil pH and organic carbon but produced modest yield gains when applied alone. However, their combined effects with mineral fertilizers under smallholder field conditions remain poorly understood. Furthermore, evidence on the multi-season response of maize and soil properties under integrated applications is scarce.

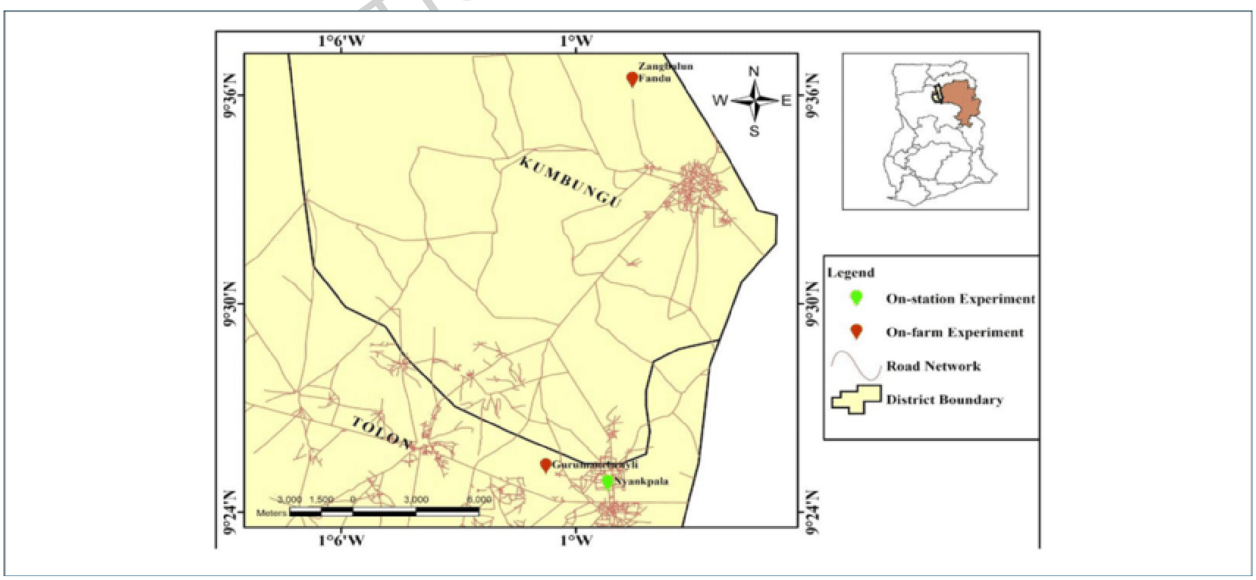
This study was therefore designed to evaluate the individual and combined effects of biochar, compost, and chemical fertilizer on maize growth, yield, and selected soil properties across two cropping seasons (2023 and 2024) in the Guinea Savanna of Ghana. It was hypothesized that integrating biochar and compost with mineral fertilizers would enhance maize productivity more effectively than sole applications while simultaneously improving soil fertility. In addition, this work provides both locally relevant insights and contributions to the global discourse on ISFM. Future research could further explore innovative organic amendments such as vermicompost, which has been shown to improve nutrient availability, microbial diversity, and soil structure with relatively less labor demand compared to conventional composting (Edwards et al., 2011; Lazcano & Domínguez, 2011).

2. MATERIALS AND METHODS

2.1. Study area

The study was conducted at the research fields of the Savannah Agricultural Research Institute (SARI), located in the Tolon District of Northern Ghana (9° 25′ N latitude, 00° 58′ W longitude), within the Guinea Savanna agro-ecological zone. The experimental field measured approximately

0.7 ha, from which the plots were demarcated. The site has a long history of continuous cereal–legume cultivation, dominated by maize, soybean, and groundnut in rotation. Before the study, the land had been cropped to maize for two consecutive seasons. Soil fertility management by farmers in the zone typically relies on low and inconsistent use of mineral fertilizer, occasional application of poultry manure or compost, and limited adoption of integrated practices. As a result, soils are generally nutrient-depleted, with low organic matter and declining productivity. A map of the study site is provided (Figure 1) to clearly indicate the geographic location of the experimental fields in relation to the wider production landscape. The Guinea Savanna is highly significant in the broader context of maize production in Ghana and West Africa. It constitutes the country's largest maize belt, contributing substantially to national food security and serving as a surplus production area that supplies other regions (MoFA, 2019; Abdulai et al., 2023). However, the soils in this zone are predominantly Ferric Lixisols, highly weathered, coarse-textured, and inherently low in organic matter and essential nutrients (Saaka et al., 2021). This makes the zone a representative hotspot for testing soil fertility management innovations, particularly integrated soil fertility management (ISFM) strategies aimed at reversing soil degradation, improving nutrient use efficiency, and strengthening resilience under climate variability. Conducting the study at this site, therefore, provides not only locally relevant insights but also lessons applicable to similar agro-ecological zones across sub-Saharan Africa.



Source: Ministry of Agriculture-Tolon District

Figure 1. Map of Ghana showing the location of the experimental sites

The area experiences a unimodal rainfall pattern from May to October, with peaks in August and September. Rainfall distribution varied considerably between the two years of study (Figure 2). In 2023, the highest rainfall occurred in August (254.3 mm) and October (238.1 mm), while in 2024, September recorded the peak (330.3 mm), followed by August (225.1 mm). Rainfall was absent in March, May, November, and December of 2024, whereas in 2023, these months received 5 mm, 126 mm, 140.1 mm, and 13.2 mm, respectively. June and July 2024 received more rainfall (149.1 mm and 85.2 mm) than the same months in 2023 (97.3 mm and 107.1 mm), suggesting shifts in rainfall timing and intensity. Average monthly temperatures were relatively stable across both years, with only minor variations (Figure 3). May was the hottest month, recording 30.2°C in 2023 and 29.1°C in 2024, while August was the coolest, with 26.4°C in 2023 and 26.8°C in 2024. On average, 2024 was marginally cooler than 2023, particularly in May, October, and November. These year-to-year climatic differences likely affected maize phenology, soil moisture availability, and the effectiveness of the soil amendments evaluated.

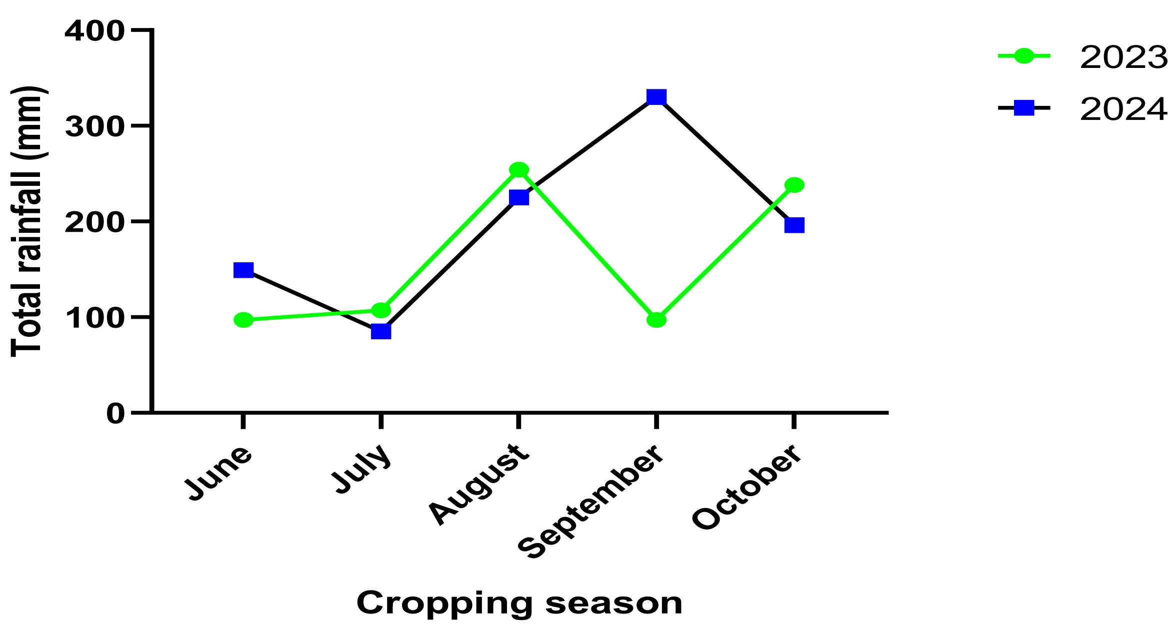


Figure 2. Total rainfall distribution in the 2023 and 2024 seasons.

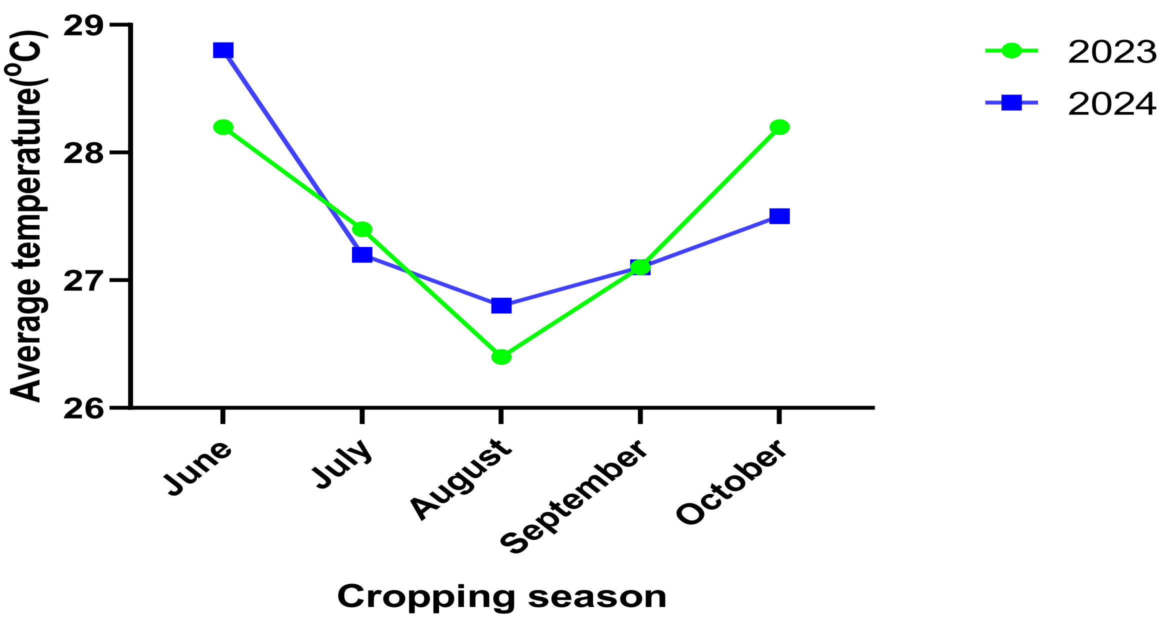


Figure 3. Temperature distribution in the 2023 and 2024 seasons

2.2. Experimental Design and Treatments

The experiment was arranged in a randomized complete block design (RCBD) with six treatments and four replications, totaling 24 plots per season. Each plot measured 4 meters by 4 meters (16 m²), with a 1-meter buffer between plots. The treatments comprised: (1) Control (no amendment), (2) Biochar alone (B), (3) Compost alone (C), (4) Chemical fertilizer alone (CF), (5) Biochar + Compost (½ BC + ½ C), and (6) Biochar + Compost + Chemical fertilizer (½ BC + ½ C + ½ CF). The treatments were selected to reflect both farmer-relevant practices and scientific interest in integrated soil fertility management. Sole applications of biochar, compost, and chemical fertilizer were included to evaluate their individual effects. The combined treatments (½ BC + ½ C, and ½ BC + ½ C + ½ CF) were designed to test whether partial substitution and integration of organic and inorganic inputs could provide synergistic benefits. The half-rate combinations were informed by previous studies (Mensah et al., 2018; Abukari et al., 2019; Fianko et al., 2023; Onawumi et al., 2024) related to agroecologies, which suggest that integrating organics with fertilizers at reduced rates can enhance nutrient use efficiency, improve soil health, and lower input costs for farmers.

2.3. Soil Sampling and Analysis

Initial soil samples were collected from the top 0–20 cm soil depth before treatment application to determine baseline properties. At physiological maturity, post-treatment soil samples were again collected from each plot during both seasons. The samples were air-dried, sieved to pass through a 2 mm mesh, and analyzed in the laboratory and the results is presented in Table 1. Soil pH was measured in a 1:2.5 soil-to-water suspension using a digital pH meter (McLean, 1982). Electrical conductivity (EC) was determined using a conductivity meter (Rhoades, 1996). Organic carbon (OC) was analyzed using the Walkley–Black wet oxidation method (Walkley & Black, 1934). Total nitrogen (N) was determined using the Kjeldahl digestion method (Bremner & Mulvaney, 1982). Available phosphorus (P) was measured using the Bray I extraction method (Bray & Kurtz, 1945), and exchangeable potassium (K) was determined by flame photometry following ammonium acetate extraction (Knudsen et al., 1982). The results from Table 1 reveal that the soil pH (6.50) falls within the moderately acidic range, which can influence nutrient availability and thereby maize growth and yield. As noted by Brady and Weil (2016), acidic conditions may restrict the availability of key nutrients such as phosphorus and nitrogen, potentially constraining maize productivity if soil pH declines further below 5.5. The low organic carbon (0.158%) and total nitrogen (0.65 g kg^{-1}) indicate poor soil fertility, a condition common in degraded tropical soils (Chen et al., 2010). Such deficiencies are critical for maize production, as limited nitrogen and organic matter restrict biomass accumulation and grain yield, thereby highlighting the need for fertility-enhancing inputs. The available phosphorus (6.98 mg kg^{-1}) is also below the critical threshold for maize, which often requires ≥15 mg/kg for optimal nodulation and growth (Sainju et al., 2014). The exchangeable potassium (254 mg kg^{-1}) is relatively moderate but may still limit yield potential when coupled with other nutrient constraints. These baseline conditions justify the use of organic and inorganic inputs as a strategy to enhance maize productivity. They also help contextualize the crop's response to the treatments applied.

Table 1: Physico-chemical characteristics of the soil at 0-20 cm depth at Nyankpala

Soil properties	Values
%sand	61.6
% silt	23.76
% clay	14.64
Texture	Sandy loam
pH (1:2.5 H_2O)	6.50
EC (dS/m)	0.0019
Available phosphorus (P) (mg kg^{-1})	6.98
Organic carbon (%)	0.158
Total nitrogen (N) (g kg^{-1})	0.65
Exchangeable potassium (mg kg^{-1})	254
Exchangeable Calcium (cmol (+)/kg)	2.6

Exchangeable Magnesium (cmol (+)/kg)	1.2
Cation exchange capacity	4.11

2.4. Biochar and Compost Preparation

Biochar was produced from rice husk using a slow pyrolysis process at approximately 500°C in a locally fabricated drum. Biochar was ground, sieved with a 2mm sieve, and analyzed before application. Compost was prepared using cattle manure, rice straw, and maize stover through aerobic decomposition over 3-4 months. The biochar had a pH of 8.5 and contained approximately 65% carbon, while the compost was rich in nitrogen, phosphorus, and potassium with values of 1.5 g kg^{-1}, 1.8 mg kg^{-1}, and 1.82 mg kg^{-1}, respectively. Compost and biochar chemical characteristics are presented in Table 2.

Table 2. Selected chemical properties of biochar and compost applied to the experimental plots in 2023 and 2024.

Property	Unit	Biochar	Compost
Moisture	%	9.8	22.5
Ash	%	16.5	21.35
Fixed C	%	65	17.6
pH	(1:2.5 H_2O)	8.5	7.30
EC	(µS/cm)	1.5	4.5
N	g kg^{-1}	0.67	1.50
P	mg kg^{-1}	0.85	1.80
K	mg kg^{-1}	2.23	1.82

2.5. Treatment Application and Crop Establishment

Biochar and compost were each applied at a rate of 5 t ha^{-1} when used individually, or at 2.5 t ha^{-1} each when applied in combination. The maize was planted at a spacing of 75 cm × 25 cm (population of about 53,333 plants ha^{-1}), giving approximately 85 planting stations per 4 m × 4 m plot. This corresponded to about 8.0 kg of amendment per plot (≈94 g per planting station) when applied singly, or 4.0 kg per plot (≈47 g per planting station) for each amendment when combined. The mineral fertilizer (NPK 15–15–15) was applied at the recommended rate equivalent to 90 kg N ha^{-1}, 60 kg P_2O_5 ha^{-1}, and 60 kg K_2O ha^{-1}. Of this, 60 kg N, 60 kg P_2O_5, and 60 kg K_2O were applied as basal fertilizer two weeks after planting, while urea (46% N) was top-dressed six weeks after planting to supply the remaining nitrogen.

When mineral fertilizer was integrated with organic amendments, it was applied at half of the recommended rate. In the fully integrated treatment (½ BC + ½ C + ½ CF), each amendment was applied at 50% of its full rate. These rates were informed by national maize production guidelines (MoFA, 2010) and previous studies in the Guinea Savanna and related agroecologies, which have shown that 5 t ha^{-1} of organics and recommended fertilizer levels enhance maize performance without being prohibitive for farmers (Mensah et al., 2018; Ezike et al., 2016; Abukari et al., 2019). Organic inputs were incorporated 2-3 weeks before planting, while fertilizer was applied in two equal splits: at sowing and four weeks after emergence. The maize variety used was Zea mays L. (cv. Wang Dataa). Weed control was done manually at three and six weeks after emergence. The same plots were maintained across both seasons (2023 and 2024) to assess residual effects. Organic and inorganic amendments were reapplied in 2024 at the same rates as in 2023. After each harvest, maize stover and cobs were left on each plot to decompose naturally, contributing some organic matter to the soil. This was done to ensure the work reflects the Integrated soil fertility management strategy.

2.6. Data Collection on Growth and Yield Parameters

Growth assessment focused on SPAD chlorophyll readings and plant height. Chlorophyll content was measured at tasseling using a Minolta SPAD-502 meter, with readings taken from the topmost fully expanded leaf of ten randomly selected plants per plot. Plant height was measured from the soil surface to the tip of the tassel at physiological maturity. At harvest, data were collected on several yield and yield components. The number of cobs per plot was determined from all plants within the net plot, while cob weight was recorded from the harvested cobs. Stalk weight was obtained from oven-dried biomass of stalks, and grain yield was calculated from shelled grain, adjusted to 12.5% moisture content, and converted to tonnes per hectare. The 100-seed weight was determined from a randomly selected grain sub-sample. Finally, the harvest index was calculated as the ratio of grain yield to total aboveground biomass. This combination of growth parameters, yield, and yield components offered an integrated assessment of treatment effects on maize growth performance and overall productivity.

2.7. Statistical Analysis

Data were subjected to analysis of variance (ANOVA) using GenStat (version 12). In the statistical model, treatments were considered fixed factors, while blocks (replications) were treated as random factors. Since the experiment was conducted across two cropping seasons (2023 and 2024), seasons were treated as a fixed factor, and the analysis was combined over the two seasons to account for seasonal variability and treatment × season interactions. Treatment means were separated using the Least Significant Difference

(LSD) test at the 5% probability level. Before analysis, data were tested for normality and homogeneity of variance, with appropriate transformations applied where assumptions were not met.

3. RESULTS

3.1. Effects of treatments and seasons on SPAD readings, plant height, and stalk weight

SPAD chlorophyll values varied significantly with treatment and season ($p = 0.002$) (Table 3). The highest chlorophyll content (47.17) was found in 2023 under ½BC + ½C + ½CF, followed closely by ½BC + ½C (45.47) and BC (44.07). The lowest was observed in the control (28.84). In 2024, values declined slightly, with ½BC + ½C (43.24) and CF (41.84) performing best, while the control (32.00) and C (33.91) remained the lowest (Table 3). Plant height was not significantly affected by the interaction of treatment and season ($p < 0.001$). In 2023, the tallest plants (185 cm) were recorded under ½BC + ½C + ½CF, which was statistically comparable to C (181 cm), CF (179 cm), and ½BC + ½C (178 cm), while the control (166 cm) and BC (165 cm) were the shortest (Table 3). In 2024, plant heights were generally lower, ranging from 132 cm under the control to 175 cm under ½BC + ½C + ½CF, though significant differences were not seen among treatments compared with 2023. The treatment × season interaction significantly affected stalk weight ($p = 0.005$; Figure 4). In 2023, CF produced the heaviest stalks (3.80 t ha^{-1}), followed by C (2.67 t ha^{-1}), while the control recorded the lowest (1.60 t ha^{-1}). In 2024, ½BC + ½C produced the heaviest stalks (3.43 t ha^{-1}), which were significantly higher than the control (2.17 t ha^{-1}) and ½BC + ½C + ½CF (2.30 t ha^{-1}) (Figure 4).

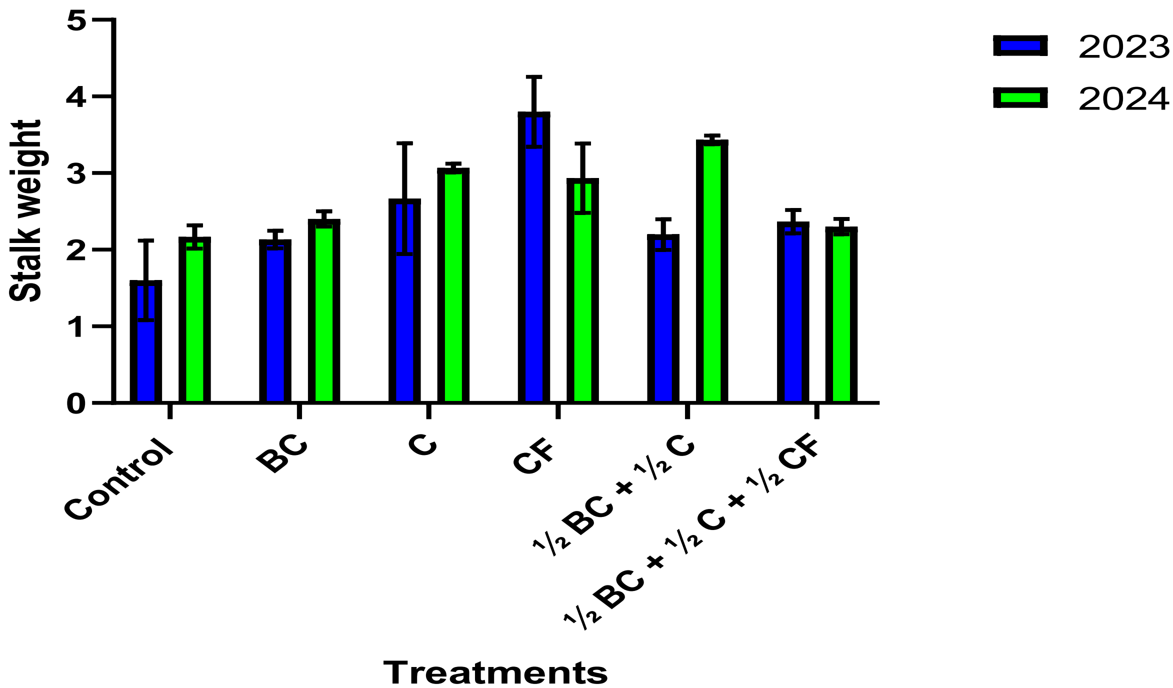


Figure 4. Effect of treatments on stalk weight of maize during the 2023 and 2024 cropping seasons. BC = Biochar; C = Compost; CF = Chemical Fertilizer; ½ = Half of the recommended rate.

Table 3: Effect of Treatments and seasons on growth parameters of maize during the cropping season

Treatment	SPAD (μmol m^{-2})		Plant height (cm)		Cob number (No $plot^{-1}$)	
	Cropping season					
	2023	2024	2023	2024	2023	2024
Control	28.84^{d}	32.00^{d}	166^{c}	132^{a}	6^{d}	23^{c}
BC	44.07^{b}	38.57^{c}	165^{c}	156^{a}	19^{c}	35^{b}
C	35.83^{c}	33.91^{d}	181^{ab}	156^{a}	25^{bc}	27^{c}
CF	41.49^{b}	41.84^{b}	179^{ab}	147^{a}	45^{a}	39^{ab}
½BC + ½C	45.47^{ab}	43.24^{ab}	178^{b}	166^{a}	23^{c}	39^{ab}
½BC + ½C + ½CF	47.17^{a}	40.43^{bc}	185^{a}	175^{a}	32^{b}	47^{a}
LSD (5%)	3.197		21.00		9.06	
Pr (T x S)	0.002		0.331		0.005	
CV	4.80		7.50		17.80	

Means followed by the same letter are not significantly different at the 5% probability level ($p < 0.05$). BC = Biochar; C = Compost; CF = Chemical Fertilizer; ½ = Half of the recommended rate. LSD = Least Significant Difference, Pr = probability, CV= Coefficient of Variation, T x S = Treatment and Season interaction.

3.2. Effect of Treatments and seasons on the number of cobs per plot and cob weight

Cob number per plot was significantly affected by the interaction of treatment and season ($p < 0.001$) (Table 3). In 2023, CF produced the highest cob number (45), followed by ½BC + ½C + ½CF (32), while the lowest was under control (6). In 2024, ½BC + ½C + ½CF produced the most cobs (47), with the weakest in control (23) (Table 3). Cob weight, however, was not significantly affected by treatment × season (p = 0.071). The application of fertilizers and organic amendments had a significant influence on cob weight (Table 4). In 2023, the chemical fertilizer (CF) treatment produced the highest cob weight (2.93 t ha^{-1}), representing a 54.2% increase over the control (1.90 t ha^{-1}). However, in 2024, the highest cob weight was obtained from the biochar + compost (½ BC + ½ C) treatment (3.15 t ha^{-1}), reflecting a 63.2% improvement over the control.

3.3. Effect of treatments on grain yield, 100-Seed Weight, and Harvest Index

Grain yield differed significantly across treatments and seasons (p = 0.016; Table 4). In 2023, ½BC + ½C + ½CF recorded the highest yield (2.53 t ha^{-1}), followed by CF (2.23 t ha^{-1}), while control was the lowest (1.23 t ha^{-1}). In 2024, ½BC + ½C (2.94 t ha^{-1}) and ½BC + ½C + ½CF (2.82 t ha^{-1}) performed best, while control remained the least productive (1.24 t ha^{-1}) (Table 4). A significant treatment × season interaction was also observed for 100-seed weight (p = 0.011) (Table 4). In 2023, ½BC + ½C + ½CF (26 g) recorded the heaviest seeds, followed by CF (25 g), while the control produced the lightest (18 g). In 2024, both ½BC + ½C + ½CF and C had the heaviest seed weights (28 g), while treatment CF and ½ BC+½C had the lightest seeds in 2024 (Table 4). Harvest index was not significantly affected by treatment × season (p = 0.296) (Table 4). Harvest index (HI) was, however, significantly enhanced by integrated treatments. In 2023, ½ BC + ½ C (1.08) and ½ BC + ½ C + ½ CF (1.05) recorded the highest HI values, showing 66.2% and 61.5% improvements over the control (0.65). In 2024, ½ BC + ½ C + ½ CF achieved an even greater HI of 1.20, an 84.6% increase relative to the control (Table 4).

Table 4: Effect of Treatments and cropping season on cob weight, 100-seed weight, and harvest index of maize during the 2023 and 2024 cropping seasons

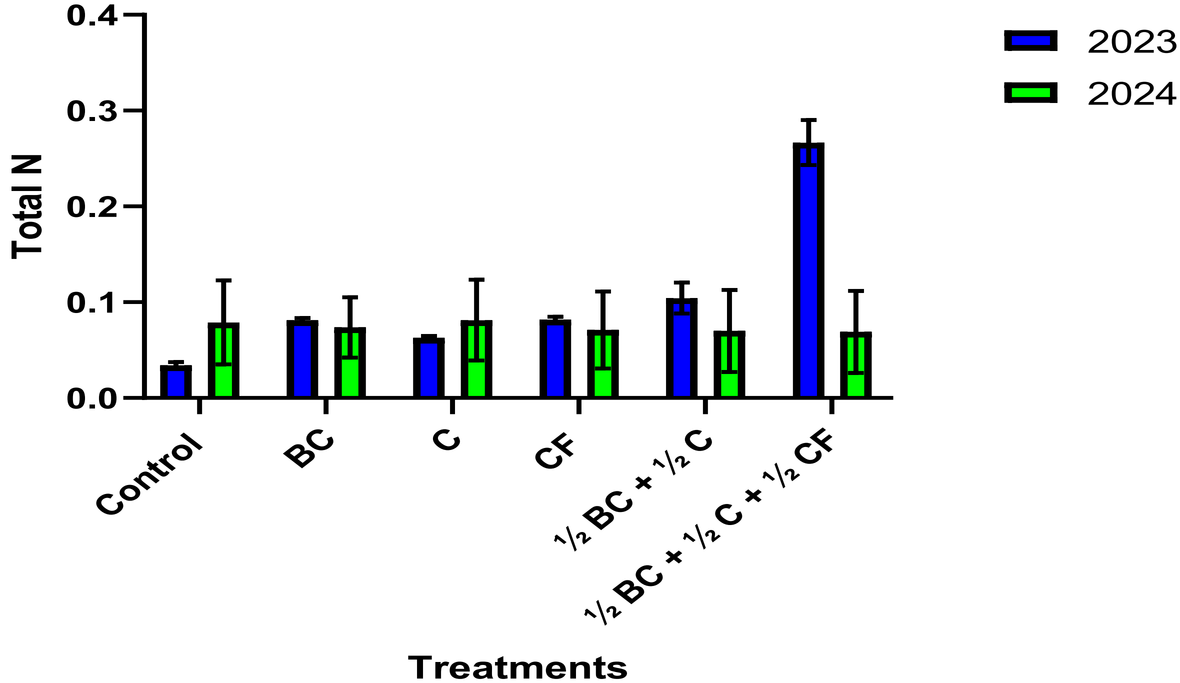
Treatment	Cob weight (t ha^{-1})		Grain yield (t ha^{-1})		100-seed weight (g)		Harvest index (%)	
	Cropping season							
	2023	2024	2023	2024	2023	2024	2023	2024
Control	1.90^{a}	1.93^{a}	1.23d	1.24^{d}	18^{c}	26^{b}	0.65^{a}	0.65^{a}
BC	2.03^{a}	2.94^{a}	1.73^{c}	1.97^{c}	22^{b}	27^{ab}	0.85^{a}	0.72^{a}
C	2.17^{a}	2.70^{a}	2.00^{bc}	2.15^{c}	22^{b}	28^{a}	0.92^{a}	0.80^{a}
CF	2.93^{a}	2.83^{a}	2.23^{b}	2.65^{b}	25^{ab}	26^{b}	0.77^{a}	0.97^{a}
½BC + ½C	1.90^{a}	3.15^{a}	2.00^{bc}	2.94^{a}	24^{ab}	25^{b}	1.08^{a}	0.94^{a}
½BC + ½C + ½CF	2.47^{a}	2.43^{a}	2.53^{a}	2.82^{a}	26^{a}	28^{a}	1.05^{a}	1.20^{a}
LSD (5%)	0.75		0.358		3.00		0.278	
Pr (T x S)	0.071		0.016		0.011		0.296	

CV	18.20	9.90	7.00	18.60

Means followed by the same letter are not significantly different at the 5% probability level ($p < 0.05$). BC = Biochar; C = Compost; CF = Chemical Fertilizer; ½ = Half of the recommended rate. LSD = Least Significant Difference, Pr = probability, CV= Coefficient of Variation, T x S = Treatment and Season interaction.

3.4. Soil chemical properties

All measured soil properties (pH, EC, OC, N, P, and K) were significantly affected by treatment × season ($p < 0.001$). Soil pH ranged from 5.69 under control to 6.67 under ½BC + ½C + ½CF in 2023, and from 5.62 under CF to 6.64 under ½BC + ½C + ½CF in 2024 (Table 5). Soil EC increased significantly under CF and ½BC + ½C + ½CF, with values above 1100 dS/m in 2023, compared with 817 dS/m under control (Table 5). Organic carbon was highest under ½BC + ½C + ½CF (1.64% in 2023; 1.33% in 2024), while the lowest was in control (0.76% in 2023; 0.64% in 2024) (Table 5). Similarly, nitrogen content was highest under ½BC + ½C + ½CF (0.2667% in 2023), while no difference was observed in 2024 (Figure 5). Available phosphorus increased markedly under ½BC + ½C + ½CF (117.43 mg/kg in 2023; 113.35 mg/kg in 2024), compared with the lowest in the control (83.77 and 66.18 mg/kg, respectively) (Figure 6). Potassium also improved with treatments, being highest in 2024 under ½BC + ½C + ½CF (43.90 mg/kg), while the lowest was recorded under control (27.01 and 27.37 mg/kg) (Table 5).



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301 Figure 5. Effect of treatments on total N (%) of the soil during the 2023 and 2024 cropping seasons

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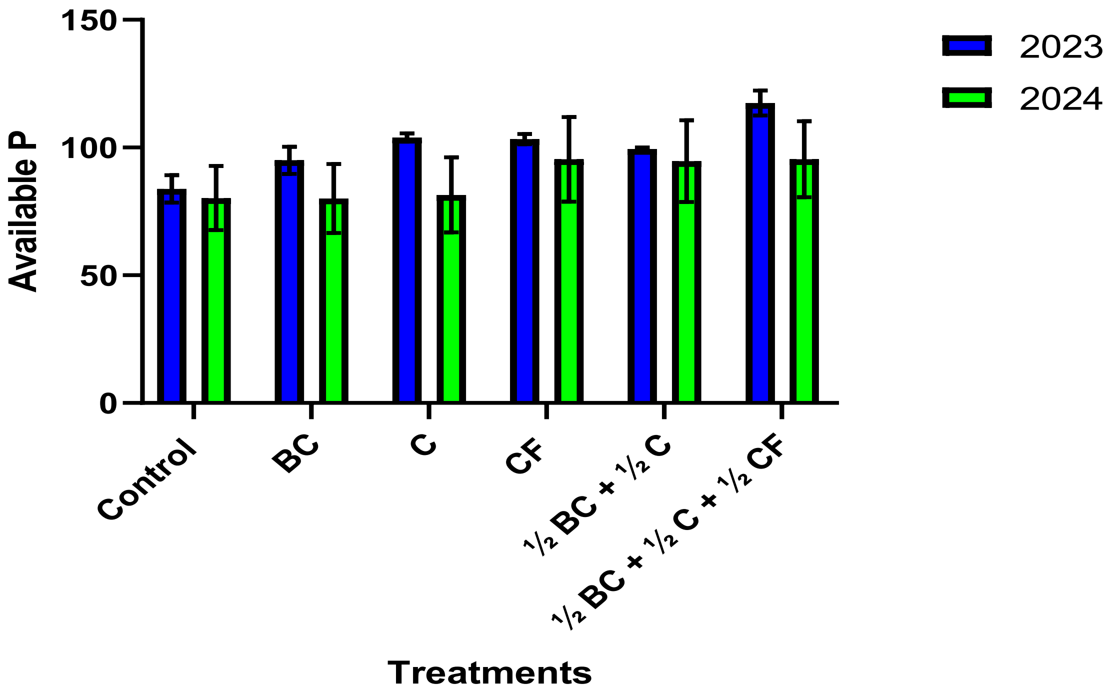

Figure 5. Effects of treatments on available P (mg kg^{-1}) of the soil during the 2023 and 2024 cropping seasons

Table 5. Effects of treatments on soil pH, EC, organic carbon, and potassium during the 2022 and 2023 cropping seasons

Treatment	pH (1:2.5 H_2O)		E C(dS/m)		OC (%)		K (mg/kg)	
	Cropping season							
	2023	2024	2023	2024	2023	2024	2023	2024
Control	5.69^{e}	5.65^{d}	817^{e}	775^{d}	0.76^{e}	0.64^{e}	27.01^{f}	27.37^{f}
B	6.10^{d}	6.17^{c}	945^{d}	799^{cd}	0.91^{d}	0.97^{c}	29.83^{e}	36.54^{d}
C	6.43^{c}	6.52^{b}	1019^{c}	806^{cd}	1.33^{b}	0.90^{d}	33.17^{d}	31.79^{e}
CF	6.53^{b}	5.62^{d}	1109^{b}	855^{b}	1.55^{a}	1.00^{c}	37.47^{b}	29.79^{e}
½BC + ½C	6.47^{bc}	5.65^{d}	1004^{c}	815^{c}	1.03^{c}	1.20^{b}	39.17^{b}	43.01^{b}
½BC + ½C + ½CF	6.67^{a}	6.64^{a}	1115^{a}	844^{b}	1.64^{a}	1.33^{a}	38.87^{b}	43.90^{a}
LSD (5%)	0.150		41.80		0.174		3.607	
Pr (T x S)	<.001		<.001		<.001		<.001	
CV	1.40		2.70		9.30		6.10	

Means followed by the same letter are not significantly different at the 5% probability level ($p < 0.05$). BC = Biochar; C = Compost; CF = Chemical Fertilizer; ½ = Half of the recommended rate. LSD = Least Significant Difference, Pr = probability, CV= Coefficient of Variation, T x S = Treatment and Season interaction.

3.6. Correlation Analysis

Correlation analysis was conducted to examine the relationships among soil chemical properties, physiological parameters, growth characteristics, and yield-related traits of maize in 2023 and 2024 (Tables 6 and 7). In 2023, grain yield showed a strong and significant positive correlation with SPAD chlorophyll readings (r = 0.73***), cob number (r = 0.77***), and 100-seed weight (r = 0.76***). These findings align with previous studies that highlight the importance of chlorophyll content and reproductive components in determining maize productivity (Rukundo et al., 2021; Zhang et al., 2020). Grain yield also correlated significantly with soil pH (r = 0.88***), EC (r = 0.94***), organic carbon (r = 0.84***), and phosphorus (r = 0.86***), indicating that soil fertility status plays a crucial role in enhancing maize yield under the study conditions (Agegnehu et al., 2016; Lehmann et al., 2011).

SPAD values had significant positive correlations with several key traits, including 100-seed weight (r = 0.68**), harvest index (r = 0.60*), and multiple soil chemical properties (e.g., pH, EC, OC, N, P, and K). In 2024, similar trends were observed. Grain yield maintained a significant correlation with SPAD (r = 0.72***), cob number (r = 0.81***), and harvest index (r = 0.81***). Notably, cob weight was not significantly correlated with grain yield (r = 0.13). Phosphorus (r = 0.78***) and organic carbon (r = 0.79***) remained significantly associated with grain yield, reinforcing the importance of soil fertility improvement strategies such as organic amendments and integrated nutrient management. Unlike in 2023, 100-seed weight in 2024 showed weak or negative correlations with most traits, including a non-significant correlation with grain yield (r = -0.03), which may reflect inconsistencies in seed development or kernel filling due to uneven rainfall distribution. However, SPAD remained a consistently strong indicator of overall crop performance across both years.

Table 6. Pearson correlation coefficients among physiological, growth, yield traits, and soil chemical properties of maize in 2023.

Variable	SPAD	Plant h.	Stalk wt.	Cob no.	Cob wt.	Grain y.	100-SW	HI	pH	EC	OC	N	P	K
SPAD	1.00													
Plant height	0.33	1.00												
Stalk weight	0.22	0.28	1.00											
Cob number	0.48*	0.29	0.70**	1.00										
Cob weight	0.25	0.37	0.69**	0.79***	1.00									
Grain yield	0.73***	0.48*	0.49*	0.77***	0.58*	1.00								
100-seed weight	0.68**	0.59*	0.39	0.70**	0.70**	0.76***	1.00							
Harvest index	0.60*	0.10	-0.08	0.13	-0.32	0.56*	0.14	1.00						
pH	0.70**	0.42	0.57*	0.70**	0.46*	0.88***	0.71**	0.58*	1.00					
EC	0.70**	0.44	0.69**	0.82***	0.62*	0.94***	0.71***	0.49*	0.94***	1.00				
Organic carbon	0.47*	0.46	0.61*	0.70**	0.62**	0.84***	0.60*	0.36	0.84***	0.91***	1.00			
Nitrogen	0.67**	0.28	0.03	0.35	0.22	0.73***	0.53*	0.58*	0.63**	0.64**	0.64**	1.00		
Phosphorus	0.63**	0.45	0.36	0.63**	0.44	0.86***	0.71**	0.53*	0.88***	0.86***	0.84***	0.79***	1.00	
Potassium	0.69**	0.55*	0.41	0.50*	0.28	0.73***	0.59*	0.59*	0.84***	0.78***	0.68**	0.57*	0.67**	1.00

*Note: *, *, *and *** indicate significance at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.*

Table 7. Pearson correlation coefficients among physiological, growth, yield traits, and soil chemical properties of maize in 2024.

Variable	SPAD	Plant h.	Stalk wt.	Cob no.	Cob wt.	Grain y.	100-SW	HI	pH	EC	OC	N	P	K
SPAD	1.00													
Plant height	0.58*	1.00												
Stalk weight	0.40	0.18	1.00											
Cob number	0.78***	0.65**	0.12	1.00										
Cob weight	0.17	-0.05	0.56*	-0.19	1.00									
Grain yield	0.72***	0.57*	0.54*	0.81***	0.13	1.00								
100-seed weight	-0.21	0.28	-0.34	0.06	-0.26	-0.03	1.00							
Harvest index	0.54*	0.53*	0.11	0.85***	-0.44	0.81***	0.15	1.00						
pH	0.12	0.51*	-0.24	0.20	-0.38	0.12	0.80****	0.37	1.00					
EC	0.46*	0.31	0.22	0.60*	-0.05	0.75***	-0.01	0.74***	0.08	1.00				
Organic carbon	0.69**	0.69**	0.28	0.87***	-0.10	0.79***	0.07	0.76***	0.33	0.43	1.00			
Nitrogen	0.49*	0.67**	0.48*	0.61*	0.25	0.73***	0.08	0.53*	0.30	0.36	0.72***	1.00		
Phosphorus	0.62*	0.76***	0.08	0.91***	-0.23	0.78***	0.30	0.86***	0.52*	0.54*	0.88***	0.76***	1.00	
Potassium	0.58*	0.73***	0.18	0.74***	0.01	0.67**	0.10	0.59*	0.36	0.27	0.85***	0.72***	0.83***	1.00

*Note: *, *, *and *** indicate significance at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.*

4. DISCUSSION

The combined application of biochar, compost, and mineral fertilizer significantly improved maize growth, yield, and soil fertility compared with the control and single amendments. Although the fertilizer-only treatment (CF) performed better than the integrated treatments in 2023, the differences disappeared in 2024, indicating that the benefits of integrated nutrient management may become more evident over time. Other growth parameters, such as plant height and chlorophyll content (SPAD), were consistently higher under integrated treatments, particularly ½BC + ½C + ½CF, which ranked among the best-performing options in both seasons. These results suggest that improved nutrient availability and uptake could be a possible reason for the enhanced crop performance observed when biochar was combined with compost and chemical fertilizer, supporting the hypothesis that integrated nutrient management tends to be more effective than the application of single sources of fertility.

The higher SPAD values recorded in the integrated treatments reflect improved nitrogen availability and assimilation. Biochar is known to reduce nitrogen losses by adsorbing ammonium and nitrate ions and modifying mineralization processes, while compost supplies readily available organic N and stimulates microbial activity. When combined with mineral fertilizer, these mechanisms likely create a more balanced and sustained nitrogen supply for the crop. The observed increase in chlorophyll content under integrated treatments is consistent with previous findings that biochar-based amendments enhance leaf nitrogen status and photosynthetic efficiency. Liu et al. (2020) demonstrated that biochar combined with nitrogen fertilizer significantly improved nitrogen uptake and use efficiency, thereby increasing SPAD values and maize growth, while Ye et al. (2020) also reported higher crop yields under biochar–fertilizer combinations compared with fertilizer or biochar alone.

The yield response followed a similar pattern. The highest grain yields were observed in the combined treatments, particularly ½BC + ½C + ½CF, which consistently outperformed the control and single amendments across both seasons. Although the ½BC + ½C treatment improved yield compared with the control, it did not perform better than the fertilizer-only (CF) treatment. Biochar or compost applied alone gave modest improvements, but the synergistic effect of combining organic and inorganic sources was more pronounced. These findings align with the meta-analysis of Ye et al. (2020), which concluded that biochar alone rarely increases yields substantially but has strong positive interactions when applied with mineral fertilizer. The complementary functions of the amendments explain this synergy: biochar improves soil structure and nutrient retention, compost enriches organic matter and micronutrients, and mineral fertilizer provides readily available nutrients. This combination likely enhanced assimilate partitioning during grain filling, as reflected in the higher 100-seed weight observed under integrated treatments.

Soil chemical properties also responded positively to biochar-based treatments. Soil pH increased significantly in biochar-amended plots, consistent with the liming effect of biochar arising from its alkaline ash content and capacity to neutralize exchangeable acidity. Similar trends have been reported in acidic tropical soils by Chimdi et al. (2012) and Jeffery et al. (2017). The increase in pH likely alleviated aluminum toxicity, creating a more favorable environment for root growth and nutrient uptake. Organic carbon content was also higher in biochar- and compost-amended soils, in agreement with Nguyen et al. (2022), who reported that biochar additions enhance soil organic carbon by contributing stable carbon fractions and reducing decomposition rates of added organic matter. The improvement in soil N, P, and K under combined treatments can be attributed to the nutrient-holding capacity of biochar, the nutrient contribution of compost, and the immediate availability of mineral fertilizers. Amarasinghe et al. (2022) similarly found that compost–biochar mixtures increased SOC and enhanced the availability of P and K.

Correlation analysis provided further insights into the relationships among soil fertility, physiological parameters, and yield performance. In 2023, grain yield exhibited strong positive associations with SPAD readings, cob number, and 100-seed weight, confirming the importance of chlorophyll status and reproductive traits as determinants of maize productivity. Similar findings have been reported by Rukundo et al. (2021) and Zhang et al. (2020), who emphasized the predictive value of leaf chlorophyll and yield components such as cob number. Grain yield also correlated strongly with soil pH, electrical conductivity, organic carbon, and phosphorus, indicating that improved soil fertility was a major driver of yield increases. These results corroborate earlier reports by Agegnehu et al. (2016) and Lehmann et al. (2011), which highlighted the role of organic amendments and biochar in improving nutrient status and crop productivity. SPAD values further correlated positively with 100-seed weight, harvest index, and several soil chemical properties, reinforcing their use as indicators of crop nitrogen status and yield potential.

In 2024, similar relationships were observed, with grain yield maintaining strong associations with SPAD, cob number, and harvest index. Soil phosphorus and organic carbon remained significantly correlated with yield, suggesting that organic amendments contribute to sustained fertility and productivity across seasons. However, 100-seed weight showed a weaker relationship with yield in 2024, likely due to uneven rainfall distribution affecting kernel development. Despite seasonal variability, SPAD remained a consistent predictor of yield, underscoring its utility as a rapid, non-destructive indicator of crop performance.

The seasonal differences observed, with generally lower growth and yield in 2024 compared with 2023, are likely to reflect temporal dynamics in nutrient release and microbial activity influenced by climatic factors, particularly rainfall distribution. The delayed mineralization of compost and gradual nutrient release from biochar may have interacted with moisture availability to influence nutrient cycling and uptake over time. Although microbial processes were not directly measured in this study, the enhanced performance of integrated treatments suggests that biochar and compost likely stimulated soil biological activity, improved nutrient turnover, and increased nutrient use efficiency. Such biological contributions are increasingly recognized as critical for sustaining soil fertility in tropical systems (Lehmann et al., 2021; Liang et al., 2023).

Overall, the results support the conclusion that integrating biochar with compost and mineral fertilizer enhances soil health and maize productivity more effectively than single applications. The mechanisms involve improved nutrient retention, increased organic soil matter, favorable soil chemical conditions, and better synchronization between nutrient release and crop demand. The correlation results further emphasize that maize yield is closely linked to physiological traits such as chlorophyll content and cob number, as well as soil fertility indicators such as pH, phosphorus, and organic carbon. These findings are consistent with regional and global evidence, reinforcing the value of integrated nutrient management for sustainable intensification in smallholder farming systems. Nonetheless, to strengthen the understanding of biochar–compost–fertilizer interactions, future studies should quantify the temporal and biological dynamics underlying these effects, including microbial responses and nutrient transformation processes. Multi-season and on-farm studies would be valuable to refine optimal rates and combinations for wider adoption in the Guinea Savanna zone of Ghana.

6. CONCLUSION

The findings of this study confirm that the individual and combined applications of biochar, compost, and chemical fertilizer influenced maize growth, yield, and soil fertility under the Guinea Savanna conditions of Ghana. Consistent with the study's objective and hypothesis, the integration of biochar and compost with mineral fertilizer enhanced maize productivity more effectively than the sole applications, while also improving soil properties across both seasons. These results highlight the importance of combining organic and inorganic nutrient sources as an effective approach to managing soil fertility in low-input, rainfed farming systems. By strengthening the linkages between soil quality indicators and crop performance, integrated nutrient application enhances the ecological foundation of maize production systems. This approach promotes higher input efficiency, improved soil management, and more resilient yields amid changing climate conditions. Beyond its agricultural benefits, integrated nutrient management supports broader sustainability goals by reducing dependence on external inputs and promoting the use of locally available organic resources. Its relevance extends to policies on regenerative agriculture, climate adaptation, and smallholder livelihood improvement. Scaling these integrated practices will require supportive institutional frameworks, participatory research, and targeted investments in extension services. Future work should emphasize long-term monitoring, landscape-scale impacts, and farmer-led innovation to fully realize the potential of integrated soil fertility management in sub-Saharan Africa.

Data Availability: The datasets generated and/or analysed during the current study are available upon request.

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Author Contributions

All authors reviewed and approved the final manuscript. **ALAA** conceived and designed the study, conducted the investigation, and prepared the original manuscript draft. **ALAA, AH, and AYB** contributed to methodology refinement, supervised data collection and analysis, and participated in manuscript review and editing.

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