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Effect of Biochar and Inorganic Fertilizer on Soil Biochemical Properties in Njoro Sub-County, Nakuru County, Kenya

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Abstract

Declining soil fertility is a major constraint to potato farming, the second most important food crop in Kenya. The objective of the study was to determine the effect of different rates of biochar and inorganic fertilizer on some soil properties; soil pH, soil phosphomonoesterases, inorganic nitrogen and extractable phosphorus. The study was conducted for two seasons (short and long rains) at two locations (Egerton University agricultural field and farmer's field in Mau Narok) using a split-plot design in a randomized complete block (RCBD) arrangement with variety as the main plot and soil amendments as the subplot. Biochar and Diammonium Phosphate (DAP) at 0, 5, and 10 t·ha^{-1} and 0, 250, and 500 kg·ha^{-1} respectively, were applied, resulting in nine treatment combinations. Two potato varieties (*Shangi* and *Destiny*) were used in the study. A combination of 5 t·ha^{-1} biochar and 500 kg·ha^{-1} DAP and sole application of biochar at 5 t·ha^{-1} resulted in an increase of 1.25, 2.54 units in soil pH in two seasons, respectively. Similarly, a combination of 5 t·ha^{-1} biochar and 250 kg·ha^{-1} DAP increased soil available phosphorus by 105 units from 30.7 mg·kg^{-1} to 136 mg·kg^{-1}. The application rate of 5 t·ha^{-1} biochar with 250 or 500 kg·ha^{-1} DAP significantly increased soil nitrate by 102.11 and 116.14 units, respectively. Soils amended with biochar at 5 t·ha^{-1} combined with 500 kg·ha^{-1} DAP, 10 t·ha^{-1} of biochar combined with either 250 kg or 500 kg of DAP gave the highest alkaline enzymes (mM pNP × kg^{-1} × h^{-1}). However, the highest acid soil phosphomonoesterases were obtained under the sole application of DAP at 500 ha^{-1}. Thus, using biochar with chemical fertilizer seems a plausible option to ameliorate the declining nutrient base of farmland in Kenya, which could sustainably support potato growth.

Keywords

Biochar, Inorganic Nitrogen, Phosphorus, Soil pH, Phosphomonoesterases

1. Introduction

Productive soil is an indispensable resource to smallholder farming communities of Sub-Saharan Africa (SSA) in addressing food, nutritional and income insecurity [1]. However, the declining soil fertility due to continuous nutrient mining, imbalanced organic matter (OM) levels and reduced nutrient replenishment efforts by farmers such as inappropriate use of organic and chemical fertilizer application, pose a significant threat to sustainable crop productivity and farmers' livelihoods [2] [3] [4] [5]. To mitigate the low soil fertility issue, farmers continuously focus on the application of chemical fertilizers as sole soil amendment to replenish the depleted nutrients for improved crop yield [6]. However, due to the intensified soil degradation in SSA, the soils have limited OM and nutrient reserves resulting in reduced soil responsiveness to chemical fertility. Furthermore, given the high cost of fertilizers, farmers have been forced to apply lower rates than recommended, which insufficiently affects optimal crop yield. Thus, the application of chemical fertilizers solely provides limited success in unravelling the low soil fertility [7]. Therefore, this calls for sustainable integrated soil fertility management (ISFM) approaches that will enhance soil fertility through restoration of OM and nutrient reserves [8].

The integration of biochar with chemical fertilizers has recently become a common ISFM approach [9]. Biochar is a carbon (C)-rich organic material made by thermal degradation of biological matter under anaerobic conditions [10] [11] [12]. Biochar possesses several inherent qualities namely, high organic carbon content, high specific surface area, high porosity, as well as alkaline pH that have been reported to significantly improve various soil physicochemical and biological properties that impact soil productivity and crop yield [13] [14] [15]. Several studies have shown that the incorporation of biochar to soil improves soil structure, soil aggregate stability and aeration, water-holding capacity, nutrient cycling and microbial diversity [16] [17] [18] [19] [20]. Elsewhere, it has been proved that biochar also influences the cation exchange capacity, increases pH, nutrient retention [16] [17]. For instance, studies by Bai *et al.* [21] and Xu *et al.* [22], indicate that addition of biochar not only enhances soil organic nitrogen (nitrate and ammonium) but also minimizes its loss to leaching, possibly because organic carbon in biochar gets sequestered upon application to the soil. Secondly, biochar makes phosphorus readily available by decreasing soil acidity and increasing cation exchange capacity [12] [23]. Due to biochar's ash content and liming capacity, it favors the growth of crops that do not thrive well in acidic soils [23] [24] [25]. In addition, biochar alters soil's microbial activity by increasing acid and alkaline phosphomonoesterase enzymatic activity depending on the soil pH and thus ameliorating organic P mineralization [24] [26]. Thus, combining biochar with chemical fertilizers will enhance soil fertility through restoration of OM and nutrient reserves, hence improving crop yields [27]. Biochar in form of charcoal dust is readily available in SSA and would act as a cheap and sustainable soil amendment to resource-constrained farmers [23], which has enabled biochar to gain global attention over the past years [28] [29] [30].

Despite the various benefits of biochar, only limited research on the effect of biochar on soil properties has been done in Kenya that has resulted in low utilization of biochar in farming. Unfortunately, little is known about the right combination of biochar and other fertilizers and its effect on soil properties under potato (*Solanum tuberosum* L) production, which is the second important crop after maize in Kenya. Hence, this study was conducted to determine the effect of different rates of biochar and inorganic fertilizer on soil phosphomonoesterases, inorganic nitrogen, extractable phosphorus, and soil pH over two cropping seasons. The findings from this study would be a scientific basis to advocate for integrated biochar and chemical fertilizer application in Kenya.

2. Materials and Methods

2.1. Study Site Description

Field-based experiments were carried out for two cropping seasons (short rains of September to December 2020 and long rains of April to August 2021) at two sites in Njoro Sub-county, Nakuru County. Both study sites are situated in the Agro-ecological zone III [31]. The first study site was in field 17 at Egerton University demonstration farm (0˚23'S; 35˚35'E) at an altitude of 2238 m above sea level and receives bi-modal rainfall of approximately 1000 mm annually with average temperatures of 18˚C - 21˚C [31]. It has Mollic Andosols soils that are moderately fertile with good drainage, friable and smeary feel, dark reddish-brown color, and sufficient depth. The second site was at a farmer's field (0˚39'S; 35˚57'E), located in Mau Narok ward, Mathanga Uta village, Nakuru county, at 2900 m above sea level. The area also receives bimodal rainfall with an annual average of 1300 mm, minimum temperatures of 6˚C to 14˚C, and maximum temperatures of 22˚C to 26˚C [31]. This site commonly has Mollic Andosols soils characterized by crumby structure, good drainage, friable consistence, dark brown loams with clay loam texture, and medium organic matter [31]. These site characteristics provide suitable conditions for potato growth [31].

Prior to experimental set up, the soil was sampled at soil depths (0 - 15 cm and 15 - 30 cm) and analyzed for total nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), cation exchange capacity (CEC), soil pH, total organic carbon (OC) and soil texture class as described by Okalebo *et al.* [32] (**Table 1**).

2.2. Source of Varieties, Biochar, and Fertilizers

Two potato (*Solanum tuberosum L)* varieties (*Shangi* and *Destiny*) were used for the study and were both sourced from Agricultural Development Corporation (ADC), Molo. These varieties are the most preferred by farmers in Nakuru because they are high-yielding and quick maturing. They also have moderate resistance to most diseases, especially late blight (*Phytophthora infestans*), potato virus X (*Potato virus X*), and potato leaf roll virus (*Potato leaf roll virus*) [33]

[34]. Biochar (charcoal dust) was sourced from charcoal producers in Nakuru County and thoroughly mixed to make a composite. Before application, the composite biochar was crushed and sieved through a 3 mm mesh to produce a relatively fine powder [35], a biochar sample was analysed for total N, P, K, and Mg. The inorganic fertilizer, Diammonium Phosphate, DAP (18:46:0), was purchased from Meya Agri Traders Limited in Nakuru town, Kenya.

2.3. Treatment Combination and Experimental Design

The field experiments were set up in Randomized Complete Block Design (RCBD) at each study site with three blocks and two main treatments (varieties and soil amendment combinations). The treatments were laid in a split-plot pattern in each block with potato variety as main-plot and soil amendments as sub-plots. The main two treatments included potato variety with two levels (*Shangi* and *Destiny*). The second treatment included an integrated soil amendment, which was combined three DAP levels (0, 250, 500 kg·ha^{-1}), and three biochar levels (0, 5, and 10 t·ha^{-1}) to make nine soil-amendment combinations *i.e.* B0D0 (control), B0D250 (250 kg·ha^{-1} DAP), B0D500 (500 kg·ha^{-1} DAP), B5D0 (5 t·ha^{-1} biochar), B5D250 (5 t·ha^{-1} biochar with 250 kg·ha^{-1} DAP), B5D500 (5 t·ha^{-1} biochar with 500 kg·ha^{-1} DAP), B10D0 (10 t·ha^{-1} biochar), B10D250 (10 t·ha^{-1} biochar with 250 kg·ha^{-1} DAP), B10D500 (10 t·ha^{-1} biochar with 500 kg·ha^{-1} DAP).

2.4. Soil and Biochar Analysis

Soil samples were taken twice *i.e.* before planting at two depths (0 - 15 cm and 15 - 30 cm) and after harvesting at one depth (0 - 15 cm) using soil auger in zigzag sampling pattern. All soils were air dried and sieved using a 2mm sieve except those for soil phosphomonoesterases and inorganic nitrogen that were sampled and kept in a cool ice box with ice cubes to avoid drying. On the other hand, biochar was crushed and sieved through a 3 mm mesh [35].

Total carbon was determined by the Walkley-Black method using sulphuric acid and aqueous potassium dichromate. Cation exchange capacity (CEC) and exchangeable cations were extracted in 1M ammonium acetate as described by Okalebo *et al.* [32]. Calcium and magnesium were determined by atomic absorption spectrophotometry, and sodium and potassium were measured using flame photometry [32]. Soil texture was determined by the hydrometer (Bouyoucos) method [32]. Soil and biochar pH was measured in a 1:2.5 (w/v) soil-water solution using a digital pH meter [32].

Soil samples for phosphomonoesterases enzymes analysis were randomly obtained from the rhizosphere by carefully excavating the soil next to the roots using a soil auger to minimize bulk soil *i.e.*, soil outside the rhizosphere or soil not penetrated by roots was avoided. The soil samples were transferred into a clean bucket and thoroughly mixed to get a composite sample. Of the composite sample, 50 g was placed in bag and taken to laboratory for further analysis. To ensure the soil samples were not exposed to high temperature during transit to laboratory, samples were transported in a cool box filled with ice cubes. At arrival in the laboratory, samples were stored at 4˚C in the refrigerator until analysis [36]. The activity of phosphomonoesterase enzymes was determined by quantifying the amount of p-nitrophenol produced after a 37˚C incubation period of 1 hour for hydrolysis [37]. As described by Tabatabai *et al.* [38], 1 g of soil was assayed at pH 6.5 and pH 11 for acid and alkaline phosphomonoesterases respectively, and incubated with 1 ml of p-nitrophenyl phosphate solution at 37˚C for 1 hour. Then, the yellow colour intensity of p-nitrophenol was quantified using a spectrophotometer at wavelength of 400 nm. Phosphomonoesterase enzymes' activity was measured as mM pNP × kg^{-1} × h^{-1} *i.e.* number of moles of p-nitrophenol produced by 1 kg of a soil at 37˚C per hour [38]. Inorganic soil nitrogen (NO_3^--N and NH_4^+-N) were extracted in 0.5 M K_2SO_4 and measured by the colorimetric method [32]. For biochar, total N and P were determined by the digest method, where the biochar was treated with hydrogen peroxide, sulphuric acid, selenium, and salicylic acid [32]. While for soils, total N was determined by the Kjeldahl method and extractable P by Olsen method [32] (**Table 1**).

Table 1. Biochar and soil chemical and physical properties at the onset of field trials.

Study site	Soil Sample				Biochar
	Egerton		Mau-Narok		
Soil depth (cm)	0 - 15	15 - 30	0 - 15	15 - 30	
Total nitrogen (gkg^{-1})	0.24	0.24	0.26	0.24	0.35
Phosphorus ($mg·kg^{-1}$)	18.50	22.00	30.70	27.60	0.08
Potassium ($Cmol·kg^{-1}$)	1.80	1.40	1.36	0.56	0.73
Calcium ($Cmol·kg^{-1}$)	9.00	10.20	4.60	3.80	1.19
Magnesium ($Cmol·kg^{-1}$)	5.02	4.85	3.36	3.26	0.22
Sodium ($Cmol·kg^{-1}$)	0.20	0.30	0.90	0.50	--
Cation exchange capacity ($Cmol·kg^{-1}$)	29.00	32.00	24.30	25.70	--
Soil pH-H_2O (1:1)	6.01	6.15	5.00	5.20	10.2
Total Org. Carbon ($g·kg^{-1}$)	2.59	2.60	2.87	2.59	--
Acid phosphomonoesterases (mM pNP × kg^{-1} × h^{-1})	100	--	98	--	--
Alkaline phosphomonoesterases (mM pNP × kg^{-1} × h^{-1})	87	--	102	--	--
Sand %	58.00	60.00	56.00	56.00	--
Silt %	14.00	12.00	14.00	14.00	--
Clay %	28.00	28.00	30.00	30.00	--
Texture class	SCL	SCL	SCL	SCL	--

SCL—Sandy clay loam.

2.5. Data Analysis

Normality test was done on the data to ensure its meets the assumptions of Analysis of variance (ANOVA). Analysis of variance (ANOVA) was thereafter done using the General Linear Model procedures of SAS 9.3 version. Treatment means that were significantly different were separated using Tukey's honestly significant difference at P < 0.05.

3. Results

3.1. Soil pH

Soil pH was significantly affected by the soil amendments applied ($P \leq 0.001$) (Table 2). Treatments without biochar *i.e.*, plots that received only DAP and the control significantly lowered soil pH compared to treatments when biochar was added in both sites. This was consistent across the two sites and seasons. At Egerton, treatment B5D500 increased soil pH from the initial 6.01 to 6.55 and 7.25 in fields planted with *destiny* and *shang*i respectively in both seasons. This was not significantly different from other treatments that had biochar. At Mau Narok in the short rain season, soil amendment B5D0 gave the highest soil pH of 7.54 from the initial soil pH of 5.00 which was not significantly different from B10D250 and B10D500 on soils planted with *destiny*. However, in the same season under soils grown with *shangi,* B5D500 had the highest soil pH of 7.39 from the initial soil pH of 5.00. Still, this was not significantly different from the soil amendments of B5D0, B5D250 B10D500. In the long rain season, B5D0 had the highest soil pH for both varieties that was not significantly different from all the other amendments that had biochar (Table 2).

Table 2. Biochar and DAP effects on soil pH at two agro-ecological zones in Kenya.

Treatment	Egerton				Mau Narok			
	Short rain season		Long rain season		Short rain season		Long rain season	
	Destiny	*Shangi*	*Destiny*	*Shangi*	*Destiny*	*Shangi*	*Destiny*	*Shangi*
B0D0	5.66^{abc}	5.99^{bc}	5.05^{c}	4.99^{c}	5.43^{d}	5.31^{d}	4.97^{c}	5.29^{bc}
B0D250	5.55^{bc}	5.75^{c}	4.90^{c}	5.07^{c}	5.46^{d}	5.55^{d}	5.24^{bc}	5.05^{c}
B0D500	5.42^{c}	6.14^{abc}	5.27^{bc}	5.19^{bc}	5.36^{d}	5.60^{cd}	5.19^{bc}	5.29^{bc}
B5D0	6.01^{abc}	6.23^{abc}	5.93^{a}	5.71^{ab}	7.54^{a}	6.68^{ab}	5.69^{abc}	6.24^{a}
B5D250	6.19^{abc}	6.77^{abc}	5.65^{ab}	5.93^{a}	6.43^{c}	6.61^{ab}	5.49^{abc}	5.72^{abc}
B5D500	6.55^{a}	7.25^{a}	5.65^{ab}	5.79^{ab}	6.58^{bc}	7.39^{a}	6.07^{ab}	6.29^{a}
B10D0	6.07^{abc}	6.86^{abc}	6.01^{a}	5.24^{bc}	6.49^{bc}	6.58^{b}	6.28^{a}	6.51^{a}
B10D250	5.92^{abc}	6.78^{abc}	5.70^{ab}	5.75^{ab}	7.26^{a}	6.33^{bc}	5.82^{abc}	5.76^{abc}
B10D500	6.38^{ab}	7.04^{ab}	5.82^{ab}	6.02^{a}	7.11^{ab}	6.85^{ab}	6.08^{ab}	6.00^{ab}
MSD	*0.95*	*1.12*	*0.57*	*0.64*	*0.69*	*0.78*	*1.03*	*0.87*

Means with the same letter(s) within a column are not significantly different at ($p < 0.05$), MSD: Minimum Significance Difference, B: Biochar, D: DAP.

3.2. Soil Phosphomonoesterases

Both acid and alkaline phosphomonoesterase enzymes were significantly affected by soil amendment ($P \leq 0.001$) (**Table 3**), (**Table 4**). There were significant differences in the response of both enzymes to the applied treatment factors. Sole application of biochar was not significantly different from unamended soils for the acid enzymes. Combination of biochar and DAP induced significant increases in soil alkaline enzymes. Generally, the controls (soils with no amendment) recorded the lowest levels of alkaline enzymes that were not significantly different from alkaline enzymes under sole application of DAP. In Egerton during the short rains, soil amendment B5D500 under both varieties, gave the highest alkaline enzymes. However, in the long rains, soils under B10D500 planted with *Shangi* gave the highest alkaline enzymes while for *Destiny* the highest was under B10D250 but still these two were not significantly different from B5D500 (**Table 3**). In Mau Narok, B10D500 amended soils gave the highest alkaline enzymes for both varieties during both rainfall seasons. For the acid soil phosphomonoesterases in Mau Narok, the highest levels were under the recommended rate of DAP followed by integration of biochar and DAP which were not significantly different (**Table 4**).

3.3. Soil Inorganic Nitrogen

Soil ammonium and nitrate were significantly influenced by incorporated soil

Table 3. Effect of biochar and DAP on soil acid and alkaline phosphomonoesterases at Egerton, Kenya.

	Egerton							
Variety Treatment	Short rain season (Oct - Dec 2020)				Long rain season (April - July 2021)			
	Destiny		*Shangi*		*Destiny*		*Shangi*	
	Acid enzyme	Alkaline enzyme	Acid enzyme	Alkaline enzyme	Acid enzyme	Alkaline enzyme	Acid enzyme	Alkaline enzyme
B0D0	165.49^{cd}	61.69^{d}	127.49^{b}	76.67^{d}	56.81^{cd}	23.85^{c}	90.46^{a}	29.50^{b}
B0D250	241.18^{a}	36.29^{e}	114.84^{b}	87.33^{d}	76.81^{bc}	28.92^{bc}	98.94^{a}	33.68^{ab}
B0D500	261.77^{a}	102.09^{c}	185.97^{a}	109.79^{c}	101.02^{a}	36.44^{abc}	115.48^{a}	32.89^{ab}
B5D0	135.25^{d}	122.91^{abc}	118.96^{b}	119.00^{bc}	53.14^{d}	32.44^{abc}	84.81^{a}	29.33^{b}
B5D250	230.41^{ab}	137.48^{a}	163.03^{a}	150.26^{a}	91.47^{ab}	37.88^{ab}	101.88^{a}	35.98^{ab}
B5D500	188.46^{bc}	139.13^{a}	163.91^{a}	144.55^{a}	95.05^{ab}	37.94^{ab}	112.78^{a}	38.24^{ab}
B10D0	155.53^{cd}	106.24^{bc}	104.48^{b}	110.04^{c}	59.22^{cd}	35.93^{abc}	83.39^{a}	27.44^{b}
B10D250	182.07^{c}	124.39^{abc}	161.49^{a}	131.86^{ab}	84.97^{ab}	43.83^{a}	100.49^{a}	36.99^{ab}
B10D500	166.80^{cd}	133.87^{ab}	162.68^{a}	144.41^{a}	90.96^{ab}	43.43^{a}	100.91^{a}	43.45^{a}
MSD	*44.76*	*27.79*	*33.81*	*21.67*	*23.19*	*13.23*	*NS*	*11.16*

Means with the same letter(s) within a column are not significantly different at ($p < 0.05$), MSD: Minimum Significance Difference, NS: Not Significantly Different, B: Biochar, D: DAP. Units: units (mM pNP × kg^{-1} × h^{-1}).

Table 4. Effect of biochar and DAP on acid and alkaline phosphomonoesterases at Mau Narok, Kenya.

	Mau Narok							
Variety Treatment	Short rain season (Oct – Dec 2020)				Long rain season (April - July 2021)			
	Destiny		*Shangi*		*Destiny*		*Shangi*	
	Acid enzyme	Alkaline enzyme	Acid enzyme	Alkaline enzyme	Acid enzyme	Alkaline enzyme	Acid enzyme	Alkaline enzyme
B0D0	109.46^{cd}	23.41^{d}	87.15^{def}	25.92^{d}	92.67^{abc}	18.73^{b}	85.31^{ab}	28.07^{c}
B0D250	135.06^{bc}	88.71^{c}	136.52^{bc}	36.73^{d}	101.66^{abc}	18.42^{b}	97.30^{ab}	29.47^{c}
B0D500	174.54^{a}	94.36^{c}	179.49^{a}	106.94^{b}	108.22^{ab}	30.83^{ab}	111.19^{a}	30.39^{c}
B5D0	101.91^{de}	123.40^{ab}	76.43^{ef}	116.16^{b}	74.10^{c}	32.52^{a}	94.03^{ab}	31.37^{c}
B5D250	111.98^{cd}	140.01^{a}	107.72^{cde}	123.43^{b}	107.85^{ab}	37.94^{a}	106.30^{ab}	38.93^{abc}
B5D500	154.44^{ab}	135.40^{a}	134.12^{bc}	120.79^{b}	112.52^{a}	37.76^{a}	113.43^{a}	42.61^{abc}
B10D0	69.61^{e}	90.72^{c}	72.22^{f}	75.43^{c}	80.67^{bc}	33.51^{a}	75.81^{b}	36.38^{bc}
B10D250	154.69^{ab}	106.61^{bc}	114.45^{cd}	103.27^{b}	90.77^{abc}	40.76^{a}	86.77^{ab}	49.84^{ab}
B10D500	146.18^{ab}	143.62^{a}	156.27^{ab}	150.36^{a}	88.76^{abc}	44.13^{a}	93.20^{ab}	51.99^{a}
MSD	*33.09*	*26.29*	*34.28*	*25.96*	*27.98*	*13.55*	*30.81*	*15.53*

Means with the same letter (s) within a column are not significantly different at ($p < 0.05$), MSD: Minimum Significance Difference, NS: Not Significantly Different, B: Biochar, D: DAP. Units: units (mM pNP × kg^{-1} × h^{-1}).

amendments ($P \leq 0.001$) (Table 5), (Table 6). Applied soil amendment of B5D500 gave the highest soil nitrate in Egerton for both short and long rain seasons for both varieties The lowest soil nitrate concentration was observed where no soil amendments were applied (Table 5). Conversely, in Mau Narok, B5D0 and B5D250 gave the highest soil nitrate in short and long rain seasons under *Shangi* Like Egerton, the control treatment gave the lowest soil nitrate in Mau Narok (Table 6). Still in Egerton, soil amendment B5D500 gave the highest soil ammonium in Egerton in the short rain season for both varieties. However, in the long rain season at Egerton, treatments B5D500 and B5D250 were not significantly different for soil ammonium (Table 5). The same trend was observed in Mau Narok for soil ammonium (Table 6).

3.4. Extractable Phosphorus

Soil phosphorus significantly varied with the applied soil amendments ($P \leq 0.001$). Significant increases in soil P were observed from applying the recommended rate of DAP and the combination of biochar and inorganic fertilizer, DAP. Low soil P levels were found in soils under sole biochar and unammended soils. Soil P levels differed during the growing seasons ($P \leq 0.001$) (Table 7). The highest soil phosphorus of 136 mg·kg^{-1} was observed under B5D250 grown with *Shangi* variety in the short rain season at Mau Narok. The lowest 2.0 mg·kg^{-1} was found in soils amended with B5D0 during the long rains planted with *Destiny* in

Table 5. Effect of biochar and DAP on soil nitrate and ammonium at Egerton, Kenya.

Variety Treatment	Egerton							
	Short rain season				Long rain season			
	Destiny		*Shangi*		*Destiny*		*Shangi*	
	Nitrate-N	NH_4^+	Nitrate-N	NH_4^+	Nitrate-N	NH_4^+	Nitrate-N	NH_4^+
B0D0	57.34^{d}	11.97^{e}	84.74^{d}	23.11^{c}	35.78^{ef}	42.49^{d}	26.92^{f}	13.81^{d}
B0D250	112.79^{bc}	29.49^{cd}	174.58^{b}	30.46^{bc}	81.43^{d}	56.96^{c}	58.90^{de}	28.12^{bc}
B0D500	136.46^{ab}	41.75^{bc}	187.88^{ab}	38.53^{ab}	129.12^{c}	78.11^{b}	103.55^{bc}	38.52^{ab}
B5D0	72.15^{cd}	15.54^{e}	93.98^{d}	22.83^{c}	25.55^{f}	25.37^{ef}	20.22^{f}	20.74^{cd}
B5D250	136.17^{ab}	47.63^{ab}	202.11^{ab}	36.46^{ab}	159.57^{b}	84.98^{ab}	120.84^{b}	38.53^{ab}
B5D500	160.39^{a}	57.19^{a}	216.14^{a}	48.11^{a}	194.67^{a}	92.14^{a}	154.57^{a}	50.18^{a}
B10D0	58.84^{d}	13.01^{e}	109.37^{d}	20.73^{c}	18.49^{f}	18.07^{f}	36.33^{ef}	14.33^{d}
B10D250	122.10^{ab}	20.32^{de}	142.70^{c}	24.58^{c}	71.43^{d}	35.28^{de}	76.53^{cd}	21.49^{cd}
B10D500	117.07^{ab}	30.77^{cd}	174.43^{b}	30.45^{bc}	55.76^{de}	57.37^{c}	86.94^{cd}	28.27^{bc}
MSD	*43.49*	*13.19*	*30.05*	*11.78*	*28.43*	*13.95*	*30.82*	*12.05*

Means with the same letter(s) within a column are not significantly different at ($p < 0.05$), Nitrate-N: Nitrate Nitrogen ($MgNO_3$/L), NH_4^+: Ammonium nitrogen ($MgNH_4^+$/L), MSD: Minimum Significance Difference, B: Biochar, D: DAP.

Table 6. Effect of biochar and DAP on soil nitrate and ammonium at Mau Narok, Kenya.

Variety Treatment	Mau Narok							
	Short rain season				Long rain season			
	Destiny		*Shangi*		*Destiny*		*Shangi*	
	Nitrate-N	NH_4^+	Nitrate-N	NH_4^+	Nitrate-N	NH_4^+	Nitrate-N	NH_4^+
B0D0	84.32^{d}	18.38^{ef}	131.76^{c}	13.19^{e}	39.63^{b}	76.64^{d}	34.76^{f}	63.67^{d}
B0D250	117.86^{cd}	36.25^{bcd}	190.89^{b}	34.58^{cd}	137.00^{a}	113.04^{c}	61.43^{ef}	146.74^{c}
B0D500	140.05^{bc}	45.27^{b}	242.36^{a}	48.76^{bc}	146.92^{a}	153.07^{b}	118.88^{cd}	191.65^{b}
B5D0	103.38^{cd}	15.03^{f}	116.45^{c}	15.67^{e}	36.24^{b}	40.73^{e}	82.41^{de}	68.09^{d}
B5D250	179.37^{ab}	43.70^{bc}	134.12^{c}	61.33^{b}	151.63^{a}	177.18^{a}	162.61^{ab}	276.43^{a}
B5D500	206.98^{a}	74.50^{a}	185.52^{b}	88.09^{a}	165.74^{a}	185.21^{a}	173.12^{a}	265.21^{a}
B10D0	117.62^{cd}	33.40^{d}	68.17^{d}	25.33^{de}	40.67^{b}	37.28^{e}	65.84^{ef}	59.62^{d}
B10D250	178.59^{ab}	27.17^{de}	134.67^{c}	33.31^{cd}	123.59^{a}	38.00^{e}	106.69^{cd}	82.14^{d}
B10D500	173.32^{ab}	33.97^{cd}	128.85^{c}	38.01^{cd}	73.59^{b}	65.16^{d}	123.65^{bc}	88.95^{d}
MSD	*40.79*	*9.97*	*37.89*	*16.65*	*47.78*	*21.44*	*39.42*	*33.04*

Means with the same letter(s) within a column are not significantly different at ($p < 0.05$), Nitrate-N: Nitrate Nitrogen ($MgNO_3$/L), NH_4^+: Ammonium nitrogen ($MgNH_4^+$/L), MSD: Minimum Significance Difference, B: Biochar, D: DAP.

Table 7. Effect of biochar and DAP on soil phosphorus (P) at two agro-ecological zones in Kenya.

Variety	Short rain season				Long rain season			
	Egerton		Mau Narok		Egerton		Mau Narok	
	Destiny	*Shangi*	*Destiny*	*Shangi*	*Destiny*	*Shangi*	*Destiny*	*Shangi*
B0D0	16.63^{e}	33.90^{ab}	29.73^{d}	11.02^{d}	4.40^{a}	3.53^{a}	4.92^{a}	4.23^{a}
B0D250	28.70^{bc}	24.37^{bc}	45.47^{c}	19.48^{d}	3.87^{a}	6.20^{a}	3.05^{a}	4.12^{a}
B0D500	38.32^{ab}	30.17^{ab}	98.17^{a}	37.27^{c}	4.16^{a}	7.60^{a}	5.53^{a}	3.37^{a}
B5D0	17.60^{de}	39.83^{a}	23.70^{de}	16.10^{d}	4.20^{a}	4.50^{a}	2.00^{a}	3.30^{a}
B5D250	26.89^{cd}	40.07^{a}	33.73^{cd}	136.00^{a}	4.87^{a}	4.52^{a}	3.62^{a}	3.77^{a}
B5D500	40.20^{a}	36.60^{a}	15.48^{e}	87.83^{b}	6.78^{a}	5.30^{a}	2.10^{a}	3.20^{a}
B10D0	16.23^{e}	32.07^{ab}	90.37^{a}	17.10^{d}	3.88^{a}	5.73^{a}	6.23^{a}	4.37^{a}
B10D250	28.30^{bc}	24.07^{bc}	100.47^{a}	37.47^{c}	3.48^{a}	5.60^{a}	2.80^{a}	4.53^{a}
B10D500	29.90^{bc}	18.80^{c}	74.47^{b}	42.90^{c}	4.53^{a}	8.12^{a}	3.12^{a}	5.28^{a}
MSD	*10.12*	*11.15*	*10.12*	*11.15*	*NS*	*NS*	*NS*	*NS*

Means with the same letter(s) within a column are not significantly different at ($p < 0.05$), P: Phosphorus ($mg \cdot kg^{-1}$), MSD: Minimum Significance Difference, NS: Not Significantly Different, B: Biochar, D: DAP.

Mau Narok. However, the low soil phosphorus under B5D0 was not significantly different from soil phosphorus levels of other soil amendments. In Egerton, during the short rains, the highest soil phosphorus was under soils amended with B5D500 planted with *Shangi* and was not significantly different from soils under a recommended rate of DAP all planted with *Destiny*. Soil amendment B10D0 had the least soil phosphorus, which was not significantly different from B5D0, and the control which were all planted with *Destiny*. However, in the long rains, the highest soil phosphorus was found in B10D500 planted with *Shangi* and did not differ significantly from the soil phosphorus in all the other soil amendments. In Mau Narok, during the short rains, B5D250 treated soils planted with *Shangi* had the most soil phosphorus. Unamended soils planted with *Destiny* had the least soil phosphorus. Soils amended with B10D0 had the highest soil phosphorus in the long rain season but were not significantly different from all the other soils under the different soil amendments (**Table 7**).

4. Discussion

4.1. Soil pH

Soil pH is a very vital soil chemical property that affects nutrient availability, and consequently impacts crop performance. It influences the availability of plant nutrients, mainly nitrogen and phosphorus [39] [40]. If the soils are very acidic (<5.5), there is a tendency for some nutrients to be fixed, leading to their imbalances in the soil [41]. Initially, before biochar was added, soil pH of the two sites was acidic, *i.e.*, 6.01 and 5.00 at Egerton and Mau Narok respectively, which is typical of most potato-growing areas in Kenya. With biochar application, this rose to acceptable range of 5.5 - 6.5 necessary for potato growth in Kenya. Soil acidity in these areas is attributed to constant use of chemical fertilizers, mostly DAP, which supply H^+ ions whose accumulation in soil will acidify the soils in the long run [41]. The cheap and environmentally friendly biochar thus stands as a right amendment to raise the soil pH to suitable range for potato growth.

In this study, there was an increase in soil pH after applying biochar amendments, mainly at the end of the first season, either singly or in combination with inorganic fertilizer. Increments of biochar from 5 $t \cdot ha^{-1}$ to 10 $t \cdot ha^{-1}$ either in sole or in combination with fertilizer resulted into either an increase or a decrease in soil pH. The increase in soil pH could be due to alkaline nature of biochar; thus, there was a liming effect of biochar on the soils. These results agree to findings by Mensah *et al.* [23]. Many studies have found similar results of increased soil pH after applying biochar to acidic soils [14] [42] [43] [44]. Biochar is also known to produce carbonates that are liming in nature that aid in raising the soil pH by reacting with soil hydrogen ions [45]. However, in the long rain season, there was a decline in soil pH after applying biochar. This decrease in soil pH can be attributed to the soil's buffering capacity. Meng *et al.* [46] and Wang *et al.* [47] established that different soil types have different buffering capacities which determine their response to changes in their soil pH. Elsewhere, studies have observed a decline in soil pH after biochar use [48] [49] [50] [51]. This could be due to oxidation of COO- a form of acidic carboxyl groups [52]. Yang *et al.* [53] also found out that biochar caused a sharp decline in soil pH after biochar application in which the biochar effect could not be manifested, which could have been due to the short period of two months. This calls for long-term biochar studies to adequately quantify the amendment's sustainability. On the other hand, sole application of DAP lowered soil pH due to its acidifying character. This is because this fertilizer promotes nitrification leading to a lower soil pH [48] [54]. However, integration of biochar and DAP showed an increase in soil pH. This is consistent with the results obtained by Chan *et al.* [55] who found an increase in soil pH when biochar was combined with nitrogenous fertilizer of ammonium nitrate.

4.2. Soil Phosphomonoesterases

Soil phosphorus enzymes, especially the soil phosphomonoesterases, play a pivotal role in mineralizing organic P to inorganic P that can be utilized by plants [56]. The soil phosphomonoesterases are pH-dependent with acid phosphomonoesterases thriving in acidic soils ranging from 4 to 6.5 while the alkaline phosphomonoesterases are dominant in alkaline soils of pH 9 to 11 [57]. The sites in this study were generally acidic, explaining the dominance of acid phosphomonoesterases over alkaline phosphomonoesterases.

Soils treated with DAP showed high soil enzyme levels; the inorganic fertiliser was source of substrate to the enzymes [58]. Similar results were also reported by

Rejsek *et al.* [58]. Also Margalef *et al.* [26] reported increased phosphomonoesterases activities after applying inorganic nitrogenous fertilisers. Acid phosphomonoesterases were higher than the alkaline phosphomonoesterases after amendment with biochar. Similar results were obtained by Antonious *et al.* [59] after amending soils with biochar where the acid phosphomonoesterases were raised by 115% whereas the alkaline phosphomonoesterases did not show significant differences. In this study, biochar increased soil enzyme levels. This is attributed to biochar's potential to refine soil microbial activity by promoting a conducive microhabitat and modifying the rhizosphere [60]. However, some studies have reported low enzyme levels under biochar amended soils due to the biochar inhibiting the enzymes or substrate [48]. There was reduced enzyme activity in the long rain season. This is attributed to the dry season and the reduced soil nutrients. Phosphomonoesterase activity is driven by soil moisture and soil nutrients in which the enzymes' activities decrease more during dry soil periods [26]. The low reduced enzyme activity could also have been due to spraying the potatoes with chemicals to control diseases. These chemicals inhibit soil enzymatic activity where the enzymes are denatured and inhibited by the chemical compound in the pesticides [61]. In a study done by Maria *et al.* [61], Ridomil fungicide that was also used in this study decreased acid phosphomonesterases by 73%. Literature also shows a decrease in soil P enzymes following fumigation [62].

4.3. Inorganic Soil Nitrogen

Soil inorganic nitrogen (SIN) is important to plants since plants take up inorganic nitrogen in the forms of ammonium and nitrate [63] [64] [65]. The highest increases in soil nitrate and ammonium for the two sites in the two seasons were observed in plots where biochar interacted with diammonium phosphate. This is attributed to reduced nutrient leaching and mineralization which improves nutrient availability [66] [67]. Elsewhere, studies have shown that biochar significantly enhances soil inorganic nitrogen [67] [68]. Also, the combination of biochar and DAP could increase both ammonium and nitrate because of the synergistic effect of the two fertilizers. [39] reported an increase in soil inorganic nitrogen due to synergism between biochar and NPK fertilizer in soils grown with maize for one season. It is suggested that biochar could have enabled this by decreasing the leaching of nitrogen ions, enhancing nitrification by promoting the nitrifiers' microbial activity and reducing the rate of volatilization. However, the combination of DAP at recommended rate of 500 kg·ha^{-1} with biochar at 10 t·ha^{-1} resulted in lower inorganic nitrogen than with 5 t·ha^{-1}, and this could be due to the increased soil C/N ratio that led to immobilization of nitrogen. This was also reported by Huang *et al.* [69], who observed a decline in mineral nitrogen when biochar application increased from 10 to 30 t·ha^{-1}. These results show that biochar can adsorb ammonium nitrogen [70]. The performance of biochar in soils depends on various factors such as environmental factors, fertilization, soil and biochar properties, biochar application rates and climatic conditions

[70].

Addition of biochar to soils has shown a positive, negative or neutral effect on soil inorganic nitrogen [66]. This is evidenced in this study in which there were positive results in the first season which declined in the second season, and this was due to the dry season that was experienced in the second season. Soil inorganic nitrogen concentration also varied across the sites since the sites have different soil properties and variation in soil inorganic nitrogen was attributed to climatic conditions. Generally, the use of biochar in combination with DAP gave the highest inorganic nitrogen content in both seasons across sites

A single application of biochar at B5D0 and B10D0 gave low soil inorganic nitrogen results and this was due to the low nitrogen content of 0.35 $g \cdot kg^{-1}$ in the biochar used. This is in line with Mensah *et al.* [23] who also attributed the low soil inorganic nitrogen to the low nitrogen in the biochar used. Furthermore, the biochar could have retained the ammonium and nitrates, reducing their concentration in the soil solution [71]. This could also be attributed to the immobilization of N [66]. Addition of inorganic fertiliser gave high soil inorganic nitrogen. This is because inorganic fertilizers readily release nutrients to the soil and enhance nitrification by availing the substrate to the microbes [66]. Additionally, there could have been reduced soil inorganic nitrogen losses like immobilisation and denitrification [48]. This study showed varying trends across the two seasons, similar results were reported by McElligott *et al.* [72] who suggested long-term studies to track the effectiveness of biochar as an amendment.

4.4. Soil Phosphorus

Phosphorus availability in the soil depends on several factors, such as soil pH and organic matter. Phosphorus tends to be fixed in strongly acidic soils, mainly below 5.5 [73]. This leads to nutrient deficiency in most crops [74]. However, potatoes can tolerate acidic soils. Phosphorus availability for potatoes can be increased by raising the pH to 6 - 7 [41]. Across the two seasons and sites, there was an increase in soil phosphorus from the sole application of DAP and the combination of DAP with biochar. An explanation for this is the ready supply of phosphorus through the chemical fertilizer and additive effect associated with biochar given the optimal pH which made phosphorus readily available [43].

Additionally, the biochar promoted phosphorus mineralization from organic P to inorganic P. These results are in line with those of Farooque *et al.* [75], in which biochar application significantly increased available soil phosphorus. Some studies attribute the positive effect of biochar on soil phosphorus to the phosphorus contained in the biochar itself [74]. However, for this study, the biochar phosphorus was very low at 0.08 $mg \cdot kg^{-1}$ and could not lead to a more significant increment in soil phosphorus. The P differences in sites are because the performance of biochar in soils relies mainly on environmental conditions, soil properties, and climatic conditions [76] [77]. At 10 $t \cdot ha^{-1}$ of biochar, available soil phosphorus was reduced, and this may be due to immobilization in which the phosphates are strongly sorbed on the biochar surfaces.

One of the main mechanisms in which biochar increases soil available P is the enhancement of arbuscular mycorrhiza, which promotes P availability and uptake [60]. Literature showed that the enzymatic activity of phosphatases declined during insufficient soil moisture, thus reducing phosphorus mineralization, resulting in low available phosphorus [26]. The low phosphorus levels in the long rain season could be due to the drop in soil pH since increased acidity tends to fix soil P, making it unavailable in the soil. Furthermore, positive effects of biochar are usually observed in strongly acidic and nutritionally poor soils [77]. However, the study sites were not deficient in P, which could have led to lower soil phosphorus content after biochar incorporation. Also, the low P levels could be attributed to immobilisation and sorption of P onto the biochar surfaces [77].

5. Conclusion

Declining soil fertility lowers potato productivity in Kenya. Sustainable strategies need to be put in place to solve this problem. Here we propose the use of biochar at 5 $t \cdot ha^{-1}$ combined with DAP at 500 $kg \cdot ha^{-1}$ (B5D500) that synergistically led to better chemical soil properties and enzyme build up. The obtained results from this study show that the combination of biochar and inorganic fertilizer had a significant effect on selected soil properties. The decline in soil properties in the second season after the amendment application for some soil properties calls for long-term studies to evaluate the long-term effects of the use of biochar on soil properties.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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