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Research

Effect of Biochar Mixed With Different Phosphorus Rates on Selected Soil Chemical Properties in Western Kenya

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Abstract

Low maize productivity in Acrisols and Ferralsols caused by phosphorus (P) fixation poses a constraint to food security in Bungoma County, Kenya. Continuous application of ammonia-based fertilizers has further intensified soil acidification, leading to declining soil productivity. This study evaluated the effect of biochar combined with different P fertilizer rates on selected soil chemical properties and maize performance. Field experiments were conducted during the long and short rainy seasons of 2023 at Kibabii (Acrisols) and Chwele (Ferralsols). A split-plot design with three replicates was used, where biochar sources formed the main plots and P fertilizer rates constituted the subplots. Biochar was applied at 5 t ha^{-1} at planting, together with three P rates (0, 13, and 26 kg P ha^{-1}). Nitrogen fertilizer was applied at 75 kg N ha^{-1} in split applications. Maize hybrid H513 (Kenya Seed Company) was planted at a spacing of 75 × 25 cm. Soil chemical properties including pH, total nitrogen, soil organic carbon (SOC), and available phosphorus were analyzed. Data were subjected to analysis of variance (ANOVA) using GenStat (14th edition, 2012), and treatment means were separated using the Least Significant Difference (LSD) test. The interaction between biochar and P rate was not significant ($p \leq 0.413$), indicating no synergistic influence on maize yield. Correlation analysis between soil chemical properties and grain yield showed a positive relationship with available P ($r = 0.5169$) and negative relationships with soil pH ($r = -0.3340$) and SOC ($r = -0.1132$).

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Statement of Sustainability: This study acknowledges that application of Biochars mixed with different rates of P could contribute to a more sustainable and resilient agricultural sector, long-term economic growth, and environmental protection.

1. Introduction

Western Kenya is one of the densely populated regions in the Kenya, with about 700 humans per km^2 with farm sizes averaging 0.5 ha (KNBSa, 2019a) of which about one – third is planted to maize (staple food in the region). Over 95% of the total farming community in this region is smallholder who often harvest maize yields below 1 t ha^{-1} $season^{-1}$ (Omenyo, 2013). The low maize crop production in this region, particularly in areas under rainfed agriculture, is mainly attributed to the low soil fertility that continues to decline and low use of either inorganic or organic fertilizers (Omenyo, 2013). This leads to nutrient deficiency, which is prevalent in many such crop production systems. As such, there is urgency for new approaches to improve yields, reduce negative effects and enhance sustainability for small scale farmers as well as large scale farmers and commercial producers (Sarah et al., 2025). The dominant soil types in Bungoma county are the ferralsols and acrisols that have low soil fertility due to P fixation by sesquioxides and N losses.

P and N are primary macronutrients which is required in large quantities for fertilization of crops, especially in acrisols and ferralsols soils. It is estimated that up to 90% of the soluble P applied in these soils rapidly assumes insoluble forms due to the

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fixation reactions of phosphate (Behera et al., 2014). P is fixed in these soils by two major reactions i.e. adsorption and precipitation (Santos et al., 2019). The former occurs mainly through ligand–exchange reactions (i.e. formation of inner–sphere complexes) of P-OH groups with exposed –OH/OH_2 groups in Fe and Al oxy-hydroxides and short–range ordered aluminosilicates. Over time, after this initial adsorption, local solutes may become concentrated causing the latter precipitation of Al/Fe phosphate, with some phosphate becoming occluded and isolated from solution. These reactions depend on soil pH and the saturation of surface binding sites with P (Santos et al., 2019). Therefore, increase in crop production has resulted in high demand for inorganic fertilizers.

An example of highly weathered tropical soil that fix P are Ferralsols equivalent to Oxisols in USDA Soil Taxonomy (IUSS, 2014). Ferralsols are red and yellow tropical soils with a high content of sesquioxides. They are rich in Aluminium (Al) and Iron (Fe) hence high P fixation. Ferralsols occur on gently undulating to undulating topography. They are very old, highly weathered and leached soils with a pH ranging 4.8 – 6.3. They have poor fertility, which is restricted to the top soil, as the subsoil has a low cation exchange capacity (Mg, Ca, K deficient). P and N are always deficient in ferralsols. They have good physical properties including an excellent capacity to hold moisture with proper management. Ferralsols are prone to erosion thus the need to maintain high organic matter. The average total P concentrations ranges 360 mg kg^{-1} of soil in A horizons and 212 mg kg^{-1} of soil in Bw layers (IUSS, 2014). The available P in ferralsols ranges between 0.4 – 25 mg kg^{-1} of soil. Another soil with high P fixation similar as ferralsols is acrisols. Acrisols are strongly weathered with low base saturation. They occur in the coffee zones in the sub-humid areas, on undulating to hilly topography. The sub-soil is often not very porous hence impeding root spreading. Acrisols have a relatively low water-storage capacity. They have a low pH (4.5 – 5.5), thus acidic. They also have Al and Mn toxicities and low levels of nutrients and nutrient reserves. Acrisols have high phosphorous (P) fixation and boron and magnesium deficiencies. The total P in acrisols ranges between 15.6 – 410 mg kg^{-1} of soil while the available P ranges between 0.29 – 30.6 mg kg^{-1} of soil (Singh et al. 2015). The application of biochar as a soil amendment is therefore proposed to reduce P fixation and improve the soil fertility in these soils.

Biochar reduces nutrient leaching, stimulation of soil microbes, increased microbial biomass and activity (Nepal et al., 2023), enhancing crop growth and yield, reducing anthropogenic greenhouse gas fluxes and increasing carbon sequestration (Patel and Panwar, 2023). Biochar, often used as a soil amendment to increase soil pH, is a carbonised organic material produced through various thermochemical conversion technologies and Feedstocks (Nguyen Van et. al., 2025). Application of biochar improves the soil pH through liming effect and formation of chelates with these oxides hence releasing the fixed P into the soil for plant absorption (Kätterer et al., 2019). Biochars capacity to decrease acidity enhances soil biological processes, including N fixation and nutrient cycling, resulting in reduced nitrous oxide emissions from the soil (Nguyen Van et. al., 2025). The effects of biochar vary depending on application rates, quality/type of Feedstocks, time following biochar application (short, medium or long-term), method of application (e.g., surface application or tilled to a certain depth), crop response to the biochar, and environment (e.g., soil type or climate conditions) (Premalatha et al., 2023). The short, medium and long-term benefits of biochar amendment have been widely studied, with reports of improved soil quality, increased resource use efficiency, and reduced environmental pollution (Wang et al., 2022). Many previous studies have reported the promising short-term effects of biochar on soil behaviour and plant growth, primarily in low-nutrient and acidic soils under controlled conditions (Khan et al., 2024). However, under field conditions, the impacts of the same biochar may be different (Nguyen Van et. al., 2025). Furthermore, understanding the benefits of biochar application for soil health and plant productivity is essential for optimizing use in agriculture (Guan et al. 2024).

Majority of farmers in western Kenya applies fertilizers with high N and P concentrations at planting, which accelerates soil acidification. P applied to deficient soils often becomes unavailable due to fixation process, limiting its effectiveness for crop uptake. This leads to large amounts being supplied to cater for fixation and to leave some for use by crops. Phosphate fertilizers are expensive and resource constraint farmers hardly afford required amounts and for those than can afford it, becomes uneconomical and unsustainable. Efforts to improve soil fertility through the use of organic amendments like manure and compost, and the development of slow-release fertilizers have been tested but these approaches have limitations. Manure for example releases nutrients slowly and it is also not available on farms in the recommended amounts, while some fertilizers e.g. DAP, Urea, MAP etc., though environmentally friendly, still pose long-term risks to soil health through acidification. Liming strategy is also hindered by bulkiness of agricultural lime required to correct the soil pH making it unviable solution. This necessitates alternative soil management strategies, such as the use of biochar, either alone or in combination with inorganic fertilizers. Biochar has the potential to address soil chemical properties in acrisols and ferralsols by enhancing reducing soil acidity thereby releasing fixed nutrients into the soils and optimizing maize productivity. It offers a promising tool for sustainable soil management, mitigating the negative effects of conventional fertilizers while ensuring long-term soil health and productivity. However, there is limited information on biochar effectiveness in improving soil chemical properties therefore increasing maize productivity in different soils of tropics. This study objective was to analyse the effect of biochar mixed with different P rates on selected soil chemical properties in the study areas. It was hypothesised that there is no significant difference in the effect of biochar-P combinations on selected soil chemical properties in the study areas.

2. Materials and Methods

2.1. Study Area

The experiments were set at Kibabii university farm (0.56990N, 34.55930E) and in Chwele farm (0.73590N, 34.57780E) in Bungoma County, Kenya. Agriculture is the backbone of Bungoma County, with 78% of households engaged in crop and livestock farming. About 50% of people living in the county earn their income directly from the agricultural sector, compared to 44% of the national population in Kenya (KNBS, 2019b). The major food crops grown in Bungoma county are maize, beans, finger millet, sweet potatoes, bananas, Irish potatoes, and assorted vegetables. These are grown primarily for subsistence, with the excess sold to meet other family needs. The main cash crops grown include sugar cane, cotton, coffee, sunflower, and tobacco. The main livestock include cattle, sheep, goats, donkeys, pigs, poultry, and bees. Historically (defined as 1985-2015), Bungoma County receives an annual average rainfall of more than 1400 mm. The annual average temperature ranges between 10-25 °C, although elevation affects temperatures and most of the land area experiences an annual average temperature of more than 20°C. The eastern part of the county, primarily Tongaren and Webuye sub-counties, is the driest, receiving less than 1000 mm of average rainfall every year. The northern part of the county, covering the Mt. Elgon region, is significantly cooler than the southern parts (Mainly covering Bumula and Kanduyi sub counties), with temperature differences on the order of 10°C or more (MoALFC, 2021). Through the application of Biochars combined with phosphate fertilizers, farmers can increase maize productivity in the low fertile soils through improved soil chemical properties.

2.2. Biochar Production

The biochar feedstock's consisted of Wood sawdust (WS) from sawmills within Kakamega town, Coffee Husk (CH) from Kimukung'i Coffee Factory in Bungoma County and Sugarcane bagasse (SB) from Butali Sugar Factory in Kakamega County. The biomasses were chosen due to their availability and contrasting characteristics in terms of nutrients, cellulose, and lignin contents. The feedstock's were collected and transported to KALRO Kakamega station for biochar bulking and pyrolysis using the fabricated metal kilns. The biochar kiln used in the experiment was designed by BionerG Ltd UK (patent pending) and was fabricated at Sigalagala National Polytechnic. KALRO installed weight sensors and thermocouples connected to a data box for real-time data collection, in accordance with BionerG C-GoTM system design guidelines. This kiln was specifically engineered to efficiently convert various feedstock's, such as sugarcane bagasse, coffee husks and wood sawdust into biochar. During the production process, the weights of the feedstock's were meticulously recorded both before and after pyrolysis, along with the total processing time. The kiln design allowed for precise monitoring and control of pyrolysis conditions, ensuring consistent and high-quality biochar production. After pyrolysis, the biochar was mechanically crushed into a fine powder (especially the biochar from sugarcane bagasse) and then packed into gunny bags, making it suitable for storage and use. The biochar chemical analysis results are shown in Table 1.

Table 1. Biochar chemical analysis.

Parameter	Coffee husk (CH)	Sugarcane bagasse (SB)	Wood sawdust (WS)	Typical range
pH	10.52	8.57	10.83	7-14
EC (mS/cm)	493	152	208	200-800
CEC (cmol (+) kg^{-1})	7.64	2.01	3.51	> 10
Organic Carbon (%)	76.4	71.3	67.4	0.5-3
Ash (%)	4.38	5.13	7.64	0.03-0.07
Total P (%)	1.43	0.97	0.48	0.05-0.5
Pb (g/cm^3)	0.23	0.28	0.36	0.3-0.6
Yield (%)	37.7	35.0	37.3	30

Source: Kibabii University Agricultural Laboratory, 2023

2.3. Soil Sampling

Before biochar mixed with P fertilizer applications, six subsoil samples were taken with a soil auger from the top (0–20 cm) soil depth in a random manner based on procedures described by Okalebo et al. (2002). Soils were thoroughly mixed and about 500g composite sample packed in a polythene bag, properly labelled and was taken to Kibabii University agricultural laboratory for chemical analysis for both physical and chemical analyses. After biochars mixed with P fertilizer applications, composite soil samples were also taken from each plot at different intervals as described above during the cropping period (long and short rains of 2023) to monitor the changes in soil chemical properties.

2.4. Laboratory Analysis

Soil samples were air-dried and the ones taken before treatment applications were analysed for pH (1: 2.5; soil: water), available P, exchangeable bases, organic carbon (% C) and total N (%N). Soil samples taken after treatment applications were analysed for pH,

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organic carbon (%C), total N (%N) and available P. The grain samples were analysed for N and P contents. Detailed procedures for both soil chemical and plant analyses are outlined in Okalebo et al. (2002). The chemical characteristics were analysed as follows; The pH of the soils were analysed using electrode method. Soil P was analysed using the UV spectrometry according to Olsen method. Olsen method accurately estimates plant-available P in soils by simulating root uptake, providing reliable fertilizer recommendations, and being effective in a wide range of soil conditions. Total N was analysed by the Kjeldahl oxidation method while soil total carbon was determined by the Walkley Black (WB) method (Nelson and Sommers, 1996).

3. Results and Discussion

3.1. Initial Soil Characterization at Experimental Sites

The initial characterization of the study sites (Table 2) showed that the soils in Chwele was slightly more acidic (pH 4.69) compared with the soil in Kibabii (pH 5.96). Kibabii soil was found to be within agronomical acceptable ranges known to support optimal maize growth, highlighting that the soil conditions were generally favourable for plant development. However, Chwele soil was extremely acidic. Acid soils with low basic cations in the soil makes it unsuitable for maize production. Kibabii soils have higher contents of exchangeable bases, clay and organic matter compared to Chwele soils. Generally, both soils had available P deficiencies (9.2 and 3.4 mg kg^{-1}, below the optimal range of 10-20 mg kg^{-1}), low total N (0.128% and 0.215%, below the optimal range of 1.0-2.0%), and low soil organic carbon (2.342% and 1.292%, categorized as low compared to the optimal range of 3-5%).

Table 2. Selected physico-chemical top soils (0-20 cm depth) properties of the experimental sites in Kibabii and Chwele, Bungoma County.

Parameter	Kibabii	Chwele
pH (1:2.5 soil: water)	5.96	4.69
Olsen P (mg kg^{-1})	9.2	3.4
% Nitrogen (N)	0.128	0.215
% Carbon (C)	2.342	1.292
C:N ratio	10.093	10.893
Exchangeable acidity (mg kg^{-1})	0.493	0.934
Exchangeable bases (cmol+ kg^{-1}) (Mehlich extraction)		
Ca	3.749	3.488
K	0.648	1.896
Mg	0.831	0.61
Micronutrients (mg kg^{-1}) (EDTA extraction)		
Zn	0.205	0.199
Fe	2.391	2.56
Cu	0.072	0.143
Soil Texture (Bouyoucos Hydrometer method)		
% Content		
Sand	57	76
Clay	24	11
Silt	19	13
Textural class	Sandy clay loam	Sandy loam
IUSS WRB Soil Classification	Orthic Acrisol	Rhodic Ferralsol

3.2. Effect of Biochar and Phosphorus on Soil Chemical Parameters

3.2.1. Soil pH

Biochar application, especially in combination with P fertilizer, significantly ($p \leq 0.001$) enhanced soil pH compared to the control in Chwele site. The soil pH increased with the increasing cropping period 4.90 to 5.70 during the cropping season as shown in Table 3.

This could be attributed to the alkaline nature of biochar due to the presence of alkali and alkaline metals in feedstock's that are not volatilized during pyrolysis. When biochar interacts with water, these oxides and carbonates dissolve, yielding hydroxide and carbonate ions, leading to an increase in soil pH. The alkalinity of biochar depends on three important factors: organic functional groups; carbonate content, and inorganic alkali content (Geng et al., 2022; Jemal and Yakob, 2021). Therefore, biochar application to soil could either increase or decrease soil pH based upon the original soil properties (e.g., pH, texture), biochar source, biochar pH and alkalinity. This could be the cause of the rise of soil pH from acidic range in both Kibabii and Chwele soils under coffee

Table 3. Soil pH under different treatments.

Treatments		4 WAS	5 WAS	6 WAS	7 WAS	8 WAS	9 WAS	10 WAS	15 WAS
Coffee Husks	0 kg	4.72a	5.37a	5.65bc	5.51a	5.59a	5.63b	5.64b	5.64b
	13 Kg	4.91d	5.49c	5.66bc	5.57a	5.68abcd	5.68bc	5.69bc	5.74bc
	26 Kg	4.97g	5.62d	5.66bc	5.79bc	5.68abcd	5.68bc	5.69bc	5.71bc
Sugarcane Bagasse	0 kg	4.84c	5.39b	5.64bc	5.68b	5.64abc	5.50a	5.51a	5.44a
	13 Kg	4.95f	5.50c	5.48a	5.69b	5.62ab	5.69bc	5.70bc	5.61ab
	26 Kg	5.04i	5.63d	5.68cd	5.81c	5.79bcd	5.66bc	5.67bc	5.68b
Sawdust	0 kg	4.73b	5.37a	5.68cd	5.75bc	5.82cd	5.70c	5.71c	5.68b
	13 Kg	4.93e	5.49c	5.60b	5.70bc	5.85d	5.71c	5.72c	5.903c
	26 Kg	4.98h	5.62d	5.74d	5.71bc	5.66abcd	5.67bc	5.68bc	5.68b
Grand mean		4.90	5.50	5.64	5.69	5.70	5.66	5.67	5.67
e.s.e.		0.0029	0.0028	0.021	0.0324	0.0579	0.0177	0.0177	0.062
l.s.d.		0.0087	0.009	0.064	0.0972	0.1736	0.053	0.053	0.1859
%CV		10.1	0.1	20.7	11.1	10.8	20.5	8.5	21.9

Mean values with same letter in a column do not differ significantly ($p \leq 0.05$), WAP- Weeks After Planting

husks biochar treatment. The result is in agreement with the finding of Geng et al. (2022) who reported application of compost prepared from coffee husk improved the fertility of the soil and pH of the soil.

3.2.2. Total N (%)

Soil total N was generally affected ($p \leq 0.05$) by various biochar sources. It increased throughout the experiment as indicated in Table 4. Biochar application generally increased soil N and enhanced its retention by reducing N losses. This may be due to improved soil N management by reducing N leaching and increasing retention, acting like a sponge for nutrients via high surface area and cation exchange capacity (CEC), while also boosting microbial activity that immobilizes N. The findings are in line with Abujabhah et al. (2018) who got increased soil N due to addition of biochar on sandy soils. In addition, although the application of biochar increased the soil total N in both sites, it decreased in the control treatments and 13 kg P ha^{-1} treatments. The main reason for this is that the application of biochar loosens and ventilates the soil and transmits light, which is conducive to the growth of crop roots as well as soil microbial growth (Liu et al., 2021). In return, soil microbes will aid in N fixation as well as P availability through microbial processes. Availability of total N will in return enhance crop growth and development as well as yields. This explains the soil total N differences recorded under different treatments as well as yields.

Table 4. Total N (%N) under different treatments.

Treatment		4 WAS	5 WAS	6 WAS	7 WAS	8 WAS	9 WAS	10 WAS	15 WAS
CoffeeHusks	0 kg	0.125a	0.128ab	0.116bc	0.109bc	0.210ab	0.221a	0.237a	0.233a
	13 Kg	0.124a	0.126a	0.1727d	0.165d	0.214ab	0.237abc	0.282b	0.280b
	26 Kg	0.139ab	0.145bc	0.1717d	0.165d	0.214ab	0.248cde	0.301bc	0.295b
Sugarcane Bagasse	0 kg	0.159ab	0.176d	0.0613a	0.054a	0.204a	0.258de	0.239a	0.221a
	13 Kg	0.177b	0.169d	0.1543cd	0.146cd	0.224b	0.264e	0.314c	0.304b
	26 Kg	0.130a	0.150c	0.161d	0.154d	0.210ab	0.254cde	0.297bc	0.288b
Sawdust	0 kg	0.130a	0.135abc	0.109b	0.103b	0.209ab	0.228ab	0.237a	0.231a
	13 Kg	0.136a	0.138abc	0.175d	0.168d	0.216ab	0.244bcd	0.295bc	0.290b
	26 Kg	0.133a	0.142abc	0.175d	0.168d	0.215ab	0.246cde	0.3023bc	0.297b
Grand mean		0.139	0.146	0.144	0.137	0.213	0.244	0.278	0.271
e.s.e.		0.012	0.0057	0.0516	0.0139	0.0058	0.0056	0.0087	0.0117
l.s.d.		0.0361	0.017	0.047	0.0416	0.0173	0.0167	0.0261	0.0351
%CV		20.9	11.9	7.6	24	14.7	10.9	15.4	17.5

Values with same letter in a column do not differ significantly ($p \leq 0.05$), WAS- Weeks After Sowing

3.2.3. Available Soil Phosphorus

Application of various sources of biochar significantly ($p \leq 0.001$) increased available P in soils by providing a direct P source, enhancing P-mineralizing microbial activity, and altering soil chemistry to make P more accessible (Table 5). This can be attributed to coffee husk biochar increasing soil P availability, especially in acidic soils, by raising soil pH and reducing fixation by aluminium and iron hence reducing leaching especially in tropical soils. These findings support the findings by (Hossain et al., 2020), who observed that biochar-enhanced fluvisols soils recorded improved phosphorous retention, reducing nutrient losses during rainfall or irrigation. Addition of different biochar to these soils resulted into a reduction of soil acidity, enabling availability of available

P at different levels. The findings are in line with Lehman et al. (2003) on Planosols soils, Muhammmad et al., 2025 on phaeozems soils, Nguyen Van et al. (2025) on cambisols soils and Jemal and Yakob (2021) on arenosols who got similar results.

Table 5. Available P (mg kg^{-1}) under different treatments.

Treatment		4 WAS	5 WAS	6 WAS	7 WAS	8 WAS	9 WAS	10 WAS	15 WAS
Coffee Husks	0 kg	7.797d	7.058a	7.088a	7.047a	7.322a	7.623a	7.719a	7.721a
	13 Kg	7.506a	7.741c	7.760d	7.756d	8.028c	8.256d	8.386d	8.388d
	26 Kg	8.516f	8.734f	8.939g	8.816g	9.264f	9.346g	10.382i	10.384h
Sugarcane Bagasse	0 kg	7.894e	7.134b	7.220c	7.152b	7.559b	8.019c	8.191c	8.201c
	13 Kg	7.743b	8.021e	8.079f	8.029e	8.423e	8.735e	8.915e	8.929e
	26 Kg	8.872h	9.06h	9.118h	9.134i	9.402g	9.792h	9.899h	9.900g
Sawdust	0k g	7.794cd	7.127b	7.205b	7.210c	7.572b	7.990b	8.154b	8.158b
	13 Kg	7.764bc	7.940d	8.051e	8.052f	8.346d	8.842f	8.942f	8.946e
	26 Kg	8.743g	8.898g	9.186i	9.016h	9.671h	9.999i	9.647g	9.652f
Grand mean		8.07	7.968	8.072	8.024	8.398	8.734	8.915	8.92
e.s.e.		0.0102	0.0091	0.003	0.0048	0.0069	0.0085	0.0049	0.0075
l.s.d.		0.0305	0.0274	0.0089	0.0142	0.0208	0.0255	0.0147	0.0224
%CV		17.6	15.8	10.9	9.09	12	16	19.8	12.6

Mean values with same letter in a column do not differ significantly ($p \leq 0.05$), WAP- Weeks After Planting

3.2.4. Soil Organic Carbon (SOC)

P rates significantly (*p≤0.001*) affected the soil organic carbon at Kibabii site. Biochars had no significant (p=0.356) on soil organic C (Table 6). This can be attributed to P fertilizer that increase SOC by improving plant growth and thus increasing carbon inputs, while also hindering the decomposition of existing organic matter. Prakongkep et al. (2020), also reported similar findings of the improved SOC levels with biochar use, especially when co-applied with organic or inorganic fertilizers, a research that was conducted in tropical soils. Maintaining SOM at a threshold level is crucial for the balanced functioning of agroecosystems and for environmental functions (Nogués et al., 2003). It also plays a vital role in the global carbon cycle (Xu et al., 2020).

Table 6. SOC (%) under different treatments.

Treatment		4 WAS	5 WAS	6 WAS	7 WAS	8 WAS	9 WAS	10 WAS	15 WAS
Coffee Husks	0 kg	2.173a	2.177a	2.182b	2.187b	2.190a	2.222a	2.289a	2.277a
	13 Kg	2.228bc	2.234b	2.242de	2.247de	2.250b	2.275b	2.345b	2.336cd
	26 Kg	2.248c	2.246cd	2.245de	2.250de	2.254b	2.300b	2.363bc	2.343d
Sugarcane Bagasse	0 kg	2.193ab	2.185a	2.160a	2.165a	2.156a	2.269a	2.307a	2.269a
	13 Kg	2.2753c	2.249d	2.224c	2.229c	2.244b	2.336c	2.369c	2.320a
	26 Kg	2.236bc	2.245cd	2.246de	2.251de	2.242b	2.295b	2.356bc	2.345d
Sawdust	0 kg	2.177a	2.178a	2.179b	2.184b	2.186a	2.229a	2.295a	2.278a
	13 Kg	2.240bc	2.238bc	2.238d	2.243d	2.248b	2.290b	2.350bc	2.331c
	26 Kg	2.243c	2.245cd	2.248e	2.253e	2.255b	2.294b	2.358bc	2.343d
Grand mean		2.224	2.2218	2.072	2.223	2.224	2.279	2.337	2.316
e.s.e.		0.01455	0.00301	0.003	0.002742	0.01256	0.0102	0.00613	0.00309
l.s.d.		0.04361	0.00903	0.0089	0.00822	0.03767	0.0305	0.01839	0.00926
%CV		11.3	10.7	10.9	6.2	9.7	17.6	10.6	11.7

Mean values with same letter in a column do not differ significantly ($p \leq 0.05$), WAS- Weeks After Sowing

3.2.5. Correlation Between Soil Chemical Characteristics and Maize Grain and Stover Yield

The analysis of correlations between soil chemical characteristics and maize performance (grain and Stover yield) revealed varying degrees of association (Table 7). Grain yield was positively correlated with available P (r = 0.5169), suggesting that soils with higher P contents tend to support better grain production. On the other hand, grain yield showed negative associations with soil pH (r = –0.3340), and SOC (r = –0.1132), indicating that excessive levels or imbalances in these parameters may suppress yield.

In addition, Stover yield correlated positively with available P (r = 0.3833), but negatively with pH (r = –0.4607). However, SOC showed a weak positive relationship with Stover yield (r = 0.0172), implying little to no effect. Total N exhibited strong positive correlations with available P (r = 0.6369), suggesting that N dynamics in the soil are closely linked with P availability. Its relationship with grain yield (r = 0.4158) and Stover yield (r = 0.3899) was moderate and positive, pointing to the critical role of nitrogen in crop productivity. Overall, the results emphasize the importance of P and nitrogen as key drivers of maize productivity, while imbalances in pH, and organic carbon may exert negative or inconsistent effects. The correlation analysis provided complementary

Table 7. Correlation between soil chemical characteristics and maize grain and Stover yield.

Parameter		Correlation coefficient						
Av. P	1	1	2	3	4	5	6	7
Grain yield (t ha^{-1})	2	0.5169	0.6462					
Ph	3	0.2746	-0.0514	-0.334	0.4777			
SOC	4	-0.3311	0.1042	-0.1132	0.3551	-0.2251		
Stover yield (t ha^{-1})	5	0.3833	0.5789	0.7752	-0.2788	-0.4607	0.0172	
Total n	6	0.6369	0.5087	0.4158	-0.2102	-0.0109	0.0025	0.3899

insights into how soil nutrient status shapes maize productivity. Grain and Stover yield were positively associated with available P , confirming the critical role of this nutrient in supporting both biomass accumulation and grain filling. These results resonate with findings from Kenya and elsewhere in sub-Saharan Africa, where P deficiencies have been linked to poor maize performance and low nutrient use efficiency (Mutuo, 2021). The observed strong correlation between Stover and grain yield further reinforces the close physiological linkage between vegetative growth and reproductive output. In contrast, negative correlations of grain yield with soil pH and organic carbon indicate that imbalances or excessive levels of these parameters may constrain crop performance. Elevated soil pH, particularly beyond the optimal range for maize, is known to reduce P solubility and micronutrient availability, leading to yield suppression (Zhao et al., 2020). The weak and inconsistent effect of soil organic carbon on yield may reflect the complexity of SOC pools, where not all organic matter fractions are readily mineralizing or beneficial for nutrient supply (Kibet et al., 2022). N displayed moderate positive correlations with both grain and Stover yield, consistent with its central role in photosynthesis and protein synthesis. Its strong associations with available P further highlight the interconnectedness of nutrient dynamics, whereby balanced nutrient supply is necessary to maximize crop response. These interactions support integrated soil fertility management approaches that combine organic and inorganic amendments to optimize nutrient availability and crop uptake.

4. Conclusion

Selected soil chemical characteristics were improved by application of biochar further highlighting the importance of P and N as key drivers of maize productivity, while imbalances in soil pH and organic carbon may undermine maize yield potential. These findings reinforce the importance of integrated soil fertility management tailored to both soil properties and seasonal conditions. The results coborrates with the study's objectives to assess the significance of biochar on soil physiochemical properties. Therefore, this research based on a multi-disciplinary framework provides a comprehensive short term understanding of biochar technology use and application on different types of soils in western Kenya based on two growing seasons. Combining biochar with fertilizers is potential tool for enhancing soil fertility, therefore integrating it into the soil fertility programmes, will help farmers address soil acidity and nutrient deficiencies challenges in their soil, leading to enhanced food security.

Author Contributions

Conceptualization; Collins Otieno Majengo, Jonathan Mutonyi, Caroline Agamala Kundu, Francis N. Muyekho; Data curation: Collins Majengo; Funding acquisition; NA; Investigation, Collins Otieno Majengo; Methodology, Collins Otieno Majengo, Caroline Agamala Kundu; Resources: Caroline Agamala Kundu, Jonathan Mutonyi: Software, Caroline Agamala Kundu; Supervision, Francis N. Muyekho, Caroline Agamala Kundu, Jonathan Mutonyi; Validation, Francis N. Muyekho, Jonathan Mutonyi; Visualization, Collins Otieno Majengo; Writing -original draft, Collins O. Majengo; Writing – review & editing, Jonathan Mutonyi, Francis N. Muyekho, Caroline Agamala Kundu.

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Declarations

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