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Impact of various soil amendments on temporal NPK release, soil quality and maize yield in tropical Alfisols of Zaria, Nigeria

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Sustainable crop production in tropical regions is challenged by poor soil fertility, necessitating effective soil amendment strategies. This study evaluated the temporal effects of five soil amendments—compost (CMP), biochar (BCH), co-composted biochar (C-BCH), a mixture of compost and biochar (CMP + BCH), and NPK fertilizer—on NPK release patterns, soil quality, and maize performance in the Alfisols of Zaria, Nigeria. The experiment followed a randomized complete block design with six treatments (including control) and three replications, applied at 15 t ha^{-1} for organic treatments and recommended rate for NPK. Key soil quality indicators measured were organic carbon (OC), cation exchange capacity (CEC), pH, bulk density (ρb), and mean weight diameter (MWD). Nutrient release was monitored at bi-weekly intervals over 12 weeks, while maize growth and yield parameters were also evaluated. Statistical analysis (ANOVA, $p < 0.05$) showed that CMP initially released the most N, P, and K, but CMP + BCH significantly improved OC (1.89%), CEC (9.13 cmol kg^{-1}), and MWD (1.36 mm), while maintaining near-neutral pH. These improvements translated into superior plant height (212.4 cm), leaf area (536.2 cm^2), and grain yield (3.45 t ha^{-1}). Among the Soil Quality Index (SQI) methods used, threshold and weighting methods aligned more with crop productivity, while the AHP method reflected long-term soil sustainability trends. CMP + BCH emerged as the most sustainable amendment under tropical conditions. Future research should investigate the long-term carbon sequestration potential of these amendments.

Keywords Alfisols, Maize, NPK temporal dynamics, Soil organic amendments, Soil quality indicators, SQI methods

In the tropics, where most soils exhibit low nutrient status and limited buffering capacity, a variety of organic and inorganic amendments have been utilized to enhance soil fertility and agricultural productivity[1] Soil health is a critical factor in ensuring sustainable agricultural productivity and environmental quality[2]. It encompasses the physical, chemical, and biological properties of soil that influence its ability to support plant growth through adequate nutrient, air, and water supply while maintaining environmental quality and improving biodiversity[3,4].

The overall effect of these amendments on nutrient availability for crop uptake and sustainable land management has been a point of discussion for several decades, especially by proponents of soil health[5]. Evaluation of agricultural soil quality has become a mainstay in the field of agricultural research, and several components have been employed for its measurement[6,7]. Among these, nutrient availability, especially for nitrogen, phosphorus, and potassium plays a vital role in crop efficiency and soil fertility. These macronutrients are essential for plant productivity, influencing key physiological processes and overall vigour[8]. However, their availability in tropical soils is limited, necessitating supplementation with various amendment sources that impose both spatial and temporal limitations[5,9].

Recent studies such as Sadra et al.[10] and Nyabami et al.[11] have demonstrated that nutrient release dynamics and their synchrony with plant demand are critical to reducing losses and maximizing efficiency. Therefore, an in-depth understanding of temporal nutrient dynamics of specific organic amendment materials is necessary to develop targeted management practices that ensure efficient nutrient utilization and long-term soil fertility.

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Over the years, several researchers have investigated the effects of various amendments on soil properties[12]. Studies have shown that compost application enhances nitrogen mineralization and phosphorus availability over time, while biochar improves soil cation exchange capacity (CEC) and moderates nitrogen release by adsorbing ammonium ions[13,14]. Co-composted biochar has been reported to combine these benefits, leading to more synchronized nutrient supply with crop demand[21]. Conversely, NPK fertilizers, although effective for immediate nutrient supplementation, are prone to rapid nutrient loss through leaching and volatilization, which can negatively affect soil structure and biological functions over repeated applications[15,16]. These findings have led to a wide-spread adoption of these amendment sources for improving soil nutrition.

However, despite their widespread use, recent literature such as[16] and[17] suggests a knowledge gap exists in terms of how these amendments influence soil health indicators over time, particularly in tropical Alfisols. Additionally, many earlier studies focused on static properties without linking temporal changes in nutrient availability to plant demand, making this study particularly relevant. As a result of its close link to soil fertility and plant growth, the temporal release pattern of NPK from various soil amendments is of particular interest to farmers, since nutrient requirements vary across different stages of plant development[18,19]. Understanding these release patterns enables land users to align agricultural operations with nutrient availability to enhance nutrient use efficiency[9]. According to[20], the availability of NPK from soil amendments depends on amendment type, inherent soil properties, and environmental conditions. For instance, organic materials may release N slowly over time, providing a steady supply to crops, while inorganic fertilizers may lead to rapid N availability followed by fixation, leaching, and potential environmental contamination. This difference affords land users the opportunity to select amendments tailored to their land's specific needs.

Moreover, with rising interest in integrated nutrient management and carbon-smart agriculture, there is a growing focus on combining organic materials such as compost and biochar—individually or co-composted to maximize benefits[21]. Given this growing interest, it is essential to evaluate their short-term nutrient release patterns in conjunction with soil health indicators, particularly in the Alfisols of Samaru, Zaria.

The current study is novel in that it concurrently compares multiple organic amendment types (compost, biochar, co-composted biochar, and compost-biochar mixture) and inorganic fertilizer (NPK), using three Soil Quality Index (SQI) calculation methods (threshold, additive, and AHP) to evaluate their performance. It also links these changes to maize (*Zea mays* L.) productivity under tropical conditions; a crop widely cultivated for food and fodder in sub-Saharan Africa[22]. This integrated approach provides a broader understanding of amendment impacts, thereby filling a major gap in previous research which often focused on crop yield responses to isolated parameters.

Therefore, the objective of this study is to determine the temporal release patterns of NPK from selected organic amendments, evaluate their effects on soil quality using indicators such as organic carbon (OC), pH, cation exchange capacity (CEC), bulk density, and aggregate stability, and assess their combined impact on maize growth and yield in tropical Alfisols. The overarching aim is to provide insights that will assist land users in developing effective soil management strategies to enhance nutrient use efficiency, improve soil quality, and mitigate environmental hazards and soil degradation.

Materials and methods

Study location

The experiment was carried out at the Institute for Agricultural Research (IAR) Farm in Samaru, Zaria, Nigeria, situated at an altitude of approximately 686 meters above sea level, with geographical coordinates 11° 11' N and 7° 38' E. The study site falls within the Northern Guinea Savanna agro-ecological zone, which experiences a tropical climate characterized by a distinct wet season from May to September and a dry season from October to April. Annual rainfall in the area averages around 1000 mm, and temperatures range from 21 °C to 30 °C[23]. Soils in this location are predominantly Alfisols, which are inherently low in organic matter and essential plant nutrients (Table 1). These soils are commonly cultivated for crops such as maize, cowpea, and pepper, although sustained productivity often relies heavily on synthetic fertilizers.

Prior to application of soil amendments, the soil was strongly acidic (pH 5.29), consistent with typical Alfisols of Zaria[24,25]. Further analysis showed low levels of nitrogen (0.80 g kg^{-1}), phosphorus (9.80 mg kg^{-1}), potassium (1.1 cmol kg^{-1}), organic carbon (5.20 g kg^{-1}), and cation exchange capacity (5.52 cmol kg^{-1}), aligning with values reported by[26]. The soil had a moderate bulk density (1.44 Mg m^{-3}), suggesting average conditions for infiltration, root penetration, microbial activity, and nutrient exchange[27]. However, the mean weight diameter

Parameters	Measured Value
pH	5.29
Organic carbon (g kg^{-1})	5.20
Total nitrogen (g kg^{-1})	0.80
Available phosphorus (mg kg^{-1})	9.80
Exchangeable potassium (cmol kg^{-1})	1.1
Cation exchange capacity (cmol kg^{-1})	5.52
Bulk density (ρ_b, Mg m^{-3})	1.44
Mean weight diameter (mm)	2.01

Table 1. Initial properties of experimental soil.

(MWD) of soil aggregates (2.01 mm) was below the 2.5 mm threshold, indicating potential susceptibility to wind erosion[28]. Collectively, these indices reflect low inherent fertility and a vulnerability to both chemical and physical degradation, emphasizing the need for amendment interventions to support sustainable crop production.

Experimental Design, treatment Materials, and application rates

A randomized complete block design was employed to evaluate six soil amendment treatments: compost (CMP), biochar (BCH), co-composted biochar (C-BCH), a 1:1 mixture of compost and biochar (CMP + BCH), NPK fertilizer, and a control with no amendments. Each treatment was replicated five times, and plots were arranged in blocks to account for spatial variability across the field. Plot dimensions were 3 m by 4 m with 1 m spacing between plots. The compost used in the study was produced following the method outlined by[29], using a combination of rice straw, dry gmelina leaves, fresh mango and eucalyptus leaves, and cow dung, which were composted under aerobic conditions for six weeks with periodic turning. The biochar was obtained from maize cobs through slow pyrolysis in a muffle furnace at 600 °C for four hours, in line with the protocol of[30]. For the co-composted biochar, maize cob biochar was incorporated during the composting process using the same feedstock and proportions as in the compost treatment. All organic amendments were applied once, two weeks before planting, at a uniform rate of 15 t ha^{-1} and incorporated into the soil to a depth of 15 cm. The NPK treatment consisted of a compound fertilizer applied at the recommended rate of 120 kg N, 60 kg P_2O_5, and 60 kg K_2O per hectare.

Soil sample collection

Soil samples were collected at two-week intervals after planting until the twelfth week, maintaining a consistent depth of 0–30 cm to monitor nutrient release dynamics. Each sampling involved taking five soil cores per plot, which were thoroughly mixed to form a composite sample before air-drying and analysis. Baseline soil properties were determined prior to amendment application to serve as reference points for assessing treatment effects.

Plant sample collection

Maize (*Zea mays*) served as the test crop, planted manually at a spacing of 75 cm by 25 cm, with two seeds per hill thinned to one. Plant growth data including height, leaf area, and chlorophyll content were collected bi-weekly from five randomly selected plants per plot. Leaf area was estimated using the non-destructive formula as described by[31], while chlorophyll content was measured using a SPAD-502 m. At physiological maturity, maize plants were harvested from the central rows of each plot to avoid edge effects. Grain yield per hectare was calculated by extrapolating weights from harvested grains, while cob diameter and length were measured using a Vernier calliper and a rule, respectively.

Laboratory analysis

Soil pH was measured in a 1:2.5 soil-to-water suspension using a glass electrode pH meter. Organic carbon (OC) was quantified using the Walkley-Black dichromate oxidation method, while total nitrogen (TN) was analysed through the Kjeldahl digestion technique. Available phosphorus (Av. P) was determined using the Bray-1 method, and exchangeable potassium (Ex. K) was extracted with neutral 1 N ammonium acetate and measured by flame photometry. Cation exchange capacity (CEC) was estimated from the same ammonium acetate extract by distillation following replacement with sodium. Bulk density (ρb) was calculated using the core method, where undisturbed soil cores were oven-dried and weighed. Aggregate stability was assessed via the Mean Weight Diameter (MWD), obtained by dry sieving air-dried aggregates through a nest of sieves of decreasing mesh sizes. All procedures adhered strictly to the methods described by[32], with quality control ensured through repeated standard samples and calibration runs.

Soil quality index (SQI) determination

To evaluate the integrated effects of soil amendment treatments on soil health, a Soil Quality Index (SQI) was computed using three different approaches: threshold-based scoring, expert-assigned weights, and the Analytic Hierarchy Process (AHP). The threshold-based scoring method utilized in this research is a proposed method that uses a threshold-based system where each soil indicator is scored on a scale from 0 (least suitable) to 1 (most suitable), depending on its proximity to optimal values for maize cultivation. Thresholds were adapted from[33], with scoring anchored on established suitability classes (S1 to N2). Indicators such as OC, CEC, and MWD followed a "more is better" paradigm, while ρ_b followed a "less is better" criterion[34]. Soil pH was assessed based on its optimal range. Each indicator's score was normalized by dividing it by the total score across all indicators, producing derived weights that summed to 1. This method accounts for both the agronomic relevance of indicators and the degree of deviation from optimum soil conditions.

In the second method, weights were assigned based on the functional relevance of each indicator to soil health and crop performance. Organic carbon, given its central role in nutrient retention and microbial dynamics, was assigned the highest weight (0.30). Soil pH, CEC, and ρ_b each received a weight of 0.20, while MWD was given a weight of 0.10 due to its secondary, though still important, role in maintaining soil structure and minimizing erosion[35].

The third method employed the AHP for deriving indicator weights based on pairwise comparisons. The comparison matrix was developed and assessed for consistency using the criteria proposed by[36]. The matrix (Table 2) yielded a maximum eigenvalue (λ_{max}) of 5.14, a consistency index of 0.035 and a consistency ratio (CR) of 0.031. Since the CR was below the acceptable threshold of 0.1, the matrix was considered consistent. The final weights from AHP were then used in the SQI computation.

For all three methods, the final SQI was calculated as the weighted sum of normalized indicator values[7]:

	OC	CEC	pH	ρ_b	MWD	Weights
OC	1	2	3	4	4	0.35
CEC	0.5	1	2	3	3	0.26
pH	0.33	0.5	1	2	2	0.17
ρ_b	0.25	0.33	0.5	1	2	0.12
MWD	0.25	0.33	0.5	0.5	1	0.10

Table 2. Pairwise comparison matrix (Saaty's scale) the and derived AHP weights.

Parameters	CMP	BCH	C-BCH	CMP + BCH	*P*-Value
TN (g kg^{-1})	7.80 ± 1.1^{a}	3.20 ± 0.65^{c}	5.60 ± 1.1^{ab}	6.00 ± 1.2^{ab}	0.023
Av. P (mg kg^{-1})	22.45 ± 4.3^{a}	19.00 ± 4.2^{b}	21.70 ± 4.3^{ab}	19.83 ± 2.5^{b}	0.048
Ex. K (cmol kg^{-1})	4.21 ± 0.9^{b}	6.15 ± 1.2^{a}	5.21 ± 1.2^{ab}	4.92 ± 0.5^{ab}	0.021
OC (g kg^{-1})	167.60 ± 19.2^{a}	99.80 ± 12.1^{bc}	95.70 ± 9.3^{bc}	103.20 ± 10.7^{b}	0.001
pH	8.16 ± 1.3^{b}	10.81 ± 1.9^{a}	8.70 ± 1.2^{b}	9.71 ± 1.7^{ab}	0.009
CEC (cmol kg^{-1})	89.23 ± 9.5^{a}	49.54 ± 6.1^{b}	54.32 ± 6.5^{b}	71.23 ± 8.4^{a}	0.001

Table 3. Chemical properties of CMP, BCH, C-BCH and CMP + BCH. Note: the data are expressed as the means ± standard deviation, and the different letters indicate a significant difference among the different treatments at $p < 0.05$ level. CMP – compost, BCH – biochar, N – total nitrogen, OC – organic carbon, CEC – cation exchange capacity.

$$Soil\ Quality\ Index\ (SQI) = \sum_{i=1}^{5} (w_i \times N_i) \quad (1)$$

Where w_i is the assigned weight and N_i is the normalized score of the *i*th indicator.

Statistical analysis

All collected data were first subjected to descriptive statistics to understand general trends and variation among treatments. One-way analysis of variance (ANOVA) was used to test for significant differences in soil properties, growth parameters, and yield across the six treatments. Where significant effects were observed, treatment means were separated using Duncan's Multiple Range Test (DMRT) at a 5% significance level to perform pairwise comparisons among treatments. In addition to statistical significance, effect sizes were calculated using Cohen's d to quantify the practical importance of treatment effects. The three computed SQI values were also regressed against key productivity indicators such as grain yield and chlorophyll content to identify the SQI method that best captured soil performance. All statistical analyses were conducted using Minitab version 17.0 and R software (version 4.3.3), ensuring reproducibility and robustness in result interpretation.

Results

Characterization of amendment materials

After production, the amendment materials were tested in the laboratory for nutrient characterization as shown in Table 3. CMP had significantly higher ($P < 0.05$) N contents than C-BCH (5.60^{ab} g kg^{-1}) and CMP + BCH (6.00^{ab} g kg^{-1}), which were statistically at par. The BCH amendments had relatively lower N content (3.20^{c} g kg^{-1}), likely due to the volatilization of N during BCH production[37,38]. Similarly, OC content was higher in CMP (167.60^{a} g kg^{-1}) and CMP + BCH (103.20^{b} g kg^{-1}) than in BCH and C-BCH. This was also attributed to the conversion of OC into its stable form at high pyrolysis temperature[39].

Amendment pH values ranged from 8.16 in CMP to 10.81 in BCH, categorizing them as strongly to very strongly alkaline[40]. BCH's high pH stems from its abundance of alkaline salts, including K and Na carbonates, as confirmed by its elevated exchangeable K content (6.15^{a} cmol kg^{-1}). This makes BCH particularly suitable for ameliorating acidic soils as reported by[41]. The CEC was highest in CMP (89.23^{a} cmol kg^{-1}) and CMP + BCH (71.23^{a} cmol kg^{-1}), likely due to high organic matter content. Humic substances in organic matter possess functional groups such as carboxyls, enhancing CEC by adsorbing cations[42]. Across treatments, high CEC values indicate strong potential to improve soil fertility, as SOM can increase nutrient retention by 30–70%[14].

Temporal nutrient release patterns

The nutrient release patterns for N, P and K were plotted for the 12-week duration of this research in Fig. 1(a-c). During the first four weeks, CMP released the highest amount of total nitrogen (2.75 g kg^{-1}), indicative of its rapid mineralization. This is consistent with reports by[43] who noted an initial N surge in NPK and CMP treatments, followed by slowed release due to microbial immobilization. Conversely, BCH-containing treatments exhibited a gradual and consistent N release pattern throughout the study. This sustained release is attributed to biochar's porous and stable matrix that retains nitrogen compounds and moderates mineralization rates[44]. The

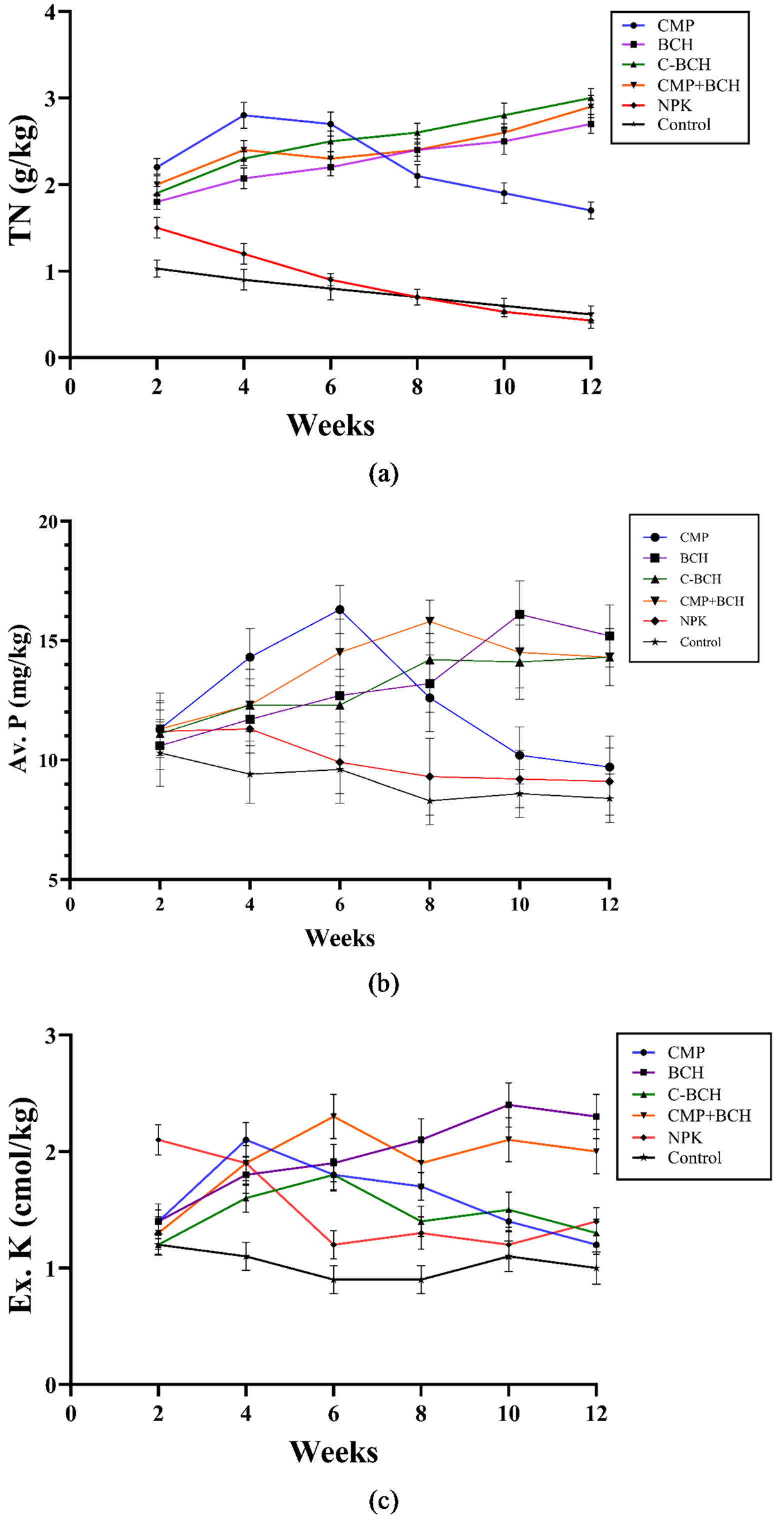

Fig. 1. **(a)** Temporal Dynamics of TN Release under Different Soil Amendment Treatments. **(b)**: Temporal Dynamics of Av. P Release under Different Soil Amendment Treatments. **(c)**: Temporal Dynamics of Ex. K Availability under Different Soil Amendment Treatments. Note: Data points and bars represent mean ± standard deviation (SD). Treatments include compost (CMP), biochar (BCH), co-composted biochar (C-BCH), compost mixed with biochar (CMP + BCH), inorganic fertilizer (NPK), and a control without amendment.

observed N decline in CMP, NPK, and control within the early weeks is likely due to volatilization, nitrification, and plant uptake[43], all of which influence N use efficiency.

A similar pattern was observed for av. P (Fig. 1b). Its content peaked at around 6 weeks in CMP-treated soils before experiencing a sharp decline. This trend aligns with findings from[45], who discussed phosphorus bioavailability dynamics under organic amendment treatments. Phosphorus availability generally decreased across all treatments after the eighth week, with the exception of BCH. This sustained phosphorus availability in BCH-treated soils is attributed to biochar's unique CEC (Table 3) and high surface area, which retain phosphorus in the soil solution and release it gradually as a buffer against rapid P depletion[46].

Potassium availability demonstrated a more complex temporal release pattern, with most treatments showing a marked decrease between weeks 6 and 8. A pronounced decline in potassium was observed after the fourth week in soils amended with NPK, likely due to potassium fixation reducing K bioavailability, as suggested by[30]. Treatments with C-BCH also enhanced K availability; however, a degree of K fixation was noted, likely due to organic matter interactions, as humic substances may form complexes with potassium ions and reduce their immediate availability[47].

Amendment effects on soil quality indicators

Organic carbon

Application of organic amendments showed marked potential in enriching soil OC content as shown in Table 4. Compared to the control (3.1 ± 0.4 g kg^{-1}), soils treated with CMP showed an effect size (Cohen's d) of −6.21 (Table 5), which demonstrates compost's potential to elevate soil carbon content substantially. Other treatments such as CMP + BCH (6.6 ± 2.6 g kg^{-1}) also showed significant improvement. The slower mineralization rates observed with BCH further stabilize carbon, mitigating OC loss over time[48]. This carbon stabilization under biochar and CMP leads to sustained nutrient release to plants, thereby improving long-term fertility[14]. Soil OC plays a direct role in enhancing nutrient retention by providing more exchange sites for nutrient cations, which in turn drives organic matter decomposition, nutrient cycling and overall soil quality[30].

Soil pH

BCH and CMP treatments increased soil pH from 5.1 ± 1.1 in the control to 6.0 ± 0.6 and 7.4 ± 1.2, respectively, with BCH showing a Cohen's d of −5.75 relative to the control. The release of organic acids, mainly carboxylic, phenolic and amino acids during organic matter decomposition contribute to soil buffering, particularly in soils prone to acidification[8]. In their study, Wang et al[49]. also found that biochar's alkaline nature counteracted soil acidity, thereby buffering pH and optimizing nutrient availability for pH-sensitive elements like phosphorus which are required by crops in macro quantities.

Cation exchange capacity (CEC)

Organic amendments significantly improved soil CEC, with CMP and CMP + BCH exhibiting higher mean CEC values of 8.0 ± 3.6 and 8.1 ± 3.6 cmol kg^{-1} respectively, compared to 5.2 ± 2.1 cmol kg^{-1} in the control (Table 4). The effect size of −7.93 for CMP relative to the control buttresses the strong effect of compost in increasing soil nutrient-holding capacity. This is influenced by the high content of OC in the amendment materials, which provides negatively charged sites for cation adsorption. Biochar contributes further with its high surface area and pH-buffering properties that promotes the creation of stable organic-inorganic complexes that reinforce soil CEC over time[50]. This synergistic effect between compost and biochar can thus sustain nutrient retention, reduce leaching, and enhance plant nutrient uptake[51].

Bulk density (ρ_b)

The ρ_b of plots treated with CMP and CMP + BCH, which averaged 1.33 ± 0.2 and 1.31 ± 0.6 Mg m^{-3} respectively shows the potential of organic amendment to improve soil physical tilth. This is emphasised by the large positive effect between organic amendment treatments and the control (Table 5). The incorporation of organic matter reduces soil compaction by promoting aggregate formation, which increases porosity and decreases particle density[49]. This process facilitates root penetration and enhances water infiltration, creating favourable conditions for plant growth[52,53].

Mean weight diameter (MWD)

The increase in MWD with CMP (2.10 ± 0.3 mm) and CMP + BCH (2.38 ± 0.2 mm) treatments, marked by the significant Cohen's value against the control (−7.70 and − 8.03) further reveals the role of organic amendments

Indicators	Control	CMP	BCH	C-BCH	CMP + BCH	NPK	*P*-Value
OC	3.1 ± 0.4^{c}	8.1 ± 2.3^{a}	7.2 ± 3.2^{a}	7.6 ± 1.6^{a}	6.6 ± 2.6^{b}	2.9 ± 1.2^{c}	0.001
pH	5.1 ± 1.1^{bc}	6.0 ± 0.6^{b}	7.4 ± 1.2^{a}	7.3 ± 1.4^{a}	6.7 ± 1.2^{ab}	4.9 ± 2.3^{c}	0.021
CEC	5.2 ± 2.1^{b}	8.0 ± 3.6^{a}	8.4 ± 2.2^{a}	8.3 ± 3.2^{a}	8.1 ± 3.6^{a}	5.1 ± 1.2^{b}	0.036
ρ_b	1.41 ± 0.2^{a}	1.33 ± 0.2^{a}	1.37 ± 0.5^{a}	1.36 ± 0.3^{a}	1.31 ± 0.6^{a}	1.40 ± 0.3^{a}	0.078
MWD	1.90 ± 0.2^{a}	2.10 ± 0.3^{a}	2.3 ± 0.3^{a}	2.33 ± 0.3^{a}	2.38 ± 0.2^{a}	1.83 ± 0.3^{a}	0.082

Table 4. Mean, SE and P-values for treatment effect on key indicators. Note: the data are expressed as the means ± standard deviation, and the different letters indicate a significant difference among the different treatments at $p < 0.05$ level.

Indicators	CMP	BCH	C-BCH	CMP + BCH	NPK
OC (g kg^{-1})					
Control	−6.21	−5.90	−6.36	−3.87	−0.12
CMP		0.24	−0.15	1.42	−5.96
BCH			−0.39	1.25	−5.76
C-BCH				1.64	−4.78
CMP + BCH					−3.22
pH					
Control	−3.33	−5.75	−4.67	−2.90	−0.33
CMP		−2.05	−1.34	0.49	−7.55
BCH			0.67	2.38	−8.63
C-BCH				1.66	−7.90
CMP + BCH					−7.44
CEC (cmol kg^{-1})					
Control	−7.93	−7.79	−8.06	−4.17	0.44
CMP		0.23	−0.18	1.78	5.93
BCH			−0.40	1.62	−5.86
C-BCH				2.00	−7.34
CMP + BCH					−3.97
ρ_b(Mg m^{-3})					
Control	1.72	−0.30	−0.15	0.81	−0.12
CMP		−1.87	−1.72	−0.78	−1.64
BCH			0.15	1.13	−0.23
C-BCH				0.98	−0.13
CMP + BCH					−0.77
MWD					
Control	−7.70	−7.79	−7.84	−8.03	−0.55
CMP		−0.20	−0.32	−0.50	−7.20
BCH			−0.11	−0.31	−6.79
C-BCH				−0.20	−6.48
CMP + BCH					−7.23

Table 5. Cohen's d matrix for soil indicator differences.

in strengthening soil aggregates (Table 4). Higher MWD values correspond with better soil structure stability, which is essential for preventing erosion and maintaining soil resilience[54]. Similar stabilization effects were reported by[55], who attributed the phenomena to microbial exudates and root biomass which aid in reinforcing soil structure by binding particles. In contrast, NPK treatments had limited effect on these properties, with majority of the post-experiment soil characteristics falling within small to medium effect ranges as compared to the control (Table 5).

Growth and yield performance of maize

Growth parameters

CMP + BCH treatment resulted in the highest average plant height (77.5 cm) and leaf area (464.6 cm^2), followed by CMP alone (Fig. 2a and b). Improved nutrient availability and soil physical condition under these treatments facilitated enhanced vegetative growth[56]. The synergy between compost and biochar stabilized OC and supported nutrient mineralization[44]. CMP + BCH also recorded the highest chlorophyll content (67.3 SPAD) (Fig. 2c), suggesting superior nitrogen retention and utilization[57]. Biochar's liming effect likely further enhanced nutrient uptake efficiency.

Yield parameters

Grain weight per plant and cob length were highest in CMP + BCH (155.6 g, 15.8 cm), surpassing both NPK and control treatments (Fig. 2d and e). The slow nutrient release from organic amendments ensured sustained supply during reproductive stages, optimizing seed filling[44]. Total yield followed a similar trend, with CMP + BCH and CMP recording the highest values (304.2 and 296.7 kg ha^{-1}) (Fig. 2f), highlighting the superior performance of organic-based amendments over single-dose application of mineral fertilizers[58].

Effects of treatments on soil quality index (SQI)

To assess treatment effects on soil quality, the SQI was computed using different methods (Table 6) and a linear regression (Fig. 3a-d) was fitted to relate SQI values to maize productivity. The threshold method, which scores indicators based on their nearness to optimal crop nutrient requirements, as suggested by[33] yielded high SQI

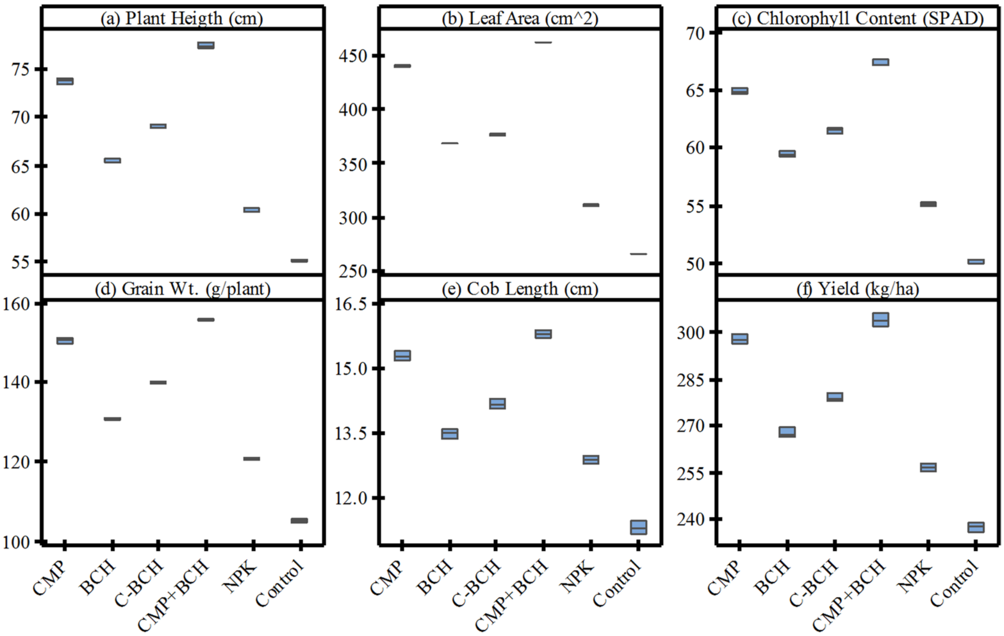

Fig. 2. Box plot of some growth and yield parameters of maize for the treatments.

Treatments	SQI (threshold)	SQI (AHP)	SQI (weighting)
CMP	0.75	0.36	0.57
BCH	0.50	0.29	0.84
C-BCH	0.50	0.29	0.88
CMP + BCH	0.50	0.29	0.91
NPK	0.25	0.26	0.15
Control	0.25	0.26	0.12

Table 6. SQI values for each treatment computed by different methods.

scores for CMP (0.75), while rating the other organic amendment treatments (0.50 each) above NPK and control (0.25 each). The method achieved a high R^2 of 69.5% and 64.5% for explaining variability in leaf area and plant height. Additionally, a significant correlation was observed for this method with grain yield in kg ha^{-1} (r = 0.82*), and grain weight per plant (r = 0.82*) (Table 7). This suggested that the threshold method of SQI determination captures improvements in soil properties that drive yield potential with comparative accuracy.

The AHP weighting method employed a structured hierarchy and scoring system that yielded values generally lower than those obtained through threshold method. The Consistency Index of 0.04 and Consistency Ratio of 0.045 were within acceptable limits, confirming the matrix's reliability in prioritizing soil parameters[59]. The normalized priority matrix derived through AHP placed high weights on OC (0.35) and CEC (0.30), acknowledging their importance in supporting soil quality[34]. However, due to its holistic weighting approach, the AHP method's SQI values yielded lower correlations with immediate crop indicators such as grain weight per plant (r = 0.73) and total maize yield (r = 0.72) (Table 7). This suggested its conservative alignment with soil quality as a function of both productivity and sustainability, as further evidenced by the comparatively lower R^2 values for SQI – AHP with productivity parameters (Table 8). This is consistent with Saaty's AHP framework, which values consistency and reliability[59].

The weighting method attributed weights to indicators based on their relative importance for soil productivity solely based on literature[6]. This method was rather adaptive since it featured a balanced correlation while attributing higher SQI values to biochar-inclusive treatments (CMP + BCH = 0.91 and C-BCH = 0.88). This is corroborated by regression parameters, which exhibited strong predictive relationships with leaf area (R^2 = 60.0%) and plant height (R^2 = 62.5%). Robust correlations to chlorophyll content (r = 0.80) and strong Cohen's d values across OC, CEC, and ρ_b for biochar treatments were observed, suggesting that this method reflect biochar's stability and slow release of nutrients, as well as highlighting other extended benefits to soil structure and plant growth. Each SQI determination method emphasizes different dimensions of soil quality, with the Threshold method aligning closely with productivity, weighting method capturing longer-term benefits, and the AHP method offering a balanced soil assessment. However, all three methods support the conclusion that organic and biochar-amended treatments significantly enhance soil quality in ways that directly benefit crop growth.

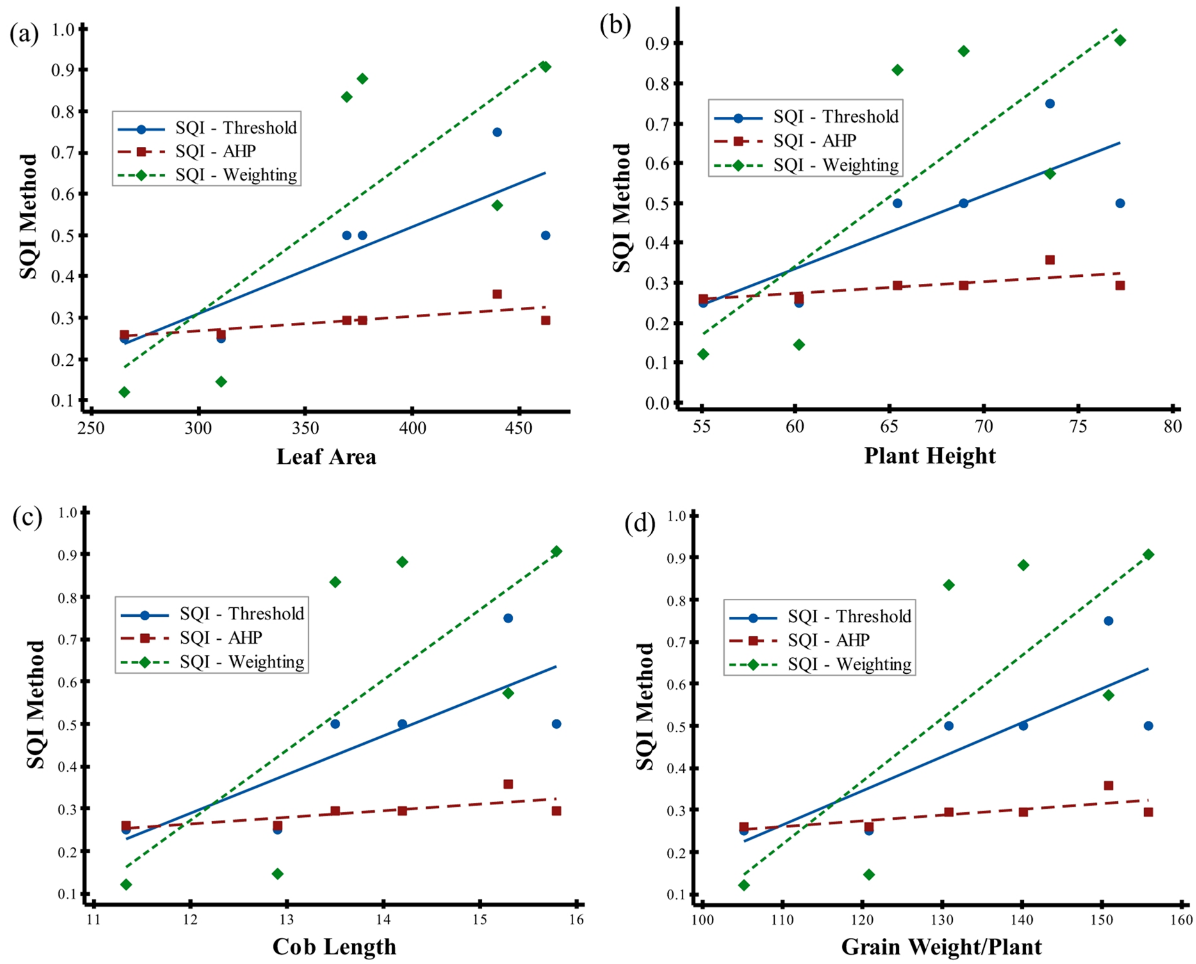

Fig. 3. Linear regression fitting between SQI methods and selected plant growth/yield parameters.

	GW/Plt.	Cob L.	GY/Ha	Plt. Height	LeafA	ChloroC
SQI - Threshold	0.82*	0.80	0.82*	0.80	0.83*	0.81
SQI - AHP	0.73	0.72	0.74	0.71	0.75	0.71
SQI - Weighting	0.78	0.74	0.74	0.79	0.77	0.80*

Table 7. Correlation matrix between different SQI methods and crop yield. GW/Plt. – grain weight per plant (g/plant), cob L. – cob length (cm), GY/Ha – total grain yield per hectare, Plt. Height – plant height (cm), ChloroC – Content of chlorophyll (SPAD).

	SQI - Threshold			SQI - AHP			SQI - Weighting		
Parameters	Slope	Intercept	R^2 (%)	Slope	Intercept	R^2 (%)	Slope	Intercept	R^2 (%)
Leaf Area	0.0021	−0.3195	69.5	0.0004	0.1630	56.2	0.0038	−0.8205	60
Plt. Height	0.0183	−0.7636	64.5	0.0030	0.0913	50.5	0.0349	−1.75	62.5
Cob L.	0.0916	−0.8096	63.5	0.0155	0.0798	51.5	0.1652	−1.709	55.1
GW/Plt.	0.0081	−0.6268	67.3	0.0014	0.1121	53.8	0.0149	−1.418	60.8

Table 8. Regression parameters between SQI methods and crop growth/yield parameter.

Conclusion

The use of soil amendments generally improved soil quality and maize productivity. The rate of nutrient release in chemical fertilizers is rapid, resulting in minimal contributions to soil quality, and often requiring split applications to maintain plant vigour and productivity. In contrast, organic-based amendments exhibited a more gradual nutrient release, promoting sustained nutrient availability throughout the growing period of crops like maize. Additionally, improvement in OC, pH balance, and CEC observed with organic amendment application contributed to a more stable soil environment conducive to plant health and productivity. Application of CMP + BCH at 15 t ha^{-1} is particularly identified among other treatments as a sustainable soil amendment strategy in tropical Alfisols, especially for addressing nutrient limitations and improving soil quality. To optimize nutrient use efficiency and synchronize nutrient availability with maize demand, it is recommended that soil amendments be applied 2–4 weeks prior to planting for maize varieties whose maturity does not exceed 120 days. This ensures that peak nutrient release, notably phosphorus and potassium around week 10 coincides with the crop's critical growth stages. Furthermore, the different methods of SQI computation highlight varying aspects of soil functionality; hence, the threshold and weighting methods are recommended when targeting soil productivity. This assessment was conducted over a single cropping season under field conditions. Although multiple replications were used to improve reliability, environmental fluctuations and cumulative amendment impacts over several seasons were not evaluated. Future studies should therefore incorporate multi-seasonal field evaluations, include broader soil health indicators such as the effects of amendments on microbial dynamics, and conduct long-term monitoring of soil carbon sequestration potential.

Data availability

The datasets generated and/or analyzed during this study are included in this article and its supplementary information files.

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Author contributions

Y.A.: wrote the main manuscript and produced the figures; M.D.: conceptualized the work and partly carried out the field world; R.J.: carried out the field measurements and data collection.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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