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Effect of coffee husk biochar and inorganic NP fertilizer on soil properties, growth and yield of potato (*Solanum tuberosum* L.) on acidic soil of southwest Ethiopia

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Abstract

Soil acidity and low soil fertility due to nutrient leaching coupled with low inorganic fertilizer usage is a major cause of low crop yields across Southwest Ethiopia. Recently, biochar potential to improve soil fertility has gained significant attention but there are limited studies on the use of biochar in combination with inorganic fertilizers. A field experiment was, therefore, conducted to investigate the effect of combined application of biochar and inorganic NP nutrient on soil physicochemical properties, growth and yield of potato in Andiracha district, Southwestern Ethiopia. The experiment was laid out in randomized complete block design (RCBD) and replicated three times. The treatment consisted of four levels of biochar rates (0, 2.5, 5 and 7.5 t ha^{-1}) and four fertilizer rates of (0, 75,100 and 125% of recommended N P rates). Data were analyzed using SAS version 9.3 Software. Analysis of variance showed that combined application of biochar and inorganic NP fertilizer had highly significant (p < 0.01) effect on days to flowering, stem number, plant height, total leaf area, total dry biomass, marketable tuber number per hill and harvest index and significant (p < 0.05) effect on marketable tuber weight and total tuber weight ha^{-1}. Combined application of 7.5 ton ha^{-1} biochar with 165 kg N and 60 kg P ha^{-1} resulted highest tuber yield (42.64 t ha^{-1}), that increased yield by 28.99% compared with recommended NP fertilizer alone (165 kg N ha^{-1} and 60 kg P ha^{-1}), and by 76.6% compared to the control. The increase was mainly attributed to the improvement in soil physico-chemical properties especially soil pH, CEC, organic matter, total N and available P which is a reflection of increase in soil fertility. Consequently, it was determined that the best course of action for potato production in the area was to apply 7.5 tons of biochar ha^{-1} together with 165 kg N and 60 kg P ha^{-1}. Therefore, the study recommends adoption of low cost biochar production techniques and capacity building to ensure satisfactory knowledge of biochar use and its adoption by potato growers for soil fertility management and enhanced crop productivity.

Keywords Biochar, Pyrolysis, Soil acidity, Potato, Tuber yield

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Introduction

Potato (*Solaneum tubrosum* L.) is one of the major staple crops produced throughout the world (Banerjee et al. 2016) and the third most consumed crop globally after rice and wheat (Nasir and Toth 2022). Potatoes are the most important root and tuber crops for consumers and a source of economy for many producers (Mikkelsen 2015). The total world potato production is estimated above

370.4 million tons in the cropping year of 2019 (FAO 2021). Potato has an important value for food security and hunger relive in Ethiopia by virtue of its ability to mature earlier than most other crops at times of critical food need (Asresie et al. 2015). The area under potato production in Ethiopia in 2018/19 cropping season was around 73,677 hectares with annual total production of 1.04 million tones (CSA 2019).

Ethiopia is endowed with suitable climatic and edaphic conditions for potato production. However, the average yield of potato estimated in Ethiopia is around 14 ton ha^{-1} (CSA 2019), but the attainable yield is 30 ton ha^{-1}. The reason for low actual yield might be related to different factors, among which poor soil fertility and sub-optimal fertilizer application rates are most determining factors (Haverkort et al 2012). Potato requires a balanced nutrient management (Islam et al. 2013) without which the growth and yield become remarkably low. Nitrogen is required in huge amounts to maintain optimum shoot and tuber growth (Stevens et al. 1999) which can be available to meet a crop's requirement based on efficient management system. Proper management of phosphorus for potato production is also a critical aspect to improve its yield. The Phosphorus fertilizers requirements are higher for potatoes as compared with many other crops due to its shallow and sparse root hair system (Mikkelsen 2015).

Soil acidity allied to soil erosion, aluminum toxicities and soil nutrient depletion are the most soil related challenges to agricultural development in most parts of developing countries depending on agriculture to feed their increasing population (Nduwumuremyi 2013). Application of lime and compost is important to improve soil health status through enriching nutrient content in the surface layer of the soil (Tantowijoyo 2006; Nduwumuremyi 2013). Biochar is the other alternative that can be used as a soil amendment to increase plant growth and yield, by reduce soil acidity and, thereby, increase nutrient availability in the soil for long period of time (Vista et al. 2015).

Biochar is a soil amendment produced from thermal degradation of organic materials such as crop residues (rice husks, coffee husks, maize stover etc.), animal wastes, through pyrolysis and it has potential to increase crop yields (Hussain et al. 2017; Muhammad et al. 2017). The use of biochar is an effective way of recycling agricultural wastes with the goal of sustainable crop production and restoration of soil fertility, at the same time reducing the overdependence on inorganic fertilizers (Kizito et al. 2019; Zhang et al. 2020). The potential of biochar as a soil improvement in agricultural fields has been recently recognized and yet it is not fully utilized. Several current reports have shown that biochar application increases growth and yield of vegetables, legumes, and tomato (Lima et al. 2021; Lacomino et al. 2022; Wacal et al. 2023). For instance, maize stover biochar applied at 27.6 t ha^{-1} improved soil chemical properties especially pH, N, P and K promoting growth and yield of tomatoes (Wacal et al. 2023). However, there are no studies conducted in Ethiopia to ascertain the ability of coffee husks biochar to improve soil chemical properties under potato production. Besides, its role in combination with mineral fertilizers is also poorly understood in the country. Therefore, this study was conducted to determine the effect of combined application of biochar and inorganic nutrients on soil physico-chemical properties, growth and yield of potato, with the aim of identifying the best combination rate of coffee husks biochar and inorganic nutrients for optimum yield of potato at Anderacha district, Southwest Ethiopia.

Materials and method

Description of the experimental site

The experiment was conducted at Gecha, Andiracha district of Sheka zone, Southwestern Ethiopia under rain-fed condition. Anderacha area receives a high amount of rainfall, with an average of 1800–2200 mm annually and mean annual average temperature between 15.1 to 27.5 °C (Haile et al. 2015). The study site is situated at 7.598779° latitudes, and 35.405884° longitudes, and at an elevation of 2039 m above sea level. The soil of Sheka area is characterized by Acrisol with a sub-surface layer of accumulated Kalonitic clay in the order Oxisol, low Cation exchange capacity, low base saturation, and low pH values (Berhane and Sahelmedhin 2003). The soil of the experimental area is strongly acidic with loam texture and medium cation exchange capacity, low organic matter contents and medium total nitrogen content, and very low available phosphorus content (Table 1).

Experimental materials preparation

Biochar was produced from locally available material (coffee husk) by the process of fast Pyrolysis with a temperature of 350 °C and 1 h retention time at Jimma University College of Agriculture and Veterinary Medicine (JUCAVM). After the process, the biochar was made to small granules and pass through 2 mm sieve in order to have the same particle size as that of the soil and was taken to experimental field for application. Seed tubers of improved potato cultivar (Belete) were collected from Holeta Agricultural Research center (HARC) and used for the experiment. This cultivar was used because it is widely grown by the local farmers for its high yield, relative diseases resistance and tuber quality. Triple

Table 1 Physical and chemical properties of the experimental soil and biochar before planting and treatment application

Parameters	Soil		Biochar
	Values	Rating	
pH water, 1:2.5	4.87	Strongly acidic	9.4
Organic carbon (%)	3.15%	Medium	18.01%
Organic matter (%)	3.38%	Low	31.06%
Cation exchange capacity (CEC)	22.12 meq/100g soil	Medium	63.23 meq/100 g soil
Total nitrogen	0.17%	Medium	1.55%
Available phosphorus	3.41 ppm	Very low	13.63 ppm
Texture			–
Clay	26		–
Silt, and	35.7		–
Sand	38.3		–
Textural class	Loam		–

Super Phosphate (TSP, 46% P_2O_5) and Urea (46% N) were used as sources of P and N fertilizer, respectively.

Experimental design and treatments

The different amounts (rates) of Biochar (BC) and different rates of recommended inorganic fertilizers (RIF) of Nitrogen and Phosphorus were laid out in randomized complete block design (RCBD) with three replications. Thirteen treatments were obtained by combination of four BC rates (0 ton BC ha^{-1}, 2.5 ton BC ha^{-1}, 5 ton BC ha^{-1}and 7.5 ton BC ha^{-1}) and four levels of the recommended NP fertilizer rates (0% NP; 75% NP; 100% NP and 125% NP, corresponding to control, 123.75 kg N ha^{-1}and 45 kg P ha^{-1}; 165 kg N ha^{-1}and 60 kg P ha^{-1} and 206.25 kg N ha^{-1}and 75 kg P ha^{-1}). Biochar alone was not included as a treatment for this study, as it does not act as actual fertilizer or does not contain any appreciable amounts of available nutrients (Major 2011). The size of each unit plot was 3 m × 3 m (9 m^2) having plant-to-plant and row-to-row spacing of 30 cm and 75 cm, respectively. Each plot consists of four rows and ten potato plants or hills per row (40 plants per plot). A distance of 1 m and 1.5 m were maintained between unit plots and blocks respectively. Border plants were planted around the experimental plots. Biochar was applied based on proposed amount per plot with hand and uniformly incorporated in to the soil before planting. Seed tubers were planted at a depth of 10 cm on raised-beds furrows with a height of 30 cm. Inorganic nutrients were applied as per the treatment for N and P. Nitrogen was applied in the form of urea and phosphorus in the form of TSP by side dressing at the time of planting. Nitrogen was applied once at the time of planting assuming that biochar

prevents nutrient leaching. Plant protection, earthling up and other management practices were applied as recommended for the crop.

Determination of soil and biochar characteristics

Soil analysis was carried out before planting by randomly collecting composite soil samples from the upper 0 to 30 cm depth at the experimental site. Some soil physico-chemical properties such as soil texture, soil pH, cation exchange capacity (CEC), soil organic matter, plant available phosphorus and total nitrogen were analyzed according to soil laboratory standard at Jimma University College of Agriculture and Veterinary Medicine (JUCAVM) soil laboratory. Soil texture was analyzed by hydrometer method (differential setting within a water column) using particles less than two millimeters diameter. Soil pH was measured potentiometrically using 1:2.5 soil samples to water ratio using a glass electrode attached to a digital pH meter. The cation exchange capacity (CEC) was determined after saturating the soil with 1N ammonium acetate (NH_4OAc) and displacing it with 1N NaOAc. Soil organic matter content was determined from soil organic carbon using wet oxidation method where the carbon was oxidized under standard conditions with potassium dichromate ($K_2Cr_2O_5$) in sulfuric acid solution. Then the organic matter content of soil was calculated by multiplying the percent of organic carbon by 1.724. Total nitrogen was analyzed by Micro-Kjeldhal digestion method with sulphuric acid. Available phosphorus was determined by Bray II (before planting) and Bray II and Olsen extraction method (after harvest) (Sahlemedin and Taye 2000). Furthermore, soil samples were collected from each experimental unit after harvest and analyzed for pH, CEC, organic matter content, plant

available phosphorus and total nitrogen at Teppi Soil Laboratory. The physical and chemical properties of Biochar were also determined before the soil amendment following above standard laboratory procedures.

Data collection

Data articulating the crop phenology and growth performance of potato: (1) days to emergence (the numbers of days from the date of planting to the date when about 50% of the plants in a plot emerged), (2) days to 50% flowering (the numbers of days from the date of planting to the date when about 50% of the plants reached flowering stage), (3) average number of stems per hill (was recorded at flowering stage by counting the main stem which came out from the seed tuber from randomly selected five hills per plot), (4) plant height (was determined by measuring the height of the plant from the base of the main shoot to the apex at full blooming stage from randomly selected five hills per plot), and (5) total leaf area (was calculated by taking three fully expanded leaves from each of five randomly selected plants per plot and tracing each leaf on a square paper). Recorded yield and yield component data were: (1) average number of marketable tubers per hill (the average number of marketable tubers per hill from the middle 16 hills), (2) average number of unmarketable tubers per hill (rotten, insect attacked and undersized or less than 25 g as suggested by Alemayehu et al. (2015)), (3) total tuber weight (tuber obtained from the middle 16 hills in 3.6 m^2 area was measured and converted to total weight per hectare), (4) weight of marketable tubers (recorded from the middle sixteen plants that were free from diseases and insect pests attack and greater than or equal to 25 gm in weight and converted to hectare (Alemayehu et al. 2015)), (5) weight of unmarketable tubers (was determined as the weight of those tubers that were rotten, insect attacked and under-sized or less than 25 gm and converted to hectare (Alemayehu et al. 2015)), (6) total dry biomass (samples were air dried for 72 h and then oven dried at 70 °C to a constant mass and weighed (Banerjee et al. 2016)), and (7) harvest index (the ratio of total dry weight of the tubers to total dry weight of plant biomass measured from five randomly selected plants at harvest).

Data analysis

All the collected data were first checked for fitting the analysis of variance (ANOVA) assumptions by normality test. Then, an analysis of variance (ANOVA) was performed on all the data in GLM model using SAS (9.2 version) statistical system (SAS 2008). Whenever the ANOVA shows significant differences between treatments, mean comparison and separation was done by using Least Significant difference (LSD) test.

Results

Coffee husk biochar and inorganic NP fertilizers effect on soil physicochemical properties

The effect of combined application of biochar with inorganic nitrogen and phosphorus fertilizer was found to be highly significant ($p < 0.01$) (Table 2) for soil pH, cation exchange capacity (CEC), soil organic matter content, total nitrogen and available phosphorus. The highest soil pH value (6.47) was obtained from combined application of 7.5 ton ha^{-1} biochar with inorganic fertilizer rates of 165 kg N and 60 kg P ha^{-1}, and this value was statistically similar with that of application of 7.5 ton ha^{-1} biochar with 123.75 kg N and 45 kg P ha^{-1} or 206.25 kg N and 75 kg P ha^{-1}. On other hand, the lowest pH value (4.90) was recorded from the control, which was statistically similar with application of all the three levels of NP fertilizer without biochar and 2.5 ton ha^{-1} biochar with 123.75 kg N and 45 kg P ha^{-1} (Fig. 1). The highest value (38.52 meq/100 g soil) of cation exchange capacity (CEC) was observed when 7.5 ton ha^{-1} biochar and 206.25 kg N and 75 kg P ha^{-1} was used in combination. This result was statistically similar with application of 7.5 ton ha^{-1} biochar with 123.75 kg N and 45 kg P ha^{-1} or 165 kg N and 60 kg P ha^{-1} P. On other hand, the lowest value (23.50 meq/100 g soils) of CEC was obtained from the control, which was statistically similar with application of the three levels of inorganic NP fertilizers with no biochar (Fig. 1).

Combined application of 7.5 ton ha^{-1} biochar with 206.25 kg N and 75 kg P ha^{-1} resulted in the highest percentage of soil organic matter (7.56%), which was statistically similar with application of 5 ton ha^{-1} biochar with 206.25 kg N and 75 kg P ha^{-1} and 7.5 ton ha^{-1} biochar with 123.75 kg N and 45 kg P ha^{-1} or 165 kg N and 60 kg P ha^{-1} (Fig. 1). On other hand, the lowest soil organic matter content (4.19%) was obtained from the control, which was statistically similar with application

Table 2 Mean square values for soil physico-chemical properties as affected by combined application of biochar and inorganic NP nutrients

Parameters	Treatment mean squares	Error mean squares	CV (%)
Soil pH	0.95[**]	0.043	3.77
Cation exchange capacity (meq/100 g)	89.22[**]	4.72	6.98
Soil organic matter (%)	3.50[**]	0.99	18.19
Soil total nitrogen (%)	0.0094[**]	0.0013	12.13
Available phosphorus (ppm)	20.30[**]	0.09	5

CV coefficient of variation

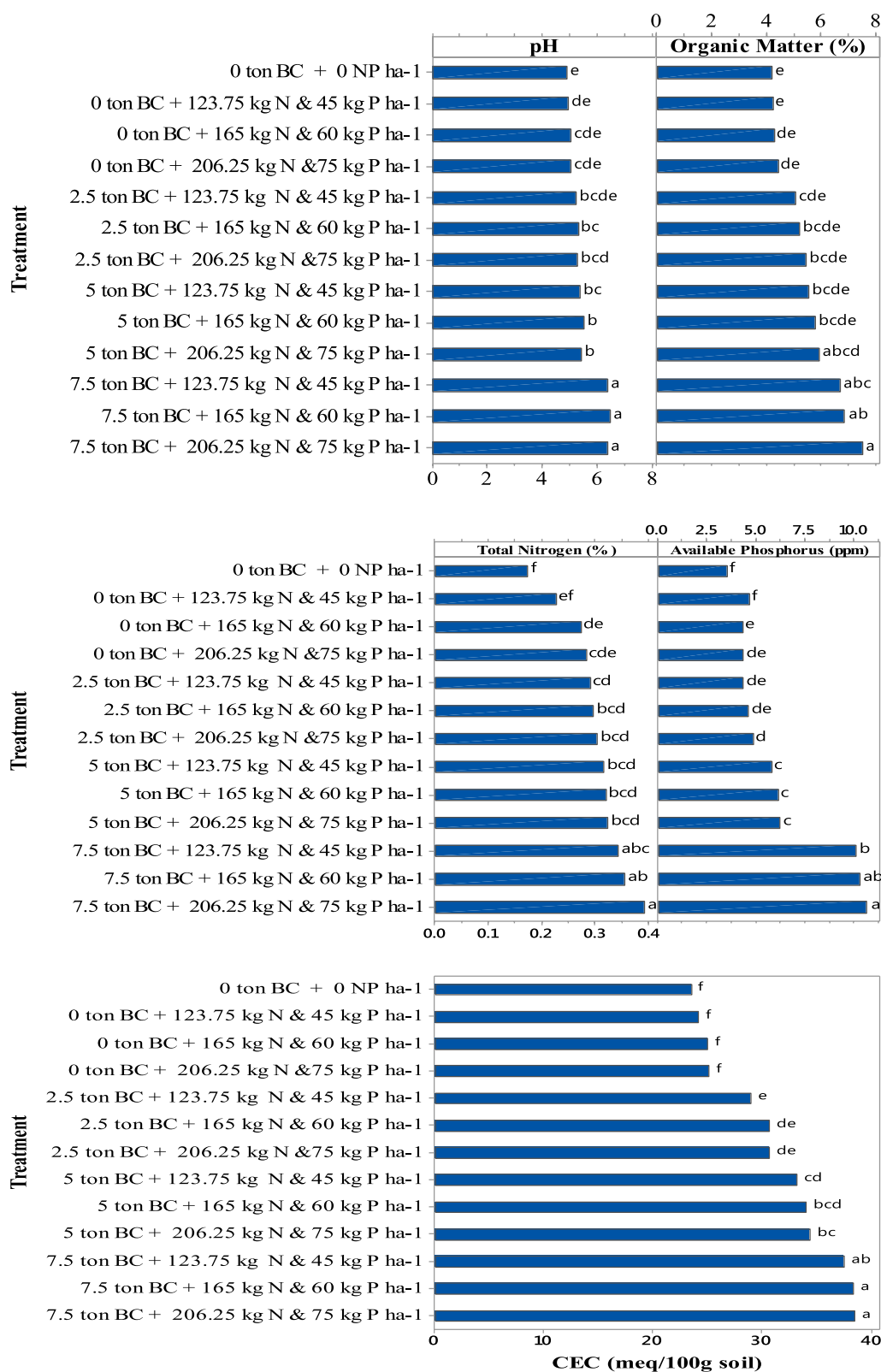**Level of significance at $p < 0.01$

Fig. 1 Soil properties (soil pH, organic matter, total nitrogen, available phosphorus, and CEC) as affected by combined application of biochar and inorganic NP fertilizer at different rates. Means followed by the same letter are not significantly different at $p < 0.05$

of all the three rates of NP fertilizer without biochar, application of 2.5 ton ha^{-1} biochar in combination with all the three rates of NP fertilizer and 5 ton ha^{-1} biochar with 123.75 kg N and 45 kg P ha^{-1} or with 165 kg ha^{-1} N and 60 kg ha^{-1} P (Fig. 1). The highest (0.39%) total nitrogen content was found from combined application of 7.5 ton biochar ha^{-1} with 206.25 kg N and 75 kg P ha^{-1} and this value was statistically similar with that of application of 7.5 ton ha^{-1} biochar in combination with 123.75 kg N and 45 kg P ha^{-1} or 165 kg N and 60 kg P ha^{-1} (Fig. 1). Whereas, the lowest amount (0.17%) was obtained from the control, which was statistically similar to application of 123.75 kg N and 45 kg P ha^{-1} without biochar. Similarly, the highest amount (10.71 mg kg^{-1}) of available phosphorus was obtained from the combined application of 7.5 ton biochar ha^{-1} with 206.25 kg N and 75 kg P ha^{-1}, which was statistically similar with application of 7.5 ton ha^{-1} biochar in combination with 165 kg N and 60 kg P ha^{-1} (Fig. 1). On the other hand, the lowest amount of available phosphorus (3.51 mg kg^{-1}) was observed for the control, which was statistically similar with application of 123.75 kg N and 45 kg P ha^{-1} without biochar.

Crop phenology and growth parameters

Combined application of biochar with inorganic nitrogen and phosphorus fertilizers showed a highly significant (p < 0.01) differences in days to 50% flowering, number of main stems per plant, plant height and total leaf area per plant. But, days to 50% emergence was not significantly (p ≥ 0.05) affected by the treatments (Table 3). The maximum period required to 50% flowering (56 days) was recorded for combined application of 7.5 ton ha^{-1} of biochar with 165 kg or 206.25 kg N ha^{-1} and 60 kg or 75 kg P ha^{-1}. This result was statistically similar with application of 2.5 ton ha^{-1} biochar with 206.25 kg N and 75 kg P ha^{-1}, 5 ton ha^{-1} biochar with three levels of NP rates and 7.5 ton ha^{-1} biochar with 123.75 kg N and 45 kg

Table 3 Mean square values for crop phenology and growth parameters as affected by combined application of biochar and inorganic NP fertilizers

Parameters	Treatment mean Squares	Error mean Squares	CV (%)
Days to 50% emergence	1.43[NS]	0.9	6.96
Days to 50% flowering	16.97[**]	2.36	2.89
Number of main stem	1.97[**]	0.46	13.06
Plant height (cm)	333.33[**]	19.27	7.73
Total leaf area (cm^2 /plant)	756,447.27[**]	7395.74	3.91

CV coefficient of variation, *NS* non significance difference between treatments

**Level of significance at p < 0.01

P ha^{-1}. While the shortest duration to 50% flowering (48 days) was recorded for the control, which was statistically in parity with application of 123.7 kg ha^{-1} N and 45 kg ha^{-1} P (Table 5). In the same manner, application of 7.5 ton ha^{-1} biochar in combination with 206.25 kg ha^{-1} N and 75 kg ha^{-1} P resulted in maximum (69.19 cm) plant height. This result was statistically similar with application of 5 ton ha^{-1} biochar with 165 kg N and 60 kg P ha^{-1} and 206.25 kg N and 75 kg P ha^{-1}. Application of 7.5 ton ha^{-1} biochar with 123.75 kg N and 45 kg P ha^{-1} and 165 kg N and 60 kg P ha^{-1} produced the same statistical results as the prior treatment combination. On the other hand, the minimum value (37.02 cm) was observed for the control (Table 2).

Combined application of 7.5 ton ha^{-1} of biochar with 165 kg N and 60 kg P ha^{-1} resulted in the highest number of main stems per hill (6.4), which was statistically similar with application of 2.5 ton ha^{-1} biochar with 206.25 kg N and 75 kg P ha^{-1}, 5 ton ha^{-1} biochar with three level of NP fertilizer and 7.5 ton ha^{-1} biochar with 123.75 kg N and 45 kg P ha^{-1} and with 206.25 kg N and 75 kg P ha^{-1}. The lowest number of main stems per hill (3.25) was observed for the control plot (without biochar and NP fertilizers), which was statistically the same with application of 123.75 kg N and 45 kg P ha^{-1} fertilizer alone (Table 4). Similarly, the highest total leaf area per hill (2804.84 cm^2) was recorded for combined application of 7.5 ton ha^{-1} of biochar with 165 kg N and 60 kg P ha^{-1}. This result was statistically similar with application of 7.5 ton ha^{-1} biochar with 123.75 kg N and 45 kg P ha^{-1} and with 206.25 kg N and 75 kg P ha^{-1}. On other hand, the lowest value for total leaf area per hill (1162.18 cm^2) was obtained from the control treatment (Table 4). Application of 206.25 kg ha^{-1} nitrogen and 75 kg ha^{-1} phosphorus fertilizer without biochar increased total leaf area by 62.5% over the control. Similarly, combined application of 7.5 ton ha^{-1} biochar with 165 kg ha^{-1} nitrogen and 60 kg ha^{-1} phosphorus increased total leaf area by 48.49% compared to application of 206.25 kg ha^{-1} nitrogen and 75 kg ha^{-1} phosphorus alone and by 141% over the control.

Yield and yield components

Combined application of biochar with inorganic nitrogen and phosphorus nutrient resulted in a highly significant (p < 0.01) difference for average number of marketable tubers per hill, total dry biomass yield and harvest index and significant (p < 0.05) difference for marketable tuber weight and total tuber weight. However, unmarketable tuber number and unmarketable tuber weight were not significantly (p > 0.05) affected by the treatments (Table 5).

Table 4 Days to 50% emergence (DE), days to 50% flowering (DF), number of main stem (SN) per hill, plant height (PH) and total leaf area (TLA) as influenced by application of biochar and inorganic NP fertilizer

Treatments	DE	DF	SN per hill	PH (cm)	TLA (cm² per hill)
0 ton BC + 0 NP ha⁻¹	14	48.33^f	3.25^d	37.02^d	1162.18^f
0 ton BC + 123.75 kg N & 45 kg P ha⁻¹	13.67	49.33^{ef}	4.13^{cd}	45.37^c	1838.95^e
0 ton BC + 165 kg N & 60 kg P ha⁻¹	13.67	51.33^{de}	5.06^{bc}	51.11^{bc}	1873.03^{de}
0 ton BC + 206.25 kg N & 75 kg P ha⁻¹	13.33	52.67^{bcd}	5.08^{bc}	51.23^{bc}	1888.86^{de}
2.5 ton BC + 123.75 kg N & 45 kg P ha⁻¹	15.00	51.67^{cde}	4.94^{bc}	52.07^{bc}	1868.57^{de}
2.5 ton BC + 165 kg N & 60 kg P ha⁻¹	13.67	52.67^{bcd}	5.17^{bc}	52.65^{bc}	1928.93^{de}
2.5 ton BC + 206.25 kg N & 75 kg P ha⁻¹	13.67	53.67^{abcd}	5.27^{abc}	53.31^b	2012.80^d
5 ton BC + 123.75 kg N & 45 kg P ha⁻¹	14.67	53.67^{abcd}	5.46^{ab}	53.34^b	2522.71^c
5 ton BC + 165 kg N & 60 kg P ha⁻¹	13.67	55.00^{ab}	5.73^{ab}	67.92^a	2670.59^{ab}
5 ton BC + 206.25 kg N & 75 kg P ha⁻¹	13.33	55.00^{ab}	5.61^{ab}	68.01^a	2578.56^{bc}
7.5 ton BC + 123.75 kg N & 45 kg P ha⁻¹	13.00	54.00^{abc}	5.78^{ab}	68.33^a	2712.90^{ab}
7.5 ton BC + 165 kg N & 60 kg P ha⁻¹	13.00	56.00^a	6.40^a	69.00^a	2804.84^a
7.5 ton BC + 206.25 kg N & 75 kg P ha⁻¹	12.33	56.00^a	5.96^{ab}	69.19^a	2746.33^a
LSD (5%)	1.59	2.59	1.15	7.39	144.92
CV (%)	6.96	2.89	13.06	7.73	3.91

Means followed by the same letter within a column are not significantly different at 5% of probability level (LSD test). *DE* days to emergence, *DF* days to flowering, *SN* stem number, *PH* plant height, *TLA* total leaf area

Table 5 Mean square values for yield and yield components of potato as affected by combined application of biochar and inorganic NP nutrient

Parameter	Treatment mean square	Error mean square	CV (%)
Marketable tuber number per hill	17.31**	2.63	15.18
Unmarketable tuber number per hill	0.21^{NS}	0.38	26.14
Marketable tuber weight (ton ha⁻¹)	87.94*	25.73	15.39
Unmarketable tuber weight (ton ha⁻¹)	0.036^{NS}	0.025	8.52
Total tuber weight (ton ha⁻¹)	85.02*	25.56	14.52
Total dry biomass yield (ton ha⁻¹)	14.55**	3.19	10.2
Harvest index (%)	0.019**	0.014	9.32

CV coefficient of variation, *NS* non significance difference between treatments, ** and * level of significance at p < 0.01 and p < 0.05, respectively

The highest number of marketable tubers (14.69) per hill was obtained from combined application of 7.5 ton ha⁻¹ biochar with 165 kg N and 60 kg P ha⁻¹, which was statistically similar with application of 7.5 ton ha⁻¹ biochar with 206.25 kg N and 75 kg P ha⁻¹, while the lowest value (5.4) was recorded for the control, which was also statistically the same with application of 123.75 kg N and 45 kg P ha⁻¹ without biochar amendment to the soil (Table 6). Application of 165 kg ha⁻¹ nitrogen and 60 kg ha⁻¹ phosphorus fertilizer without biochar amendment increased marketable tuber number per hill by 85.9% over the control. Similarly, application of 7.5 ton ha⁻¹ biochar in combination with 165 kg ha⁻¹ N and 60 kg ha⁻¹ P increased marketable tuber number by 46.31% over application of 165 kg ha⁻¹ nitrogen and 60 kg ha⁻¹ phosphorus fertilizer with no biochar and by 172% over the control.

Similarly, the combined application of 7.5 ton ha⁻¹ biochar with 165 kg N ha⁻¹ and 60 kg P ha⁻¹ resulted in the highest number (42.64 ton ha⁻¹) of total tuber weight, which was statistically similar with application of 2.5 ton ha⁻¹ biochar along with 165 kg N ha⁻¹ and 60 kg P ha⁻¹ or 206.25 kg N ha⁻¹ and 75 kg P ha⁻¹. This result was also statistically similar with application of 5 ton ha⁻¹ biochar with all the three rates of inorganic NP fertilizer and 7.5 ton ha⁻¹ biochar with 123.75 kg N and 45 kg P ha⁻¹ or 206.25 kg N and 75 kg P ha⁻¹. On other hand, the lowest (24.14 ton ha⁻¹) total tuber weight was recorded for the control, which was statistically the same with application of 123.75 kg N and 45 kg P ha⁻¹ or 206.25 kg N and 75 kg P ha⁻¹ without biochar (Table 6). Application of 165 kg ha⁻¹ nitrogen and 60 kg ha⁻¹ phosphorus fertilizer without biochar increased the total tuber yield by 37% over the control. Whereas, application of 7.5 ton ha⁻¹ biochar in combination with 165 kg N and 60 kg P ha⁻¹ increased the value by 28.99% over the same rate of NP fertilizer but without biochar application and by 76.6% over the control.

The highest (40.80 ton ha⁻¹) marketable tuber yield (Table 6) was obtained from combined application of 7.5 ton ha⁻¹ biochar with 165 kg N and 60 kg P ha⁻¹, and this was statistically similar with application of 2.5 ton ha⁻¹

Table 6 Mean marketable and unmarketable tuber number per hill and marketable, unmarketable and total tuber weight (ton ha^{-1}), total dry biomass (ton ha^{-1}) and harvest index of potato as affected by biochar and inorganic NP fertilizer rates

Treatments	Tuber number per hill		Tuber weight (ton) ha^{-1}				
	Marketable	Unmarket-able	Total	Marketable	Unmarket-able	Total dry Biomass (ton ha^{-1})	Harvest index
0 ton BC + 0 NP ha^{-1}	5.4^d	2.75	24.14^e	22.02^e	2.1	12.93^f	0.33^d
0 ton BC + 123.75 kg N & 45 kg P ha^{-1}	6.75^{cd}	2.71	26.14d^e	24.11^{de}	2.03	15.01^{ef}	0.34^{cd}
0 ton BC + 165 kg N & 60 kg P ha^{-1}	10.04^b	2.54	33.08^{bcd}	31.18^{bcd}	1.9	15.74^{def}	0.34^{cd}
0 ton BC + 206.25 kg N &75 kg P ha^{-1}	9.31^{bc}	2.58	31.03^{cde}	29.03^{cde}	2	16.84^{cde}	0.36^{cd}
2.5 ton BC + 123.75 kg N & 45 kg P ha^{-1}	11.13^b	2.44	33.89^{bcd}	32.05^{bcd}	1.84	16.64^{cde}	0.35^{cd}
2.5 ton BC + 165 kg N & 60 kg P ha^{-1}	11.44^b	2.44	35.83^{abc}	34.06^{abc}	1.77	17.58^{bcde}	0.39^{bcd}
2.5 ton BC + 206.25 kg N &75 kg P ha^{-1}	11^b	2.48	34.91^{abc}	33.11^{abc}	1.79	16.9^{cde}	0.36^{cd}
5 ton BC + 123.75 kg N & 45 kg P ha^{-1}	11.69^b	2.29	36.2^{abc}	34.43^{abc}	1.77	18.02^{bcde}	0.40^{bc}
5 ton BC + 165 kg N & 60 kg P ha^{-1}	11.83^b	2.15	37.93^{abc}	36.16^{abc}	1.77	18.98^{abc}	0.40^{bc}
5 ton BC + 206.25 kg N & 75 kg P ha^{-1}	11.69^b	2.21	36.88^{abc}	35.10^{abc}	1.78	18.39^{abcd}	0.39^{bcd}
7.5 ton BC + 123.75 kg N & 45 kg P ha^{-1}	11.89^b	2.09	39.68^{ab}	37.85^{ab}	1.83	19.31^{abc}	0.43^b
7.5 ton BC + 165 kg N & 60 kg P ha^{-1}	14.69^a	1.96	42.64^a	40.80^a	1.84	21.16^a	0.64^a
7.5 ton BC + 206.25 kg N & 75 kg P ha^{-1}	12.04^{ab}	2	40.37^{ab}	38.54^{ab}	1.83	20.07^{ab}	0.44^b
LSD (5%)	2.73	1.04	8.52	8.55	0.27	3	0.06
CV (%)	15.18	26.14	14.52	15.39	8.52	10.2	9.32

Means followed by the same letter within a column are not significantly different at 5% probability level (LSD test)

biochar with 165 kg N and 60 kg P ha^{-1} or 206.25 kg N and 75 kg P ha^{-1}. Besides, it was also statistically similar with application of 5 ton ha^{-1} biochar with the three levels of NP fertilizer rates and 7.5 ton ha^{-1} biochar with 123.75 kg N and 45 kg P ha^{-1} or 206.25 kg N and 75 kg P ha^{-1}. On other hand, the lowest yield (22.02 ton ha^{-1}) was recorded for the control treatment, which was statistically the same with application of 123.75 kg N and 45 kg P ha^{-1} or 206.25 kg N and 75 kg P ha^{-1} with no biochar application (Table 6). Application of 165 kg ha^{-1} nitrogen and 60 kg ha^{-1} phosphorus fertilizer without biochar increased marketable tuber yield by 41.6% over the control. Increasing rate of biochar also positively influenced marketable tuber weight. Accordingly, combined application of 7.5 ton ha^{-1} biochar with 165 kg ha^{-1} N and 60 kg ha^{-1} P increased marketable tuber yield by 30.85%, as compared to application of the same rate of NP alone, and by 85.3% over the control. Combined application of 7.5 ton ha^{-1} biochar with beyond 165 kg N and 60 kg P ha^{-1} showed no further increment in both marketable and total tuber yield.

Combined application of 7.5 ton ha^{-1} biochar with 165 kg ha^{-1} and 60 kg ha^{-1} inorganic nitrogen and phosphorus fertilizer, respectively, resulted in the highest value (21.16 ton ha^{-1}) of total dry biomass. This result was statistically similar with application of

5 ton ha^{-1} biochar with 165 kg N and 60 kg P ha^{-1} or 206.25 kg N and 75 kg P ha^{-1}. Combined application of 7.5 ton ha^{-1} biochar with 123.75 kg N and 45 kg P ha^{-1} or with 206.25 kg N and 75 kg P ha^{-1} also gave statistically similar result. On other hand, the lowest total dry biomass (12.93 ton ha^{-1}) was recorded from control, which was statistically similar with application of 123.75 kg N and 45 kg P ha^{-1} or 165 kg N and 60 kg P ha^{-1} with no biochar (Table 6). Application of nitrogen and phosphorus fertilizers at rates of 206.25 kg ha^{-1} and 75 kg ha^{-1}, respectively, with no biochar increased the total dry biomass by 30.2% over the control. Similarly, combined application of 7.5 ton ha^{-1} biochar with 165 kg N and 60 kg P ha^{-1} increased the total dry biomass by 25.65% over application of 206.25 kg N and 75 kg P ha^{-1} without biochar and by 63.6% over the control.

Application of 7.5 ton ha^{-1} biochar with 165 kg ha^{-1} N and 60 kg ha^{-1} P resulted in the highest harvest index (0.64). On other hand, the lowest value (0.33) for harvest index was recorded for the control treatment, which was statistically similar with application of all the three levels of NP fertilizer without biochar application and 2.5 ton ha^{-1} biochar with all the three rates of NP (Table 6). Application of inorganic nitrogen and phosphorus fertilizers at rates of 206.25 kg and 75 kg ha^{-1} respectively, without biochar

and combinations of NP with lower levels of biochar generally resulted in lower harvest index of potato. However, application of 7.5 ton ha^{-1} biochar with 165 kg ha^{-1} N and 60 kg ha^{-1} P increased harvest index of potato by 77.78% over application of 206.25 kg N and 75 kg P ha^{-1} alone and by 93.9% over the control.

Discussion

Increasing rates of inorganic NP fertilizer application from zero to 206.25 kg ha^{-1} N and 75 kg ha^{-1} P without biochar did not show significant effect on both soil pH and cation exchange capacity. Whereas, combined application of 7.5 ton ha^{-1} biochar with 165 kg ha^{-1} N and 60 kg ha^{-1} P increased soil pH by 28.63% over application of 206.25 kg ha^{-1} N and 75 kg ha^{-1} P without biochar and by 32% over the control. Combined application of 7.5 ton ha^{-1} biochar with 206.25 kg ha^{-1} N and 75 kg ha^{-1} P also increased CEC by 52.58% as compared to application of the same NP rate but without biochar and by 63.9% as compared to the control. The significant effect of biochar on soil pH might be due to its contribution to reduce soil acidity by retaining nutrients in the soil directly through the negative charge that develops on its surfaces and buffers acidity in the soil. Biochar can also affect the level of cation exchange capacity due to negative charge that develops on its surface and attracts positively charged ions (cations), such as calcium (Ca^{2+}), potassium (K^+), magnesium (Mg^{2+}) and others specifically simple forms of plant nutrients which could be taken up through plant roots. Soil pH tends to increase with increasing rates of biochar due to the displacement of H^+, Fe^{2+}, Al^{3+}, Mn^{4+} and Cu^{2+} ions from soil adsorption site (Agboola and Moses 2015).

The biochar used in this study had a pH value of 9.4, which is basic in reaction. As suggested by Major (2011) and Anteneh et al. (2014), the alkalinity of most biochars can be beneficial to acidic soils, acting as a liming agent to increase pH, and decrease exchangeable Al. The current finding is in agreement with that of Soderberg (2013), Anteneh et al. (2014) and Agboola and Moses (2015), who reported that application of biochar as soil amendment resulted in positive and significant increase in soil chemical properties such as soil pH and cation exchange capacity (CEC). Biederman and Harpole (2013) have also reported that soil pH tended to increase, becoming less acidic, following the addition of biochar.

Increasing the level of inorganic NP fertilizer rates from zero to 206.25 kg N and 75 kg P ha^{-1} did not significantly increase the amount of soil organic matter, but significantly increased the level of total nitrogen and available phosphorus. Application of 206.25 kg N and 75 kg P ha^{-1} without biochar increased total nitrogen content by 0.11% and available phosphorus content by

23.6% over the control treatment (Fig. 1). On the other hand, combined application of 7.5 ton ha^{-1} biochar along with 206.25 kg N and 75 kg P ha^{-1} increased soil organic matter content by 71%, total nitrogen content by 39.28% and available phosphorus by 133.2% over application of the same NP rate with no biochar. The combined application of biochar and inorganic NP nutrients has shown positive and significant response for soil organic matter, total nitrogen and available phosphorus contents, probably due to the nature of biochar to improve soil fertility by improving soil cation exchange capacity (CEC), and its ability to hold crucial nutrients. In line with this, it has been reported that biochar retains nutrients in the root zone and reduces their leaching rate through the soil profile by water (Major 2011). In the present study, biochar application as a soil amendment increased soil pH, P availability, cation exchange capacity (CEC) and soil organic matter content. Biochar is also known to adsorb ammonia and phosphates in the soil and facilitate plant growth and activities of phosphorus (P) solubilizing microbes, which mobilize P for uptake by plant roots (Deb et al. 2016). The current observation is also in line with the findings of Kittredge (2015) and Agboola and Moses (2015) who reported that application of biochar increased soil organic carbon, soil nitrogen, and cation exchange capacity (CEC) and enhanced nitrogen retention by reducing emissions of ammonia, then, increasing total nitrogen. Biederman and Harpole (2013) have also reported that the addition of biochar to soils resulted, on average, in increased soil phosphorus (P), total soil nitrogen (N), and total soil carbon (C) compared with control conditions. The same finding was reported by Anteneh et al. (2014), indicating that biochar can improve the chemical and biological properties of the soil including organic carbon content and other plant nutrients.

Combined application of biochar with inorganic nitrogen and phosphorus fertilizers showed a significant effect on the crop phenology and growth except on days to 50% emergence. The uniform emergence of potato plants in all the plots without variations in the applied rates of biochar and NP fertilizers (Table 4) could be attributed to the fact that sprouting process in potato is mainly controlled by the potential of the stored food in the seed tubers and does not need nutrient supply from external environment (soil). It could also be due to the same type of variety used for all experimental units. In agreement with this, Gezahegn (2011) reported that emergence of potato tubers was influenced by storage condition and physiological age of the seed tubers rather than being conditioned by fertility status of the soil. Nonetheless, application of biochar and NP fertilizer showed a significant effect on days to 50% flowering

(Table 3) of potato. Application of 206.25 kg N and 75 kg P ha^{-1}, without biochar increased the number of days to 50% flowering by four compared to the control treatment. Also application of 7.5 ton ha^{-1} biochar with 206.25 kg N and 75 kg P ha^{-1} increased the number of days to 50% flowering by three as compared to application of 206.25 kg N and 75 kg P ha^{-1} alone, and by seven days as compared to the control. This might be attributed to the characteristics of biochar to retain applied nutrients in the root zone of plants and the high amount of nitrogen and phosphorus fertilizers which enhanced vegetative growth of the crop and prolonged days required to attain 50% of flowering. In line with this, Deb et al. (2016) reported that, the importance of biochar to nutrient availability indirectly influence the growth of crops. In addition, the current finding is in agreement with observations of Alemayehu et al. (2015) and Biruk (2015) who reported that increasing nitrogen and phosphorus fertilization levels significantly delayed days required for flowering in potato.

Application of 7.5 ton of biochar ha^{-1} with 165 kg of N and 60 kg of P ha^{-1} increased main stem by 96.2% over the control and by 26.5% over application of 165 kg of N and 60 kg of P ha^{-1} alone. The improvement in potato stem number could be attributed to the combined positive effects of biochar and inorganic fertilizers, as biochar amendment to soil probably increased soil moisture content, which may have direct effect on the number of sprouts. The increase in stem number in response to N fertilization might also be associated with the influence of N on gibberellic acid biosynthesis, which has direct influence on sprouting of tuber eye and lateral stem growth and, thus, development of potato plants (Alemayehu et al. 2015). It could also be attributed to a synergistic effect of N and P in promoting cell division, cell growth, and proliferation of axillary branches (Balemi 2012; Biruk 2015). This result is in agreement with the findings of Walter and Rao (2015) who reported that co-application of biochar and mineral fertilizers showed highest number of vine in sweet potato which was a three-fold increase compared to without application of biochar and mineral fertilizers. Contrary to the current result, different researchers reported that stem number was not influenced by mineral nutrients and the trait is more influenced by inheritance of the potato crop rather than by applied mineral fertilizers (Zelalem et al. 2009), condition of seed tubers, physiological age of the seed tubers, variety and seed tuber size (Firew 2014). This variation could be due to the fact that the reported experiments have been done at different sites with different treatment arrangements and material use and also under different growing conditions.

Application of 206.25 kg ha^{-1} nitrogen and 75 kg ha^{-1} phosphorus fertilizer without biochar increased plant height by 38.38% as compared to the control treatment. While combined application of 7.5 ton ha^{-1} biochar with 206.25 kg N and 75 kg P ha^{-1} increased plant height by 35% over application of 206.25 kg N and 75 kg P ha^{-1} alone and by 86.9% over the control treatment. Beside, combined application of 7.5 ton ha^{-1} biochar with 165 kg ha^{-1} nitrogen and 60 kg ha^{-1} phosphorus increased total leaf area by 48.49% compared to application of 206.25 kg ha^{-1} nitrogen and 75 kg ha^{-1} phosphorus alone and by 141% over the control. The increase in plant height in response to combined application of biochar and NP fertilization might be ascribed to enhanced uptake of Nitrogen and Phosphorus (Walter and Rao 2015), as nitrogen fertilizer stimulates vegetative growth and phosphate initiates stem elongation in potato. The current observation is in agreement with the findings of Yilangai et al. (2014) who reported that biochar usually has the potential of activating soil microorganisms and increasing the water retention capacity of the soil thereby, increasing photosynthetic rate with a consequent increase in growth of plants. Similarly, Upadhyay (2015) has reported that application of biochar is beneficial to plant height after four weeks when potato plants need more nutrients as they start growing vigorously. The reason for the increased total leaf area per hill related to biochar and NP fertilization could be attributed to development of more above ground biomass with the expanded leaves produced in response to nitrogen (Firew 2014). Since biochar has showed to reduce soil acidity, phosphorus availability possibly enhanced that consequently has promoted rapid canopy development, contributing to root cell division tuber set, and starch synthesis. Biochar possibly improved soil physical properties such as bulk density and porosity (Walter and Rao 2015), thereby, promoted early root growth. Enhanced root growth could have enhanced the ability of plants to access nutrients. Then increased amount of nutrients with in a plant enhances leaf area expansion and more leaf number developments. The current investigation is in line with the findings of Ahmed et al. (2009) who reported that increasing nitrogen fertilizer rate enhanced vegetative growth as expressed by plant height, leaf number and leaf area per plant. Similarly, Upadhyay et al (2014) have also reported that addition of biochar was beneficial for increasing leaf number in lettuce crop. Besides, Walter and Rao (2015) also found a two-fold increase in number of sweet-potato leaves per hill by application of biochar with mineral fertilizers, as compared to either sole biochar or sole mineral fertilizer addition to the soil.

Combined application of biochar with inorganic nitrogen and phosphorus nutrient has showed a significant improvement to all measured yield and yield related characteristics of potato except for unmarketable tuber number and unmarketable tuber weight. The increase in number of marketable tubers per hill with combined application of biochar and NP nutrient could be due to the positive effect of increased rates of nitrogen and phosphorus on the size of tuber. Moreover, biochar and NP fertilizers might increase the availability of nutrients for the crop which could have positive effects on the development of large sized tubers per hill. This result is in agreement with the findings of Israel et al. (2012); Yourtchi et al. (2013) and Alemayehu et al. (2015) who reported that application of nitrogen significantly increased marketable tuber number. Furthermore, the current result was in line with the findings of Walter and Rao (2015) who reported that application of biochar alone or co-applied with NPK fertilizers significantly improved marketable tuber number of sweet potato under wet humid tropical lowland conditions of Papua New Guinea.

The increase in marketable tuber and total tuber yield with increasing rates of biochar and inorganic NP fertilizers or NP fertilizer rates alone could be due to the fact that increased rates of NP fertilizer increased total leaf area, which, in turn, increased the amount of solar radiation intercepted and partitioning of more photo assimilate to the tubers (Zelalem et al. 2009). This idea was also supported by Alemayehu et al. (2015) who stated that increment of total and marketable tuber yield in potato might be associated with N fertilization ensuring maintenance of photosynthetically active leaves for longer duration and formation of new leaves. In addition to this, integrated use of biochar and inorganic NP fertilizers could have a greater impact on total tuber yield, which might be due to improved allocation of photosynthates to the tubers due to enhanced soil physical and chemical properties as a result of biochar amendment (Walter and Rao 2015). The current result is in agreement with the findings of Alemayehu et al. (2015) and Yourtchi et al. (2013) who reported that application of nitrogen significantly increased both total and marketable tuber yield. The current investigation was also in line with the findings of Nair et al. (2013) who reported that biochar treated plots showed overall considerable increase in potato yield. Similarly, Walter and Rao (2015) have reported that integrated use of biochar and inorganic chemical fertilizers had a greater impact on total tuber yield of sweet potato. Additionally, the application of biochar and NP nutrient has resulted to the increase in total dry biomass and harvest index too. This may be due to the greater impact of these treatments on total tuber yield, which could be reflected by improved allocation of photosynthates to the tubers as a result of enhanced soil physical and chemical properties. The results of the present study are also in agreement with the findings of Zelalem et al. (2009) and Yourtchi et al. (2013) who reported that aboveground and underground biomass yields of potato were found to be significantly influenced by N and P fertilization. Above-ground biomass yield of sweet potato increased due to co-application of biochar with mineral fertilizers which was on par with the sole mineral fertilizer treatment (Walter and Rao 2015). Additionally, several current reports have shown that biochar application increases the growth and yield of vegetables, legumes, and tomatoes (Lima et al. 2021; Lacomino et al. 2022; Wacal et al. 2023). For instance, maize stover biochar applied at 27.6 t ha^{-1} improved soil chemical properties especially pH, N, P, and K promoting growth and yield of tomatoes (Wacal et al. 2023).

Conclusion

The present study demonstrated that coffee husk biochar in combination with inorganic fertilizer increased the growth and yield of potato. The addition of biochar to the soil with inorganic NP fertilizers improved most of the growth and yield parameters. Potato growth and tuber yield significantly increased when biochar was applied in combination with inorganic fertilizers as compared to either sole biochar or sole mineral fertilizer application. Application of 7.5 ton ha^{-1} of coffee husk biochar with inorganic NP fertilizer of 165 kg N and 60 kg P ha^{-1} resulted highest tuber yield (42.64 t ha^{-1}). The increase was mainly attributed to the improvement in soil physicochemical properties especially soil pH, CEC, organic matter, total N and available P which is a reflection of increase in soil fertility. Therefore, the study recommends capacity building to ensure satisfactory knowledge of biochar use and its adoption by potato growers for soil fertility management and enhanced crop productivity.

Author contributions
SS conceived and designed the experiments, performed field experiments, analyzed and interpreted the data, wrote the draft version of the manuscript, AN, MA & BH proposed the idea, involved in designing and conducting the experiment. All authors contributed to revising and editing the manuscript. All authors read and approved the final manuscript.

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