Research Article

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Combined application of poultry litter biochar and NPK fertilizer improves cabbage yield and soil chemical properties

https://doi.org/10.1515/opag-2021-0217
received June 24, 2020; accepted January 15, 2021

Abstract: Low soil fertility is a major problem limiting peri-urban vegetable production in the Kumasi metropolis. This study was conducted to assess the effects of poultry litter biochar (PLB) and NPK fertilizer application on soil chemical properties and the yield of cabbage. Twelve treatments (control, 100% NPK, 50% NPK, 2.5 t ha^{-1} PLB, 2.5 t ha^{-1} PLB + 50% NPK, 2.5 t ha^{-1} PLB + 100% NPK, 5 t ha^{-1} PLB, 5 t ha^{-1} PLB + 50% NPK, 5 t ha^{-1} PLB + 100% NPK, 7.5 t ha^{-1} PLB, 7.5 t ha^{-1} PLB + 50% NPK, and 7.5 t ha^{-1} PLB + 100% NPK) were evaluated under field conditions in a randomized block design with three replications. Combined application of PLB and NPK fertilizer improved the soil chemical properties, growth, and yield of cabbage relative to the control and sole PLB treatments. Application of 5 t ha^{-1} PLB + 50% NPK increased the soil pH, soil organic carbon, available phosphorus, and cation exchange capacity by 26.6, 41.4, 296, and 78.7%, respectively, relative to the control. Moreover, 5 t ha^{-1} PLB + 50% NPK increased the cabbage yield by 73% compared with the control. This study concludes that PLB and NPK fertilizers can be applied to improve the soil chemical properties and yield of cabbage.

Keywords: biochar, cabbage, cation exchange capacity, soil amendment, soil quality

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1 Introduction

Cabbage (*Brassica oleracea* L.) is an important leafy vegetable widely cultivated by vegetable farmers in Ghana. It belongs to the family Brassicaceae together with turnips, cauliflowers, and brussel sprouts (Franzke et al. 2011). It is widely used in the preparation of local food either cooked or used fresh in making salads. Cabbage plays an important role in human nutrition as it contains essential vitamins, minerals, and phytochemicals (Draghici et al. 2013). It serves as a major source of income for vegetable farmers involved in urban and peri-urban agriculture and all the actors in the cabbage value chain, i.e., farmers, middlemen, and market women. Cabbage farming has gained popularity in Ghana due to its lucrative returns from high yields with high profit margins particularly during the off season (December–April). In spite of the nutritional and economic benefits of cabbage, its production is, however, constrained by low soil fertility arising from continuous cropping without replacement of the lost nutrients. Cabbage farming in the Kumasi metropolis is mostly done close to streams where the soils are sandy and poor in nutrients. The global threat of climate change negatively impacts the soil fertility and crop production through erratic rainfall, prolonged periods of drought, and extremely high temperatures. The threat of climate change's impact on soil fertility and agricultural food production with the potential of reducing crop yields in regions that are more vulnerable to its impacts (Chan and Xu 2009) calls for more integrated and sustainable soil fertility management interventions to enhance crop production.

Biochar application as a soil amendment has attracted a lot of attention over the past two decades due to its agronomic and environmental benefits in the agro-ecosystems (Wu et al. 2019). Biochar is a carbon-rich solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment, which can be applied for improving the soil fertility, increasing the resource use efficiency, and reducting the greenhouse gas emissions (IBI 2012). Due to its specific properties, biochar is widely applied to soils for agricultural and environmental benefits; hence, it is important to understand its behavior and functions in the soil (Ahmad et al. 2014). Crop growth enhancement following biochar application has been attributed to its inherent structure and physicochemical properties which directly or indirectly affect the soil properties such as bulk density, porosity, and water content, which in turn promotes nutrient accumulation and growth of beneficial soil microbes (Jaafar et al. 2014). The benefits of biochar application for soil fertility improvement and carbon sequestration have been well studied (Amendola et al. 2017; Gul et al. 2015). Biochar incorporation has been found to increase soil pH, organic carbon, water-holding capacity, cation exchange capacity (CEC), and agronomic use efficiency of applied N (Abiven et al. 2015). Biochar also facilitates the cycling of nitrogen and phosphorus, thereby improving the soil fertility (Zheng et al. 2013). Generally, the elemental composition and the activity of biochar are determined by the biomass feedstock from which it is produced (Zhao et al. 2018). Biochar from animal wastes, e.g., poultry litter and biosolids, have higher levels of essential nutrients than that produced from woody or herbaceous sources (Bird et al. 2011).

Most vegetable farmers within the Kumasi metropolis use fresh poultry litter as an amendment to improve soil fertility for higher crop yields. However, the risk of food contamination by pathogens and emission of greenhouse gases remain the key food safety and environmental concerns associated with the application of fresh poultry litter for crop production (Lesschen et al. 2011). Moreover, biochar application has been shown to reduce greenhouse gas emissions from agricultural fields (Shen et al. 2017; Fidel et al. 2019) as conversion of waste biomass into biochar offers an effective means of sequestering carbon in the soil due to its recalcitrance to decomposition (Major et al. 2010). Charring of poultry litter also offers a means of optimizing its quality for application as a soil amendment as well as a renewable alternative for its disposal, which is sometimes problematic for poultry farmers.

Integrated use of organic and inorganic fertilizers has been advocated as a more sustainable means of improving soil productivity on highly weathered tropic soils. According to Bashagaluke et al. (2020), integrated application of biochar and mineral fertilizers holds promise for improving the productivity of cropping systems in sub-Saharan Africa, with higher economic returns particularly in intercropping systems. Biochar research work in Ghana mainly focused on the use of biochar produced from low-nutrient content biomass feedstock such as corn cob, rice husk, and rice straw (Yeboah et al. 2016; Calys-Tagoe et al. 2019). The effectiveness of biochar produced from nutrient-rich biomass feedstock such as poultry litter for improving soil fertility and crop yield has, however, not been assessed within the context of integrated soil fertility management.

Given the potential of biochar as an amendment to improve soil fertility and increase the use efficiency of applied N (Slavich et al. 2013), we hypothesized that combined application of poultry litter biochar (PLB) and NPK fertilizer will improve the soil quality, growth, and yield of cabbage. We conducted a field experiment to assess the effectiveness of PLB as an amendment for soil quality improvement and increased cabbage production. The objectives of the study were to (a) determine the effects of combined application of PLB and NPK fertilizer on growth and yield of cabbage, (b) determine the optimum rate of PLB and NPK fertilizer application for cabbage production, and (c) assess the effects of PLB application on soil chemical properties.

2 Materials and methods

2.1 Description of experimental site and analysis of soil properties

The experiment was conducted at the research station of CSIR – Soil Research Institute in Kumasi, Ghana, during the major planting season from April to July 2019. The area lies within the semi-deciduous forest zone of Ghana (Latitude 06°40′29.7″N, Longitude 001°40′08.2″W) at an altitude of 268 m above sea level. The area is characterized by a bimodal rainfall pattern, with the major rainy season starting from March to July and the minor season from September to November. The mean annual precipitation of the area is about 1,500 mm while the mean monthly temperatures range from 24 to 28°C. The study was conducted on a sandy loam soil classified as Ferric Acrisol (FAO 1998).

Ten core soil samples were taken from the entire experimental field at 5 m apart along a Z-plane at a depth of 0–20 cm using auger (Eijkelkamp, the Netherlands). The core samples were thoroughly mixed in a bucket and subsampled to obtain a representative composite sample for the experimental field. The composite sample after air-drying and passing through a 2-mm sieve was subjected to physical and chemical analyses. After harvesting, five core soil samples were taken from each treatment plot for analysis to determine the treatment effects on soil chemical properties. Soil pH was determined using a H1 9017 Microprocessor pH meter in a 1:2.5 suspension of soil and water. The modified Walkley-Black method as described by Nelson and Sommers (1996) was used to determine the soil organic carbon (SOC) while the total soil nitrogen was determined by the Kjeldahl method (Soils Laboratory Staff 1984). The available acid-soluble phosphorus was extracted with Bray 1 solution (HCl:NH_4F mixture) as described by Bray and Kurtz (1945) after which the color of the solution was measured photometrically using Spectronic 21 D Spectrophotometer at a wavelength of 660 nm by mixing with coloring agent (ammonium paramolybdate) and a pinch of ascorbic acid. Exchangeable calcium and magnesium were determined in 1.0 M ammonium acetate extract buffered at pH 7 using the titrimetric method. Exchangeable potassium and sodium were determined using 1.0 M ammonium acetate extract buffered at pH 7 using Microprocessor Flame Photometer FP902 PG Instruments and Atomic Absorption Spectrophotometer Agilent Technologies 240 FS, respectively. Soil texture was determined by the hydrometer method. The initial chemical properties of soils at the experimental site are shown in Table 1. The soil at the study area was characteristic of a highly weathered Ferric Acrisol with nutrient deficiencies that limit crop production. The soil was moderately acidic with low levels of nitrogen, potassium, calcium, magnesium, total exchangeable base, and CEC but had adequate amounts of available phosphorus and organic carbon (Yeboah et al. 2013).

Table 1: Initial soil physical and chemical properties

Soil property (units)	Values
pH (1:2.5 H_2O)	5.30
Total nitrogen (g kg^{-1})	1.00
Organic carbon (g kg^{-1})	10.00
Av. phosphorus (brays 1) (ppm)	26.22
Ex. Ca ($cmol_{(+)}$ kg^{-1})	3.20
Ex. Mg ($cmol_{(+)}$ kg^{-1})	0.53
Ex. K ($cmol_{(+)}$ kg^{-1})	0.36
Ex. Na ($cmol_{(+)}$ kg^{-1})	0.03
ECEC ($cmol_{(+)}$ kg^{-1})	4.87
TEB ($cmol_{(+)}$ kg^{-1})	4.12
Ex. acidity	0.75
Sand (g kg^{-1})	840.00
Silt (g kg^{-1})	100.00
Clay (g kg^{-1})	60.00
Texture	Sandy loam

2.2 Production and characterization of PLB

The PLB for this study was produced from poultry litter feedstock obtained from a local poultry farm close to the Soil Research Institute. The poultry litter was air-dried to a moisture content of 15% and was pyrolyzed at a temperature of 450°C using a slow pyrolysis batch kiln located at the Soil Research Institute, Kumasi, Ghana. The charring process had a resident time of 48 h resulting in 65% feedstock weight loss and a biochar recovery yield of 35%. After the charring process was completed, the charred poultry litter was sprinkled with water and left to cool for 3 h. It was then milled and stored in sacks till it was needed for field application. Subsamples of the charred poultry litter were taken from all the sacks, homogenized, and ground to <2 mm for chemical analysis. The pH and electrical conductivity of the biochar were determined after shaking it in deionized water for 30 mins in a 1:5 (biochar–deionized water) ratio. Total carbon and nitrogen concentrations were determined by loss on ignition and Kjeldahl methods, respectively, while total phosphorus was determined by the vanadate–molybdate method. Exchangeable cations (Ca, Mg, and K) were determined in 1 M ammonium acetate (pH 7) extract using the titrimetric method. Ash content of the biochar was determined by dry combustion in a muffle furnace at 550°C for 2 h. The PLB used for this study was alkaline in nature, with significant amounts of plant nutrients. Chemical properties of the PLB are indicated in Table 2.

2.3 Experimental design and treatments

The field experiment was laid out in randomized block design with 12 treatments, each replicated three times. The field was laid into plots measuring 3.0 × 4.8 m with

Table 2: Chemical properties of poultry litter biochar

Property (units)	Values
pH (1:5 H_2O)	11.8
EC (1:5 H_2O) dS/m	5.9
Carbon (g kg^{-1})	380
Nitrogen (g kg^{-1})	21
Phosphorus (g kg^{-1})	19
Potassium (g kg^{-1})	40
Calcium (g kg^{-1})	66
Magnesium (g kg^{-1})	11
Ash (g kg^{-1})	240
C:N ratio	18.1

an alley of 2 m between blocks and 1 m between plots. The treatments imposed consisted of control (no amendment), 100% NPK, 50% NPK, 2.5 t ha^{-1} PLB, 2.5 t ha^{-1} PLB + 50% NPK, 2.5 t ha^{-1} PLB + 100% NPK, 5 t ha^{-1} PLB, 5 t ha^{-1} PLB + 50% NPK, 5 t ha^{-1} PLB + 100% NPK, 7.5 t ha^{-1} PLB, 7.5 t ha^{-1} PLB + 50% NPK, and 7.5 t ha^{-1} PLB + 100% NPK. One hundred percent NPK corresponds to the recommended NPK fertilizer for cabbage at 90 kg ha^{-1} N, 60 kg ha^{-1} P_2O_5, and 60 kg ha^{-1} K_2O. The sources of N, P, and K were sulfate of ammonia, 23% N w/w; triple super phosphate, 46% P_2O_5 w/w; and muriate of potash, 60% K_2O w/w, respectively.

2.4 Land preparation, nursery establishment, transplanting of seedlings, and agronomic management

The land which was used in the previous season for cropping maize was ploughed and harrowed using a farm tractor. PLB treatments were spot applied on the plots 2 weeks before transplanting of seedlings. Seeds of cabbage variety Oxylus were nursed by sowing in drills at 10 cm apart on solar sterilized seed beds measuring 1.2 × 5 m. The seed beds were covered with palm fronds after sowing to provide shade. The palm fronds were removed after emergence and used to provide shade at 2 m above the seed beds. Weak and malformed seedlings were thinned out to prevent overcrowding, and the seedlings were pricked out at 7 days after emergence. Two weeks prior to transplanting the seedlings out onto the field, the seedlings were fertilized with NPK 15:15:15 liquid feed (5 g NPK L^{-1} of water) by direct application to the soil. Insect pests were controlled by erecting nets around and over the seedling beds. The seedlings were transplanted at 4 weeks after emergence at a planting distance of 60 cm between rows and 40 cm within rows. Each plot contained nine rows with seven plants per row, giving a total of 63 plants per plot.

The plots were treated with Funguran 48 h before transplanting to prevent attack by fungal and bacterial pathogens, and the seedlings were irrigated immediately after transplanting using a watering can. Basal fertilizer application was done at planting where 60 kg ha^{-1} N, P_2O_5, K_2O and 30 kg ha^{-1} N, P_2O_5, K_2O were spot applied on plots receiving 100% NPK and 50% NPK, respectively. The remaining dose of N fertilizer was applied as top dress at 5 weeks after transplanting. Regular shallow hoeing was done as and when necessary to control weed growth. Insect pests of cabbage such as caterpillars, diamondback moth, mole cricket, etc. were controlled by spraying with Bypel (*Bacillus thuringiensis*) insecticide at a dosage of 20 g 15 L^{-1} of water fortnightly.

2.5 Data collection

Data on cabbage plant height, stem girth, leaf spread, fresh leaf biomass yield, head circumference, and fresh head yield were collected during crop growth and at harvest. Data on crop growth parameters were taken weekly for a period of 4 weeks. Five plants were randomly selected from each plot and tagged for weekly plant height, stem girth, and leaf spread measurements. Plant height and leaf spread were measured using a measuring tape while stem girth was measured with a digital vernier caliper. At harvest, 10 plants were randomly selected from each plot for the determination of yield indices. Yield indices determined included cabbage head circumference, fresh leaf biomass, and head yield. Partial factor productivity of applied N (PFP_N) which is also an indication of agronomic nitrogen use efficiency (kg yield kg^{-1} N applied) was calculated using the formula:

$$PFP_N = Y_N/F_N$$

where Y_N = crop yield with applied N and F_N = amount of fertilizer N applied (kg ha^{-1})

2.6 Statistical analysis

Data collected on cabbage growth and yield indices were subjected to analysis of variance (ANOVA) using GenStat Statistical Package Version 12.01 (VSN 2008). Comparison of treatment means was done using Duncan multiple range test (DMRT) at 5% level of significance.

3 Results

3.1 Soil chemical properties

Soil chemical properties as affected by the soil amendments at the end of the cropping season are as indicated in Table 3. Soil pH from the control plots was the least (5.25) among the treatments, and this increased significantly ($p < 0.05$) following the application of all the treatments except 100% NPK which was not different from the control.

SOC also increased significantly ($p < 0.05$) following the application of the soil amendments with 5 t ha^{-1} PLB + 100% NPK, giving the highest (14.9 g kg^{-1}) SOC content; but the 50% NPK had the least (5.0 g kg^{-1}). Moreover, 5 t ha^{-1} PLB + 100% NPK significantly ($p < 0.05$) increased the SOC content by 50.5, 28.4, 12.0, and 20.1% as compared to the control, 2.5 t ha^{-1} PLB, 5 t ha^{-1} PLB, and 7.5 t ha^{-1} PLB treatments, respectively; 5 t ha^{-1} PLB + 100% NPK also increased the SOC content by 198 and 63.7% relative to the 50% NPK and 100% NPK treatments, respectively.

Application of the soil amendments significantly ($p < 0.05$) increased the available soil phosphorus relative to the control. The available soil phosphorus was least (26.37 ppm) in the control and highest (104.43 ppm) with the application of 5 t ha^{-1} PLB + 50% NPK (Table 3). The increase in the available soil phosphorus over the control following the application of the soil amendments was in the order: 100% NPK < 5 t ha^{-1} PLB < 50% NPK < 7.5 t ha^{-1} PLB < 7.5 t ha^{-1} PLB + 50% NPK < 2.5 t ha^{-1} PLB + 50% NPK < 2.5 t ha^{-1} PLB + 100% NPK < 7.5 t ha^{-1} PLB + 100% NPK < 5 t ha^{-1} PLB + 100% NPK < 2.5 t ha^{-1} PLB < 5 t ha^{-1} PLB + 50% NPK. Significant increases in CEC compared to the control were recorded for all the amendments imposed except 50% NPK, 100% NPK, and 2.5 t ha^{-1} PLB + 50% NPK and 2.5 t ha^{-1} PLB + 100% NPK which resulted in significant decreases in CEC; 7.5 t ha^{-1} PLB + 100% NPK recorded the highest CEC representing increases of 98.1, 36.0, 10.8, 25.3, and 12.0% compared with the control, 5 t ha^{-1} PLB, 5 t ha^{-1} PLB + 50% NPK, and 7.5 t ha^{-1} PLB + 50% NPK treatments, respectively.

3.2 Plant height, stem girth, and leaf spread

No significant differences were observed between the mean plant height of the control and sole PLB treatments, i.e., 2.5 t ha^{-1} PLB, 5 t ha^{-1} PLB, and 7.5 t ha^{-1} PLB (Figure 1). Combined application of NPK fertilizer and PLB, however, resulted in significant ($p < 0.05$) increases in plant height relative to the control and sole PLB treatments after 4 weeks; 2.5 t ha^{-1} PLB + 100% NPK gave the highest (39.12 cm) plant height while 2.5 t ha^{-1} PLB recorded the least (33.60 cm) plant height which was not significantly different from the control (34.02 cm). Plant height from application of 50% NPK and 100% NPK was not significantly different from the control and the other treatments.

Stem girth responded positively to PLB and NPK fertilizer application (Figure 2). Application of 5 t ha^{-1} PLB + 100% NPK resulted in the highest (2.37 cm) stem girth representing significant ($p < 0.05$) increases of 30, 29, 20, and 20% relative to the control, 2.5 t ha^{-1} PLB, 5 t ha^{-1} PLB, and 7.5 t ha^{-1} PLB treatments, respectively. Stem girth of plants from plots amended with 5 t ha^{-1} PLB + 100% NPK was comparable with that from 7.5 t ha^{-1} PLB + 100% NPK, 7.5 t ha^{-1} PLB + 50% NPK, 5 t ha^{-1} PLB + 50% NPK,

Table 3: Effects of poultry litter biochar and NPK fertilizer on selected soil chemical properties

Soil amendments	pH (1:2.5 H_2O)	SOC (g kg^{-1})	Av. P (ppm)	CEC ($cmol_{(+)}$ kg^{-1})
Control	5.25^{a}	9.90^{c}	26.37^{a}	3.72^{c}
50% NPK	5.55^{b}	5.00^{a}	41.33^{d}	1.46^{ab}
100% NPK	5.20^{a}	9.10^{b}	39.13^{b}	1.75^{b}
2.5 t ha^{-1} PLB	7.05^{h}	11.60^{d}	82.03^{k}	4.91^{d}
2.5 t ha^{-1} PLB + 50% NPK	6.62^{f}	9.90^{c}	56.99^{g}	1.30^{ab}
2.5 t ha^{-1} PLB + 100% NPK	6.52^{e}	12.60^{e}	62.89^{h}	1.25^{a}
5 t ha^{-1} PLB	5.95^{c}	13.30^{f}	40.14^{c}	5.46^{e}
5 t ha^{-1} PLB + 50% NPK	6.65^{f}	14.00^{g}	104.43^{l}	6.65^{f}
5 t ha^{-1} PLB + 100% NPK	6.38^{d}	14.90^{h}	77.82^{j}	7.15^{g}
7.5 t ha^{-1} PLB	6.79^{g}	12.40^{e}	47.77^{e}	5.88^{e}
7.5 t ha^{-1} PLB + 50% NPK	6.81^{g}	11.50^{d}	51.92^{f}	6.58^{f}
7.5 t ha^{-1} PLB + 100% NPK	7.00^{h}	14.10^{g}	75.14^{i}	7.37^{g}
p value	<0.001	<0.001	<0.001	<0.001
CV (%)	5.2	2.7	8.3	6.1

Control = no amendment; 50% NPK = 45 kg ha^{-1} N, 30 kg ha^{-1} P_2O_5, 30 kg ha^{-1} K_2O; 100% NPK = 90 kg ha^{-1} N, 60 kg ha^{-1} P_2O_5, 60 kg ha^{-1} K_2O. Values followed by the same letters in a column are not significantly different (DMRT) at 5% and *vice versa*. SOC = soil organic carbon, Av. P = available phosphorus, CEC = cation exchange capacity.

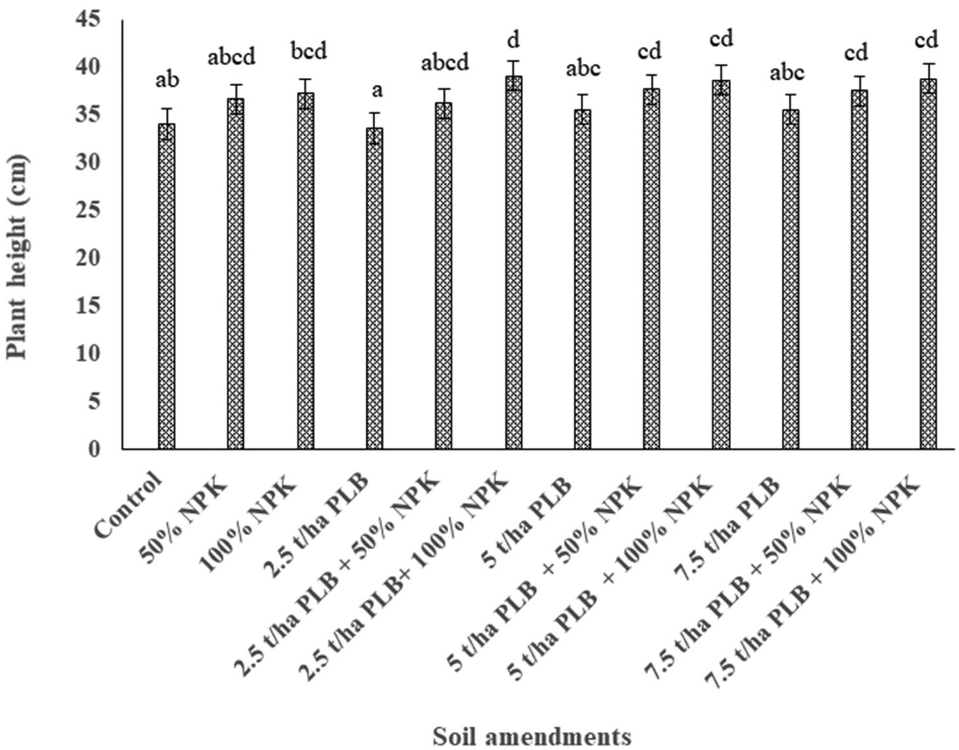

Figure 1: Effect of poultry litter biochar and NPK fertilizer application on plant height of cabbage. Error bars represent ± SED. Treatment bars followed by the same letters are not significantly different (DMRT) at 5% and *vice versa*.

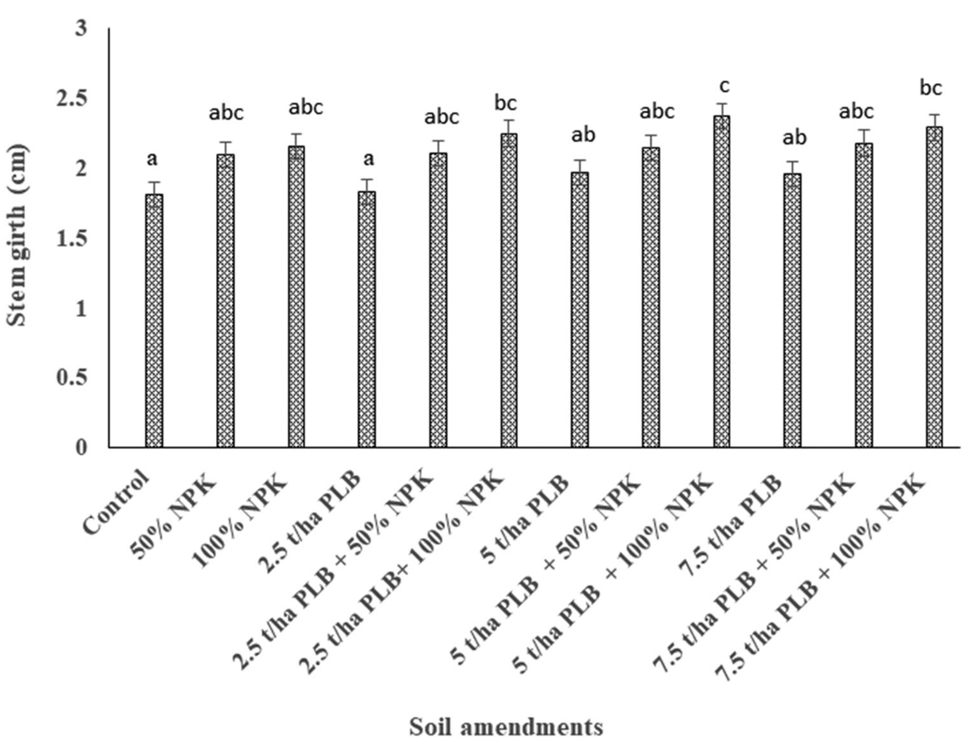

Figure 2: Effect of poultry litter biochar and NPK fertilizer application on stem girth of cabbage. Error bars represent ± SED. Treatment bars followed by the same letters are not significantly different (DMRT) at 5% level of significance and *vice versa*.

2.5 t ha^{-1} PLB + 100% NPK, and 100% NPK treatments but was significantly higher than the rest of the treatments including 50% NPK, 2.5 t ha^{-1} PLB, 5 t ha^{-1} PLB, 7.5 t ha^{-1} PLB, and the control which gave the least stem girth (1.81 cm). Plots amended with sole PLB, i.e., 2.5 t ha^{-1} PLB and 7.5 t ha^{-1} PLB had stem girths that were not significantly different from that of the control. Plots treated with sole 50% NPK and 100% NPK gave stem girths that were comparable with each other when applied solely or in combination with PLB.

The effects of PLB and NPK fertilizer application on cabbage leaf spread are shown in Figure 3. A similar trend was observed in leaf spread with the application of the treatments, where the control treatment recorded significantly ($p < 0.05$) lower (56.51 cm) leaf spread than all other treatments except the sole PLB treatments, which were comparable with that from the control. Application of 7.5 t ha^{-1} PLB + 100% NPK gave the highest (68.97 cm) leaf spread representing increases of 22.0, 20.3, 13.6, and 14.3% compared with the control, 2.5 t ha^{-1} PLB, 5 t ha^{-1} PLB, and 7.5 t ha^{-1} PLB treatments, respectively.

Combined application of either 50% or 100% NPK fertilizer with the PLB treatments significantly increased the cabbage leaf spread compared to their respective sole biochar treatments (i.e., 2.5 t ha^{-1} PLB, 5 t ha^{-1} PLB, and 7.5 t ha^{-1} PLB).

3.3 Head circumference, leaf biomass, and head yield

Cabbage head circumference, leaf biomass, and fresh head yields responded positively to the soil amendments with the control treatment recording the least head circumference, leaf biomass, and fresh head yields (Table 4).

Application of 5 t ha^{-1} PLB + 50% NPK resulted in the highest (63.22 cm) cabbage head circumference, which represented significant ($p < 0.05$) increases of 31.8, 30.1, 17.1, and 30.0% compared to the control, 2.5 t ha^{-1} PLB, 5 t ha^{-1} PLB, and 7.5 t ha^{-1} PLB treatments, respectively. Sole application of 100% NPK and 50% NPK resulted in cabbage head circumference that was not significantly different from all the biochar amended NPK fertilizer treatments except 5 t ha^{-1} PLB + 50% NPK, which recorded significantly higher head circumference (63.22 cm) than the 50% NPK treatment.

Soil amendments resulted in significant ($p < 0.05$) increases in fresh leaf biomass yield compared with the control except the sole biochar treatments (2.5 t ha^{-1} PLB, 5 t ha^{-1} PLB, and 7.5 t ha^{-1} PLB), which were comparable with the control (Table 4). Application of 2.5 t ha^{-1} PLB + 100% NPK and 2.5 t ha^{-1} PLB + 50% NPK increased the leaf biomass yield by 107.7 and 59.0%, respectively, compared to 2.5 t ha^{-1} PLB while the application of 5 t ha^{-1} PLB + 100%

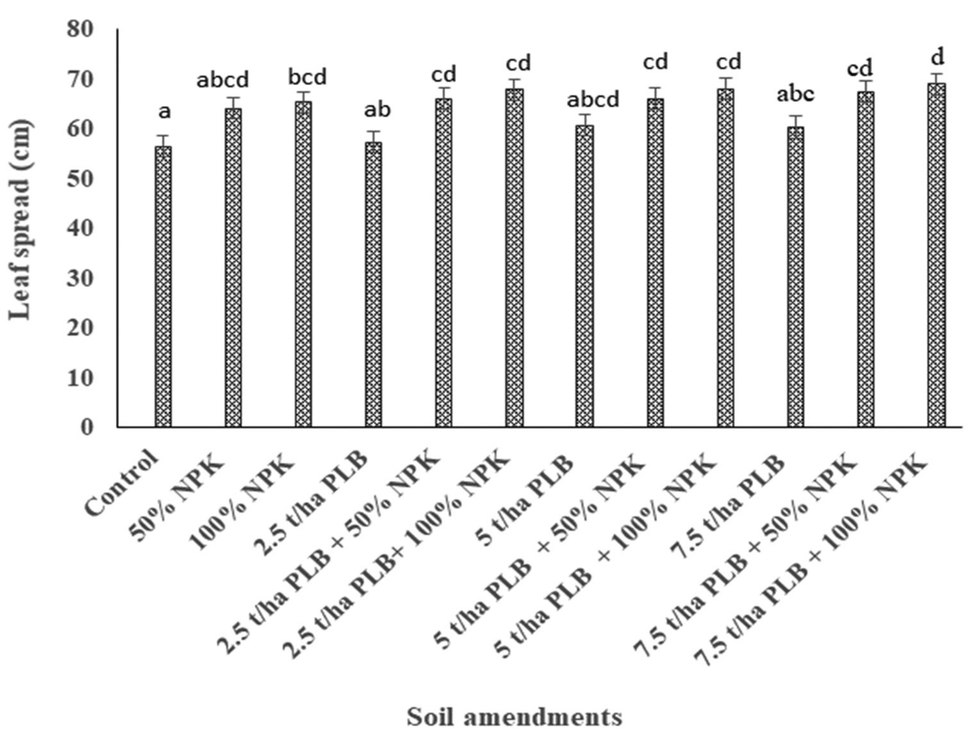

Figure 3: Effect of poultry litter biochar and NPK fertilizer application on leaf spread of cabbage. Error bars represent ± SED. Treatment bars followed by the same letters are not significantly different (DMRT) at 5% and *vice versa*.

Table 4: Effects of poultry litter biochar and NPK fertilizer on cabbage head circumference, leaf biomass, and head yield

Soil amendments	Head circumference (cm)	Fresh leaf biomass yield (t ha^{-1})	Fresh head yield (t ha^{-1})
Control	47.96^{a}	13.75^{a}	41.63^{a}
50% NPK	55.96^{cd}	23.62^{bc}	56.75^{bcd}
100% NPK	59.40^{cde}	26.62^{c}	64.60^{cde}
2.5 t ha^{-1} PLB	48.58^{ab}	14.50^{a}	45.69^{ab}
2.5 t ha^{-1} PLB + 50% NPK	59.05^{cde}	23.06^{bc}	61.50^{cde}
2.5 t ha^{-1} PLB + 100% NPK	62.24^{de}	30.12^{c}	70.56^{de}
5 t ha^{-1} PLB	54.01^{bc}	19.54^{ab}	53.44^{abc}
5 t ha^{-1} PLB + 50% NPK	63.22^{e}	24.50^{bc}	72.12^{e}
5 t ha^{-1} PLB + 100% NPK	60.24^{cde}	29.82^{c}	62.88^{cde}
7.5 t ha^{-1} PLB	48.59^{ab}	19.62^{ab}	42.44^{a}
7.5 t ha^{-1} PLB + 50% NPK	58.80^{cde}	25.88^{bc}	62.38^{cde}
7.5 t ha^{-1} PLB + 100% NPK	60.26^{cde}	29.25^{c}	62.06^{cde}
p value	<0.001	<0.001	<0.001
CV (%)	5.8	15.7	12.8

Control = no amendment; 50% NPK = 45 kg ha^{-1} N, 30 kg ha^{-1} P_2O_5, 30 kg ha^{-1} K_2O; 100% NPK = 90 kg ha^{-1} N, 60 kg ha^{-1} P_2O_5, 60 kg ha^{-1} K_2O. Values followed by the same letters in a column are not significantly different (DMRT) at 5% and *vice versa*.

NPK increased the leaf biomass yield by 52.6% compared with 5 t ha^{-1} PLB. Similarly, 7.5 t ha^{-1} PLB + 100% NPK increased leaf biomass yield by 49.0% relative to the 7.5 t ha^{-1} PLB treatment.

Combined application of PLB and NPK fertilizers resulted in significant differences in fresh head yield of cabbage, with the control treatment recording the least (41.63 t ha^{-1}) head yield while 5 t ha^{-1} PLB + 50% NPK gave the highest (72.12 t ha^{-1}). Moreover, 5 t ha^{-1} PLB + 50% NPK significantly ($p < 0.05$) increased cabbage head yield by 73.2, 57.8, 35.0, and 59.9% compared with the control, 2.5 t ha^{-1} PLB, 5 t ha^{-1} PLB, and 7.5 t ha^{-1} PLB treatments, respectively; 5 t ha^{-1} PLB + 50% NPK also significantly increased head yield by 27% compared to the 50% NPK treatment but was not different from that of the 100% NPK, 2.5 t ha^{-1} PLB + 50% NPK, 2.5 t ha^{-1} PLB + 100% NPK, 5 t ha^{-1} PLB + 100% NPK, 7.5 t ha^{-1} PLB + 100% NPK, and 7.5 t ha^{-1} PLB + 50% NPK treatments. Application of 7.5 t ha^{-1} PLB + 50% NPK significantly increased the cabbage head yield by 47% relative to the 7.5 t ha^{-1} PLB treatment.

3.4 Agronomic nitrogen use efficiency

The effect of PLB application on agronomic use efficiency of nitrogen is as shown in Table 5. No significant differences were observed in nitrogen use efficiency with application of 50% NPK, 100% NPK, 2.5 t ha^{-1} PLB + 50% NPK, and 2.5 t ha^{-1} PLB + 100% NPK treatments.

Application of 5 t ha^{-1} PLB + 50% NPK, however, significantly increased the nitrogen use efficiency ($p < 0.05$) by 133% compared with the 5 t ha^{-1} PLB + 100% NPK treatment. Similarly, 7.5 t ha^{-1} PLB + 50% NPK significantly ($p < 0.05$) increased nitrogen use efficiency by 101% compared to the 7.5 t ha^{-1} PLB + 100% NPK treatment while 5 t ha^{-1} PLB + 50% NPK increased the efficiency of nitrogen use by 27% compared with the 50% NPK treatment but this was not statistically significant.

4 Discussion

4.1 Soil chemical properties

An improvement was observed in soil chemical properties following the application of PLB and NPK fertilizers. Application of PLB resulted in significant increases in soil pH, organic carbon, available phosphorus, and CEC (Table 3). This corroborates the findings of Abiven et al. (2015) that biochar amendment improves soil chemical properties such as pH, organic carbon, and CEC. Akolgo et al. (2020) also observed an increase in soil pH following the application of biochar derived from sawdust and NPK fertilizer. The increase in soil pH following biochar application is a confirmation of biochar's potential as a liming material for managing acidic soils. Biochar's ability to increase soil pH is due to its alkaline nature arising from the inorganic minerals, i.e., carbonates, phosphates, and ash produced during pyrolysis and carbonization (Yuan et al. 2011).

PLB application significantly increased the SOC content, and this can be attributed to the high proportion of

Table 5: Effect of poultry litter biochar application on agronomic nitrogen use efficiency (ANUE)

Soil amendments	ANUE (kg yield kg^{-1} N applied)
Control	ND
50% NPK	1.26^{abcd}
100% NPK	0.72^{ab}
2.5 t ha^{-1} PLB	ND
2.5 t ha^{-1} PLB + 50% NPK	1.37^{bcd}
2.5 t ha^{-1} PLB + 100% NPK	0.78^{abc}
5 t ha^{-1} PLB	ND
5 t ha^{-1} PLB + 50% NPK	1.61^{d}
5 t ha^{-1} PLB + 100% NPK	0.69^{a}
7.5 t ha^{-1} PLB	ND
7.5 t ha^{-1} PLB + 50% NPK	1.39^{cd}
7.5 t ha^{-1} PLB + 100% NPK	0.69^{a}
p value	<0.001
CV (%)	28.5

Control = no amendment; 50% NPK = 45 kg ha^{-1} N, 30 kg ha^{-1} P_2O_5, 30 kg K_2O; 100% NPK = 90 kg ha^{-1} N, 60 kg ha^{-1} P_2O_5, 60 kg ha^{-1} K_2O. Values followed by the same letters in a column are not significantly different (DMRT) at 5% and *vice versa*. ND = not determined.

stable carbon in biochar, which is the highest among all the mineral elements contained in the ash (Yuan et al. 2011). The PLB used in this study had a carbon content of 38%, and this coupled with the recalcitrant nature of biochar to decomposition significantly contributed to the increase in the organic carbon content of the soil. Arif et al. (2017) also reported an improvement in SOC after biochar addition.

The available soil P and CEC increased in plots amended with PLB relative to the unamended control plots. The increase in the available soil P is due to biochar's ability to increase extractable P (PO_4^{3-}) in the soil solution either directly through its anion exchange capacity or by influencing the availability of the cations (Fe^{2+}, Al^{3+} and Ca^{2+}) that interact with P (Gundale and DeLuca 2007). This is made possible through biochar-mediated increase in soil pH, which prevents P from reacting with these cations by bonding of these metal cations and preventing P from being precipitated in solution through the formation of a complex. The increase in the available soil P is also due to the fact that PLB is rich in extractable soil nutrients such as P, K, Ca, and Mg as reported by Arif et al. (2017).

A significant increase was observed in CEC with increased application of PLB (Table 3). According to Atkinson et al. (2010), increases in CEC are as a result of increases in charge density per unit surface of organic matter (greater degree of oxidation) or increase in the surface area for the adsorption of cations or their combination. The increase in CEC as a result of biochar addition also confirms the report by Oladele et al. (2019) that biochar application improved the fertility of a highly weathered tropical soil through increased CEC.

4.2 Growth and yield of cabbage

Combined application of PLB and NPK fertilizers significantly increased the cabbage plant height, stem girth, leaf spread (Figures 1–3), and head yield (Table 4) over the unamended control plots, indicating the agronomic benefits of the applied amendments. Moreover, plots that received 5 t ha^{-1} PLB + 50% NPK had a 27% increase in cabbage yield compared with 50% NPK treatment. The increase in cabbage yield could be attributed to the PLB addition. The positive growth and yield response of cabbage to NPK fertilizer and PLB application confirm the low nutrient status of the soils under study, which is characteristic of highly weathered tropical soils. The response of cabbage to the application of PLB and NPK fertilizers could be attributed to the improvement in soil chemical properties.

In this study, the application of PLB significantly increased the soil pH, SOC, available phosphorus, and CEC of the soil (Table 3). The increase in soil pH from the moderately acidic (5.25) in the control plots to slightly alkaline (7.5) in the biochar amended plots brought the soil pH within the optimum range (6.5–7.0) for growing arable crops, where there is increased availability of key plant nutrients such as nitrogen, phosphorus, potassium, calcium, magnesium, etc., for plant uptake and growth (Shackley et al. 2016). Abiven et al. (2015) attributed growth and yield responses of crops following biochar application to biochar-induced improvement in soil properties such as increased soil pH, water-holding capacity, and CEC. The ability of biochar to alleviate soil acidity constraints through increased soil pH is one of the main effects of biochar on tropical soils (Jeffery et al. 2015).

The increased growth response of cabbage to biochar application could also be due to other biochar-mediated improvement in soil chemical properties such as increased soil nutrient content, CEC, and fertilizer use efficiency. The data in Table 3 indicate that the application of PLB increased SOC content, available phosphorus, and CEC. The increase in these soil chemical properties coupled with the ability of biochar to retain soil moisture through its large surface area and porosity enhanced soil nutrient retention and availability for plant uptake and growth. Increased soil carbon content is also an indication for high organic matter content which is the primary source of nutrients (N, P, K, Ca, Mg, and S) for plant growth in highly weathered tropical soils (Van Zwieten et al. 2010). An increase in soil organic matter content also improves the soil structure through soil aggregate formation which ensures a balance between air and water within the soil matrix to promote soil health and plant growth. This corroborates with the findings of Arif et al. (2017) and Oladele et al. (2019) that the beneficial effect of biochar addition on low-fertility tropical soil was through improvement in CEC, SOC, and supply of plant nutrients. Berihun et al. (2017) also observed increases in growth indices of garden pea after the application of biochar.

Combined application of PLB and NPK fertilizers significantly increased leaf biomass, head circumference, and head yield of cabbage compared with the unamended control and sole PLB application (Table 4). The increased yield response of cabbage to combined application of PLB and NPK fertilizers corroborates the work of Akolgo et al. (2020) who reported 7.7% increase in the yield of cabbage, following the application of 20 t ha^{-1} sawdust biochar on a loamy sand in Ghana. It is evident that in their study the yield increase was marginal compared with those obtained in this study where the application of PLB at a low rate of 2.5–7.5 t ha^{-1} + 100% NPK or 50% NPK increased the cabbage head yield on the average by 50 and 43% compared with the unamended control plots and sole PLB-treated plots, respectively. The yield differences could be due to the different types of biochar applied, as the agronomic value of biochar depends on the type of biomass feedstock, its nutrient content, and the pyrolysis temperature under which it is produced (Wang et al. 2013). Moreover, the effects of biochar on crop yield is influenced by factors such as the amount of biochar applied, characteristics of the biochar, and the soil type to which it is applied (Chen et al. 2019).

Biochar produced from poultry litter has been found to be rich in nutrients due to the large amounts of carbon and macro- and micro-nutrients contained in the poultry litter feedstock (Chan and Xu 2009). The PLB used in this study contained significant amounts of the primary plant nutrients (i.e., nitrogen; 21 g kg^{-1}, phosphorus; 19 g kg^{-1}, and potassium; 40 g kg^{-1}, Table 2). The observed yield increase with combined application of PLB and NPK fertilizers could also be attributed to biochar's direct effect of supply of additional nutrients and indirectly by improving soil chemical, physical, and biological properties which enhance the retention of fertilizer nutrients and plant growth (Srinivasaro et al. 2013). The improved growth parameters, i.e., plant height, stem girth, and leaf spread observed from the biochar amended plots also contributed to the yield increases in cabbage following the application of biochar and NPK fertilizer as biochar contributed to the supply and retention of nutrients needed for plant growth and biomass production through mineralization of its nutrients.

It is worth noting that the sole application of biochar, i.e., 2.5, 5, and 7.5 t ha^{-1} PLB, however, did not significantly increase cabbage fresh leaf biomass and head yields irrespective of the increase in the biochar application rates (Table 4). The lack of yield response of cabbage to sole PLB application can be explained by the fact that the nutrients in biochar alone could not meet the nutrient requirements of cabbage. This could also be attributed to the short period of time from biochar application and cabbage life span. This observation also supports the assertion by some authors that although biochar contains some amount of nutrients, its sole application does very little in directly contributing to the soil nutrient status; but rather its combined application with mineral or organic fertilizers results in crop yield enhancement. The increase in cabbage leaf biomass and head yield with combined application of PLB and NPK also confirms the report by Siddiqui et al. (2016) that biochar in spite of its low nutrient content can improve soil fertility and crop yield when it is applied in combination with other nutrient sources. This is made possible through biochar's ability to reduce leaching of fertilizer nutrients particularly N by adsorption onto its surfaces and thereby increasing the use efficiency of applied N as observed in this study and thus confirming the report by Steiner et al. (2008).

The agronomic benefit of biochar application with NPK fertilizer was clearly evident in this study, where application of 5 t ha^{-1} PLB + 50% NPK gave the highest cabbage head yield (72.12 t ha^{-1}) with a 27% increase in yield compared with the 50% NPK-treated plots (Table 4) as yield benefits of biochar addition. This partly confirms the assertion that combined application of biochar and inorganic fertilizers has the potential of increasing crop productivity while reducing the amount of inorganic fertilizer (De Gryze et al. 2010). In assessing the effect of biochar type and rate of application on maize yield indices, Yeboah et al. (2016) also reported that the application of corn cob biochar at a rate of 5 t ha^{-1} reduced mineral fertilizer input of maize by 50%. The ability of PLB to reduce mineral fertilizer input for cabbage was not consistent in this study and requires further study to validate it and determine how it is influenced by different biomass feedstock used in biochar production.

The increase in cabbage yield with the application of 5 t ha^{-1} PLB + 50% NPK can be attributed to increased N availability and improved fertilizer nutrient use efficiency following biochar application. In this study, the ability of biochar to improve the use efficiency of applied N was evident as application of 5 t ha^{-1} PLB + 50% NPK and 7.5 t ha^{-1} PLB + 50% NPK increased the N use efficiency relative to the 5 t ha^{-1} PLB + 100% NPK and 7.5 t ha^{-1} PLB + 100% NPK treatments, respectively (Table 5). An increase in the N use efficiency will enhance the plant's photosynthetic activity leading to high biomass production and increased yields. Amoakwah et al. (2017a) reported on the ability of biochar to improve the quality of sandy loam, where there was an improvement in the water-holding capacity (Amoakwah et al. 2017b) and subsequent reduction in the leaching of N fertilizer. Moreover, 5 t ha^{-1} PLB + 50% NPK resulting in the highest cabbage head yield could be attributed to the fact that plants that received this treatment had increased N use efficiency of 133% and the soil had the highest available P content of 104.43 ppm, representing an increase of 296% in the available soil P content relative to the control. The increase in soil P levels might have enhanced the plant root development for efficient absorption of water and nutrients for plant growth. The agronomic benefits of biochar addition to mineral fertilizer has been reported by many authors including Chan et al. (2008) who observed significant additional increases in radish yield which were in excess of that resulting from the application of fertilizer alone when PLB was applied together with nitrogen fertilizer. Liang et al. (2014) also reported increases in shoot biomass and crop yield as a result of biochar application.

The effect of biochar application on plant growth and yield also depends on the soil type as well as properties of the biochar applied. Although biochar generally increases the crop yield (El-Nagger et al. 2019), its effects have been shown to be more effective on soils with low to medium fertility levels than to highly fertile soils. The sandy nature of the soils under study also influenced its response to biochar application as biochar has been found to give more agronomic benefits when applied to coarse-textured (sandy) soils than fine-textured (clayey) soils (Wolf 2008). This is mainly due to the biochar's ability to increase moisture retention in soils (Fischer et al. 2019). Improved water-holding capacity will enhance plant nutrition through improved absorption of dissolved nutrients for plant growth and development.

5 Conclusion

The results of this study have revealed that combined application of PLB and NPK fertilizers significantly improved the soil chemical properties, growth, and yield characteristics of cabbage. Application of 5 t ha^{-1} PLB + 50% NPK increased soil pH, organic carbon, available phosphorus, and CEC by 26.6, 41.4, 296, and 78.7%, respectively, relative to the control. PLB at 5 t ha^{-1} + 50% NPK fertilizer is the optimum application rate for cabbage production on soils at the study site as it increased cabbage yield by 73 and 27% compared with the control and 50% NPK treatments, respectively. This study recommends combined application of PLB and NPK fertilizer as an effective amendment to improve soil chemical properties, nutrient use efficiency, and yield of cabbage on the Ferric Acrisol.

Acknowledgments: The authors are thankful to the management of CSIR-Soil Research Institute for the financial, technical, and logistical support in carrying out this work. Permission to publish the article was received from the CSIR Soil Research Institute Editorial Committee and License to publish letter was signed by the corresponding author.

Funding information: The authors are grateful to the Microbiology Division of CSIR-Soil Research Institute for the financial support to the study.

Author contributions: PO and EY conceptualized the study; BA and KOAA installed the trial and collected data; GA and PO analyzed the data and wrote the first draft; EY approved the final draft and served as the corresponding author.

Conflict of interest: The authors state no conflict of interest.

Data availability statement: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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