

Article

Potential of Biochar-Based Organic Fertilizers on Increasing Soil Fertility, Available Nutrients, and Okra Productivity in Slightly Acidic Sandy Loam Soil

Nischal Acharya ¹ , Shree Prasad Vista ² , Shova Shrestha ², Nabina Neupane ¹ and Naba Raj Pandit ^{3,*}

¹ Agriculture Department, Himalayan College of Agricultural Sciences and Technology (HICAST), Kirtipur 44600, Nepal

² National Soil Science Research Center (NSSRC), Nepal Agricultural Research Council (NARC), Lalitpur 44705, Nepal

³ International Maize and Wheat Improvement Center (CIMMYT), Lalitpur 44705, Nepal

* Correspondence: navraj20@gmail.com

Abstract: Reducing chemical fertilizers is critical for maintaining soil health and minimizing environmental damage. Biochar-based organic fertilizers reduce fertilizer inputs, improve soil fertility, increase crop productivity, and reduce environmental risks. In this study, a pot experiment was conducted in a greenhouse to assess the potential of biochar-based organic and inorganic fertilizers to improve soil fertility and Okra yield. Seven treatments with three replicates were arranged in a completely randomized design (CRD). Three treatments included biochar-blended formulations (i) biochar mixed with mineral NPK fertilizer (BF), (ii) biochar mixed with vermicompost (BV), and (iii) biochar mixed with goat manure (BM); two treatments included biochar enrichment formulations (iv) biochar enriched with cow urine (BCU) and (v) biochar enriched with mineral NPK fertilizer in aqueous solution (BFW), and the remaining two included control treatments; (vi) control (CK: no biochar and no fertilizers) and (vii) fertilized control (F: only recommended NPK fertilizer and no biochar). Mineral NPK fertilizers in BF, BFW, and F were applied at the recommended rate as urea, di-ammonium phosphate (DAP), and muriate of potash (MOP). Organic fertilizers in BV, BM, and BCU treatments were applied in equal quantities. All biochar-amended treatments showed improved soil chemical properties with higher pH, organic carbon, total N, and available P and K compared to the two non-biochar control plots (CK and F). Biochar blended with goat manure (BM) showed the highest effect on soil fertility and fruit yield. BM (51.8 t ha^{-1}) increased fruit yield by 89% over CK (27.4 t ha^{-1}) and by 88% over F (27 t ha^{-1}). Similarly, cow urine-enriched biochar (BCU) (35 t ha^{-1}) increased fruit yield by 29% and 28% compared to CK and F, respectively. Soil pH, OC, and nutrient availability (total N, available P, and available K) showed a significantly positive relationship with fruit yield. The study suggests that using biochar-based organic fertilizers, such as BCU and BM, could outperform recommended mineral fertilizers (F) and produce higher yields and healthy soils, thereby contributing to mitigating the current food security and environmental concerns of the country.

Keywords: biochar; cattle manure; soil properties; vegetable; Nepal



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1. Introduction

Okra (*Abelmoschus esculentus*), a dicotyledonous summer-season plant (Malvaceae family) grows well in a wide range of soil types (ranging from sandy loam to loamy soil) and temperatures ranging from 21 to 30 °C [1,2]. Okra is one of the most important vegetable crops in Nepal and is cultivated in the terai (lowland) and mid-hill (upland) districts [3]. The total production of okra was 284,926 metric tons with the total productivity of $13.95 \text{ metric tons ha}^{-1}$, under 20,424 ha area across the country in the year 2021 [4]. Areas under okra production increased by 12.2% within four years (from 2011 to 2015). However, the yield decreased by 0.2% during this period [5].

The declining productivity is mainly attributed to poor soil fertility (low pH, organic matter (OM), cation exchange capacity (CEC), base saturation, available nutrients), inappropriate use of chemical and organic fertilizers, and the lack of improved crop management practices by farmers. Approximately 49% of the agricultural area is reeling from soil acidification problems, especially in the Eastern region of Nepal [6,7], where 60% of soils have low phosphorous (P) and 18% of soils are deficient in potassium (K) [8].

Biochar as a soil amendment, in combination with organic and mineral fertilizers, is gaining popularity in improving soil fertility and increasing crop yields and nutrient use efficiency across the world [9,10]. Biochar is a carbon-rich product produced by the pyrolysis of a wide range of organic products [11,12], such as grass, cow manure, wood chips, rice husk, agriculture residues, sewage sludge, corn cobs, chicken litter, etc. [13]. In Nepal, the most common and economic feedstock for biochar production is the invasive plant species '*Eupatorium adenophorum*', commonly known as 'Banmara' [14].

Biochar blended with organic and mineral fertilizers has shown significant beneficial effects on soil chemical properties (pH, organic matter, and available nutrients) [10,14], physical properties (texture, bulk density, porosity) [15], and biological properties [16]. Biochar with its alkaline nature increases the soil pH of acidic soil and increases crop yield, alleviating the acid stress [17,18]. Similarly, soil organic carbon, base saturation (BS), exchangeable K, and available P were found significantly higher in the biochar-amended soils compared to non-biochar (control) soil [18]. Moreover, soil nitrogen (N) has been found higher due to reduced leaching losses and retention of nitrogen in the pores of the biochar [19]. The high porosity and low density of biochar improve soil physical properties (bulk density, texture, porosity) and microbial populations such as N-fixing rhizobia and Mycorrhizal fungi [12]. Besides improving soil properties, biochar, due to its recalcitrant nature, can sequester carbon for the long term and reduce CO₂, NO₂, and other greenhouse gas (GHGs) emissions, thereby contributing to climate change mitigation [20].

Application of biochar in combination with organic fertilizers such as cattle urine, manure, composts, and green manure or mineral fertilizers, such as nitrogen and phosphatic fertilizers, have shown higher crop yields compared to the sole application of biochar or organic and inorganic fertilizers [12,21]. Biochar mixed with manure increased radish yield by 320% compared with non-fertilized control (without biochar and fertilizer) and by 44% compared with NPK fertilized control [22]. Similarly, biochar mixed with mineral NPK fertilizers increased curd yield in cauliflower by 37% compared to the sole application of mineral fertilizer and by 59% compared to the control, in two consecutive seasons [23]. In recent years, pre-enrichment of biochar with organic fertilizers (such as cattle urine and manure) or mineral fertilizers in an aqueous solution has shown higher crop yield and nutrient use efficiency (NUE) compared with the non-enriched biochar (biochar and fertilizers added separately in the soil during planting) [24–26]. Biochar enriched with mineral nutrients in an aqueous solution increased crop yields by 105% compared to biochar and mineral fertilizers added separately (non-enriched biochar) [26]. Similarly, cattle's urine-enriched biochar increased pumpkin yield by 300% compared to control in silty loam soil [24]. A similar beneficial effect of cow urine-enriched biochar was found in the yield of cabbage and kohlrabi in Bangladesh, where the yield was increased by 60.37% and 61.53% respectively, compared to the control [27]. The positive agronomic effect of nutrient-enriched biochar is due to the organic coatings formed in the pores of the biochar, which improves the nutrient retention capacity of the biochar [28]. Nutrients that are stored in biochar pores for prolonged periods release slowly, synchronizing nutrient supply and plant demand [24]. A slow release of nutrients increases crop productivity and nutrient use efficiency (NUE) and minimizes soil nutrient losses by reducing leaching and emissions [29,30].

The agronomic benefits of biochar either mixed or enriched with organic and inorganic fertilizers are well documented in previous studies in various crops and vegetables [14,25]. There are few or no studies where the agronomic effect of biochar-based organic and inorganic fertilizers has been assessed for the okra plant. In this study, for the first time

in Nepal, the potential of biochar-based organic fertilizers: biochar mixed or enriched with organic fertilizers (cattle urine, vermicompost, and goat manure), and mineral NPK fertilizers were assessed on okra productivity under a controlled greenhouse experiment. The objective of the study was to assess the potential of biochar (mixed or enriched with organic and inorganic fertilizers) in reducing soil acidity, increasing soil organic carbon (OC), and available nutrients (N, P, and K), thereby increasing okra yield in a moderately acidic Nepalese soil. We hypothesized that the biochar-based fertilizers will improve soil fertility (pH, OC, N, P, and K) and increase okra yield compared with both the fertilized control (applying recommended mineral fertilizers without biochar) and non-fertilized control (without fertilizers and biochar).

2. Materials and Methods

2.1. Experimental Site

A pot trial was conducted in the greenhouse at National Soil Science Research Center (NSSRC), NARC (Nepal Agriculture Research Council), Khumaltar, Lalitpur (27°39'17" north latitude, 85°20'44" east longitude, and 1335 m above mean sea level). The experiment was conducted over three months, from May to July 2022. The average maximum and minimum temperatures were 28.2 °C (ranging from 28 to 28.5 °C) and 19 °C (ranging from 16.5 to 20.5 °C), respectively, during the experimental period (Table 1). Cumulative rainfall during the growing season (May to June 2022) was 300.3 mm (Table 1).

Table 1. Climatic data of the experimental site from May–July 2022.

Climate Parameters	May	June	July
Maximum Temperature	28.5 °C	28.3 °C	28 °C
Minimum Temperature	16.5 °C	20 °C	20.5 °C
Precipitation	49 mm	77.3 mm	177 mm

(Data Source: weatherpark.com, accessed on 5 August 2022).

2.2. Experimental Set Up and Cultivation Practices

The experimental design included seven treatments with three replicates in a completely randomized design (CRD). Three treatments included mixed biochar formulations (i) biochar mixed with mineral NPK fertilizer (BF), (ii) biochar mixed with vermicompost (BV), and (iii) biochar mixed with goat manure (GM); two treatments included biochar enrichment formulations (iv) biochar enriched with cow urine (BCU) and (v) biochar enriched with mineral NPK fertilizer (BFW) in aqueous solution and remaining two included non-biochar control treatments; (vi) non-fertilized control (CK: plot receiving neither biochar nor fertilizers) and fertilized control (F: plot receiving recommended NPK fertilizers without biochar) (Table 2). The chemical fertilizers NPK were applied either on their own or in combination with biochar in their dry (BF) or dissolved form (BFW), based on the recommended rate of NPK for okra in Nepal (200:180:80 kg ha^{−1}) [31]. Mineral fertilizers N, P, and K were applied as urea (46% N), di-ammonium phosphate (DAP: 46% P and 18% N), and muriate of potash (MOP; 60% K), respectively. The application of other organic amendments i.e., vermicompost, goat manure, and biochar were in equal quantity at the rate of 10 t ha^{−1}, which is equivalent to N content in mineral fertilizer, considering 39% of the total N in mineral form in the cattle compost [22].

Grows bags with a length of 30 cm, a width of 20 cm, and a height of 30 cm of 12 L were used for the experiment. The distance between the treatments was 30 cm. Small pebbles, stones, and weeds were separated from the soil and filled into the pots at a rate of 10 kg of soil per pot.

Table 2. Description of various biochar-based organic and inorganic fertilizer treatments.

Treatments	Biochar Input (kg ha ⁻¹)	Organic and Inorganic Fertilizer Inputs (kg or L ha ⁻¹)	Biochar Input (gm pot ⁻¹)	Organic and Inorganic Fertilizer Inputs (gm or mL pot ⁻¹)
Control (CK)	0	Control	0	Control
Recommended NPK fertilizers (F)	0	200:180:80 NPK	0	0.0892:0.080:0.035 NPK
NPK fertilizer-enriched biochar (BFW)	10,000	200:180:80 NPK + 80,640 L water	44.6 gm	0.0892:0.080:0.035 NPK + 360 mL water
NPK fertilizer blended with biochar (BF)	10,000	200:180:80 NPK	44.6 gm	0.0892:0.080:0.035 NPK
Cow urine-enriched biochar (BCU)	10,000	80,640 L Cow urine	44.6 gm	360 mL Cow urine
Vermicompost blended with biochar (BV)	10,000	10,000 kg Vermicompost	44.6 gm	44.6 gm Vermicompost
Goat manure blended with biochar (BM)	10,000	10,000 kg Goat Manure	44.6 gm	44.6 gm Goat Manure

Biochar and organic and inorganic fertilizers were calculated and applied to each pot as described in Table 2. BFW and BCU were prepared one day before seed sowing. In a 2 L beaker, 44.6 g of biochar, 1.25 g of urea, 1.74 g of DAP, and 0.59 g of MOP, were added and dissolved into 360 mL of water to prepare NPK fertilizer-enriched biochar (BFW) [24]. Likewise, in another 2 L beaker, 44.6 g of biochar was added to 360 mL of cow urine to prepare a urine-enriched biochar slurry (BCU) [24,26]. All organic and inorganic inputs with and without biochar (Table 2) were mixed thoroughly and deeply with soil in the pot during planting. For the recommended NPK fertilizer treatment (F), a full dose of DAP and MOP and half a dose of urea were applied during soil preparation. The remaining urea was top dressed in two equal splits at 30 and 45 days after sowing (DAS).

The seeds of *Arka Anamika*, a variety resistant to yellow vein mosaic virus, with a potential yield of 20 t ha⁻¹ were used in the experiment. The seeds were soaked overnight and sown manually through holes of 3 cm depth. Three holes were made in the soil with 4–5 seeds in each hole, separated by a distance of 5 cm. Thinning was performed after 15 DAS, to maintain three healthy and robust plants. The pots were watered on alternate days in the early morning and evening to ensure sufficient moisture during growing periods. The first weeding was performed after 15 DAS and subsequent weeding was carried out manually at 5 day intervals. Harvesting of okra fruit pods was done manually after maturity and subsequent multiple harvests were done at an interval of 2–3 days up to 90 DAS.

2.3. Agronomic and Yield Parameters

Stem girth and plant height in each pot were recorded at 15 DAS, 30 DAS, 45 DAS, 60 DAS, 75 DAS, and 90 DAS. A digital vernier caliper and measuring tape were used to measure stem girth and plant height.

Days to first harvest were counted for each plant in the pot, and its arithmetic mean was taken for all the treatments. The harvesting period is the total duration of the harvest from the first day to the final day of harvest. The length of the fruit was measured using measuring tape from the cap section to the distal end. The diameter of the fruit was measured at the center of the fruit pod using a digital vernier caliper. The weight of the individual harvested pods was measured to record the average fruit weight. The total number of fruits, harvested up to 90 DAS, in each pot was counted and the weight was measured to record the total fruit yield.

2.4. Biochar and Soil Analysis

The biochar used in this study was produced from Bracken and *Eupatorium adenophorum* (Banmara). Biochar was characterized by a pH of 9.58, total nitrogen of 0.77%, organic carbon of 13.50%, and cation exchange capacity (CEC) of 19.08 cmol_c kg⁻¹ (Table 3).

Table 3. Initial Soil Analysis.

Soil Parameters	Results	Biochar	Analytical Method
pH	5.61	9.58	Soil: Water ratio of 1:2
Texture	Sandy Loam	-	Hydrometer
Organic Matter (%)	2.12	-	Walkley and Black 1934
Organic Carbon (%)	1.22	13.5	
Total Nitrogen (%)	0.12	0.77	Kjeldahl Digestion and Distillation
Available Phosphorous (kg ha ⁻¹)	12.10	-	Modified Olsen's Bicarbonate
Available Potassium (kg ha ⁻¹)	102.3	-	Ammonium Acetate and Flame Photometer
Cation exchange capacity (cmol _c kg ⁻¹)	-	19.1	Neutral Ammonium Acetate

For the preliminary soil information, triplicate representative soil samples were collected from the field to make a composite sample. Sampled soils were analyzed for soil texture, pH, organic matter (OM), organic carbon (OC), total nitrogen (N), available phosphorous (P), and available potassium (K). For post-harvest soil analysis, soil samples were collected from all the individual pots, stored in zip lock bags, labeled well, and analyzed for the aforementioned soil properties.

The collected soil samples were air-dried for two days and passed through a 0.2 mm sieve for OM and OC analysis. For other soil parameters (pH, total N, available P, and available K), the soil was passed through a 2 mm sieve. Soil texture was determined using the hydrometer method [32]. Soil pH was measured using a pH meter (soil: distilled water ratio of 1:2) [33]. OM and OC were determined using the Walkley–Black method [34]. Total N was measured using the Kjeldahl digestion and distillation method [33]. The modified Olsen's method was used for the available phosphorous [35] and the ammonium acetate and flame photometer were used to determine the available potassium [33] (Table 3).

The preliminary analysis showed that the soil was sandy loam Inceptisol with low OM content, medium N content, and low available P and K content (Table 3).

2.5. Data Analysis

Data were analyzed using STAR (Statistical Tool for Agricultural Research), version 2.0.1 developed by International Rice Research Institute (IRRI) and SPSS (Statistical Package for Social Sciences), version 25 developed by IBM. One-way ANOVA was performed to assess the effect of biochar mixed or enriched with organic and inorganic amendments on soil properties and plant growth parameters. Tukey's HSD (honest significant difference) test was performed at a 5% level of significance to compare the mean between different treatments. Linear regression was performed to identify the relationship between soil chemical properties (pH, OC, total N, and available P and K) and okra production.

3. Results

3.1. Soil Properties

Biochar blended or enriched with mineral NPK (BFW and BF) and organic fertilizers (BCU, BV, and BM) treatments were pooled to give an average mean value for each biochar-mixed NPK (B-mineral) and organic fertilizers (B-organic). B-mineral and B-organic were compared with the average mean of non-biochar CK and F treatments (control). Soil pH increased from 5.8 (control) to 6.1 in B-mineral and up to 6.6 in B-organic pots (Table 4). OC increased from 1.5% (control) to 2% and 2.2% in B-mineral and B-organic treatments, respectively (Table 4).

Table 4. Effect of biochar-blended organic and inorganic fertilizers on soil parameters. Values are means \pm standard deviation, followed by the different letters in the column denoting significant difference at the 0.05 level using Tukey's HSD test.

Treatments	pH	Organic Matter (%)	Organic Carbon (%)	Total Nitrogen (%)	Available Phosphorous (kg ha ⁻¹)	Available Potassium (kg ha ⁻¹)
CK	5.63 \pm 0.06 d	2.30 \pm 0.39 c	1.33 \pm 0.23 c	0.13 \pm 0.01 e	23.45 \pm 12.05 d	103.09 \pm 1.35 d
F	5.94 \pm 0.38 cd	2.91 \pm 0.32 bc	1.69 \pm 0.18 bc	0.15 \pm 0.03 e	36.54 \pm 1.68 cd	121.58 \pm 0.75 d
BFW	6.08 \pm 0.04 bc	3.25 \pm 0.04 abc	1.88 \pm 0.02 abc	0.16 \pm 0.02 de	38.91 \pm 1.38 bc	242.81 \pm 2.10 c
BF	6.12 \pm 0.02 bc	3.72 \pm 0.26 ab	2.15 \pm 0.16 ab	0.20 \pm 0.02 cd	41.91 \pm 0.53 bc	250.32 \pm 1.84 c
BCU	6.47 \pm 0.05 ab	3.39 \pm 0.72 ab	1.96 \pm 0.42 ab	0.25 \pm 0.01 ab	46.91 \pm 0.41 bc	234.38 \pm 5.56 c
BV	6.61 \pm 0.04 a	3.95 \pm 0.38 ab	2.28 \pm 0.23 ab	0.23 \pm 0.02 bc	51.62 \pm 1.27 b	353.58 \pm 29.85 b
BM	6.80 \pm 0.07 a	4.16 \pm 0.09 a	2.41 \pm 0.05 a	0.28 \pm 0.01 a	75.53 \pm 4.52 a	407.83 \pm 20.97 a
Grand Mean	6.24	3.38	1.96	0.20	146.98	244.80
S.E.M.	0.12	0.30	0.18	0.01	10.88	11.43
CV%	2.38	11.16	11.14	8	9.07	5.72
p-value	0.0000	0.0005	0.0005	0.0000	0.0000	0.0000
f-value	22.74	8.56	8.59	37.75	76.28	188.32
LSD	0.42	1.05	0.61	0.04	37.15	39.03

The total nitrogen increased by 28% in B-mineral (0.18%) and by 78% in B-organic soils (0.25%) compared with the control (0.14%). Available P increased by 33% (40.4 kg ha⁻¹) in B-mineral and by 93% (58.1 kg ha⁻¹) in B-organic compared with the control (30.02 kg ha⁻¹). Similarly, available K increased by 119% (246.5 kg ha⁻¹) in B-mineral and by 195% (331.9 kg ha⁻¹) in B-organic compared with the control (112.3 kg ha⁻¹).

3.2. Plant Growth Parameters

Plant height and stem girth over a growing season measured at every 15 d interval from 15 DAS to 90 DAS are shown in Figures 1 and 2, respectively. The plant height in 90 DAS was significantly higher in BFW (130 cm), BV (141.5 cm), and BM (144.92 cm) by 34.4%, 46.4%, and 50% compared to CK (96.66 cm) (Figure 1). In 90 DAS, BV (12.27 mm) showed the highest stem girth among all the treatments, followed by BCU (12.01 mm) (Figure 2).

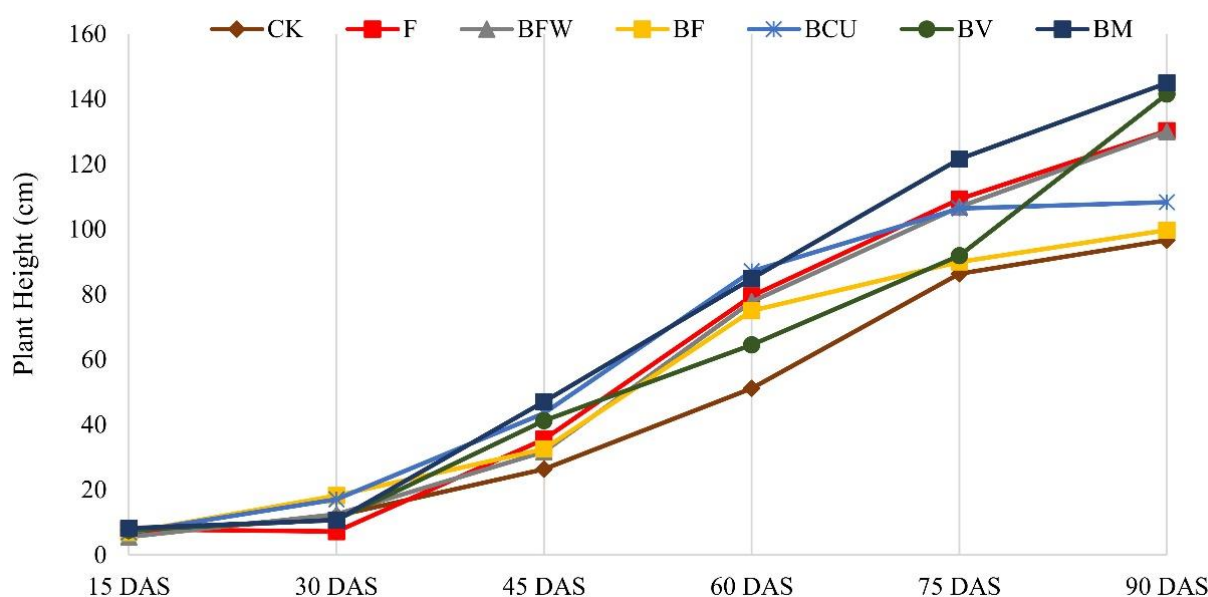


Figure 1. Effects of various biochar-blended or enriched organic and inorganic treatments on plant height recorded at every 15-day interval from 15 DAS to 90 DAS.

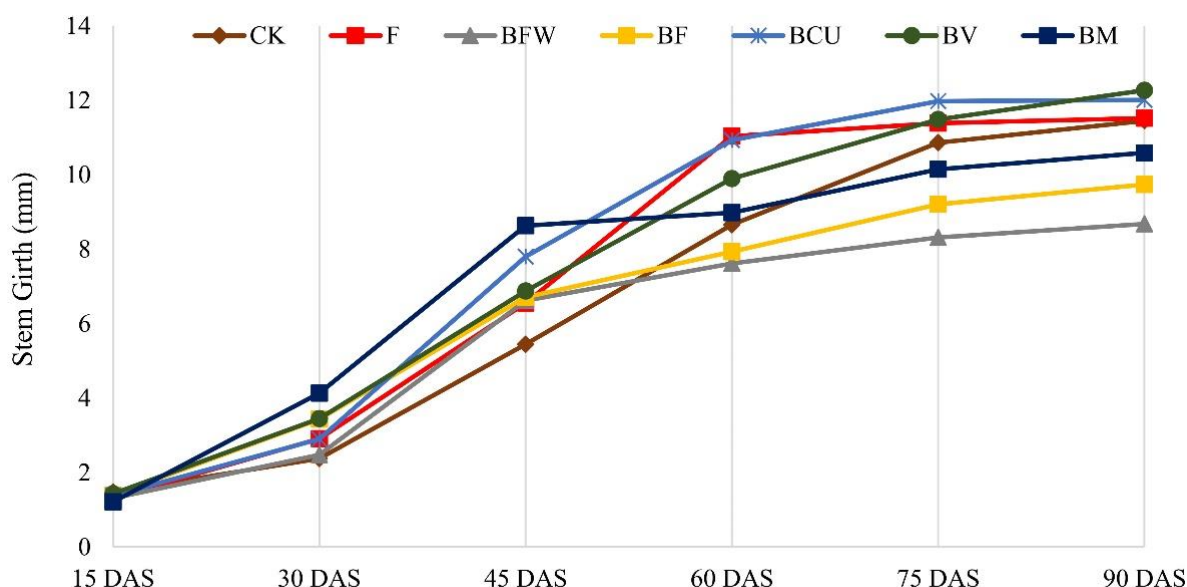


Figure 2. Effects of various biochar-blended or enriched organic and inorganic treatments on plant stem girth recorded at every 15 d interval from 15 DAS to 90 DAS.

3.3. Fruit Yield

Average fruit weight was increased by 11.61% (11.44 gm) in BFW, 22.34% (12.54 gm) in BF, 28.4% (13.16 gm) in BV and 32.4% (13.62 gm) in BM, respectively, compared to CK (10.25 gm). The number of fruits per pot in BCU (15), BV (13), and BM (17) was increased by 50%, 30%, and 70% compared with CK (10) and by 42%, 23%, and 62% compared with the F treatment, respectively (10.5) (Table 5). No significant differences were observed between the treatments on the average length and diameter of fruit (Table 5).

Table 5. Effect of biochar-blended organic and inorganic fertilizers on the yield parameters of okra. Values are means \pm standard deviation, followed by the different letters in the column denoting significant differences at the 0.05 level using Tukey's HSD test.

Treatments	Average Fruit Length (gm)	Average Fruit Diameter (mm)	Average Fruit Weight (gm)	Number of Fruits per Pot (number)	Days to First Harvest (d)	Harvesting Period (d)
CK	10.71 \pm 0.71 a	14.01 \pm 1.16 a	10.25 \pm 0.03 d	10 \pm 0 d	63.5 \pm 2.5 a	24 \pm 1 c
F	11.28 \pm 0.46 a	15.17 \pm 0.12 a	13.23 \pm 0.11 ab	10.5 \pm 0.5 cd	62 \pm 2 a	25 \pm 3 c
BFW	11.01 \pm 0.37 a	15.08 \pm 0.43 a	11.44 \pm 0.12 c	11.5 \pm 2.5 cd	57.17 \pm 0.17 c	31 \pm 1 ab
BF	10.78 \pm 0.14 a	15.2 \pm 0.19 a	12.54 \pm 0.02 b	10.5 \pm 0.5 cd	61.33 \pm 1 ab	27.5 \pm 0.5 bc
BCU	11.1 \pm 0.77 a	15.18 \pm 0.45 a	11.23 \pm 0.06 cd	15 \pm 0 ab	57.25 \pm 0.25 c	31.75 \pm 0.25 a
BV	11.95 \pm 0.85 a	15.31 \pm 0.61 a	13.16 \pm 0.62 ab	13 \pm 0 bc	60 \pm 0 abc	29 \pm 0 ab
BM	11.87 \pm 1.26 a	14.69 \pm 0.69 a	13.62 \pm 0.73 a	17 \pm 1 a	58 \pm 1 bc	31 \pm 1 ab
Grand Mean	11.24	14.95	12.21	12.5	59.89	28.46
S.E.M.	0.60	0.50	0.30	0.86	1.08	1.08
CV%	6.53	4.10	3.01	8.42	2.22	4.66
p-value	0.29	0.20	0.0000	0.0000	0.0002	0.0000
f-value	1.38	1.68	34.95	18.97	10.64	16.15
LSD	-	-	1.03	2.93	3.7017	3.70

BFW (57.17), BCU (57.25), and BM (58) showed significantly better days to first harvest by 11.0%, 10.9%, and 9.5% compared with CK (63.5) and by 8.4%, 8.3%, and 6.9%, respectively, compared with F (62) (Table 5). The harvesting period in BFW (31 d), BCU (31.75 d), BV (29 d), and BM (31 d) was longer by 29.2%, 31.8%, 20.9%, and 23.2% compared with CK (24) and by 24%, 27%, 16%, and 24% compared with the F treatment (25 d), respectively (Table 5).

Total fruit yield was increased by 38% (27.45 t ha^{-1}) in BCU and 89% (51.76 t ha^{-1}) in BM compared to CK (27.45 t ha^{-1}). Similarly, fruit yield was increased by 34% in BCU and 84% in BM compared with the F treatment (23.17 t ha^{-1}) (Figure 3).

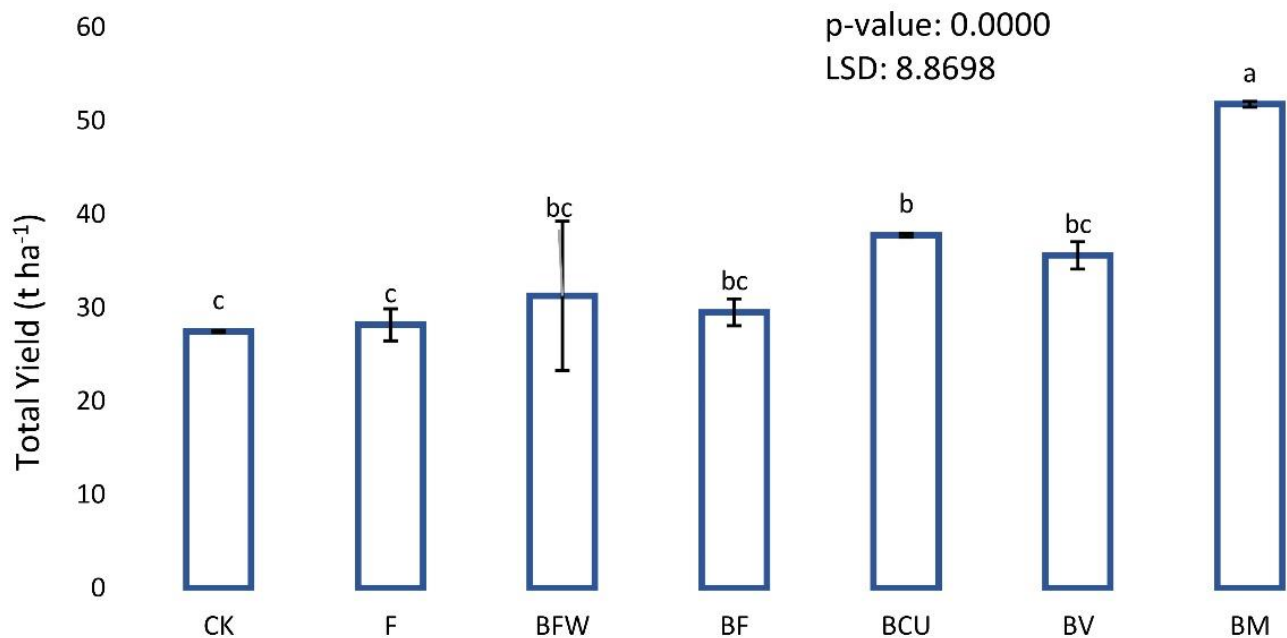


Figure 3. Total fruit yield of okra in different biochar mixed or enriched mineral (NPK) and organic fertilizers; means \pm standard deviation. Mean with different letters denote significant differences ($p \leq 0.05$) between the treatments.

3.4. Relationship between Soil Properties and Fruit Yield

A significant positive relationship ($p < 0.05$) was observed between soil parameters and total fruit yield; pH ($R^2 = 0.62$), OC ($R^2 = 0.37$), total N ($R^2 = 0.67$), available P ($R^2 = 0.76$), and available K ($R^2 = 0.60$) (Figure 4). Soil pH was found to be positively correlated with available P ($R^2 = 0.72$) and total N ($R^2 = 0.74$) (Figure 4).

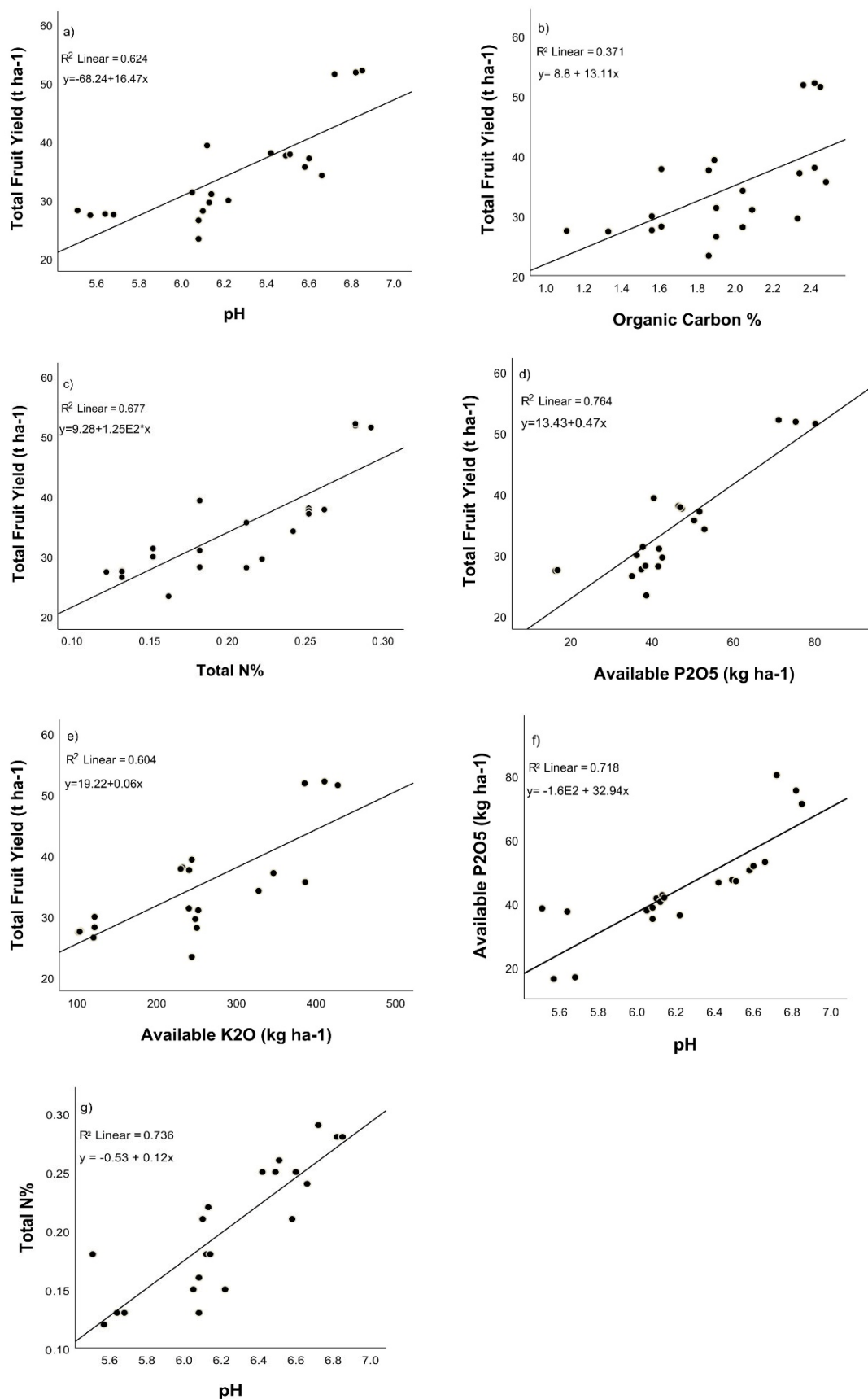


Figure 4. Relationship between soil parameters, i.e., pH, OC, total N, available P, available K, and total fruit yield (a–e), and between soil pH vs. available P (f) and total N (g).

4. Discussion

4.1. Soil Properties

Using biochar in combination with organic and inorganic NPK fertilizers has significantly improved soil properties and nutrient availability, with superior effects observed for biochar-based organic fertilizers (BCU, BV, and BM) (Table 4). In accordance with this, earlier studies have reported increased soil pH [17,22,36] and OC [22,37–39] upon biochar application in combination or enriched with mineral and organic fertilizers. An increase in soil pH is due to the alkaline nature of biochar that can quickly release base cations, such as Ca^{2+} , Mg^{2+} , and K^+ into the soil solution, and reduce H^+ and Al/Ca ratio [17,40]. Moreover, biochar has reactive pH-dependent functional groups, such as phenolic (OH) and carboxylic acid (COOH), which could increase the soil pH [40]. Moreover, the small fraction of ash content in biochar could result in the subsequent dissolution of hydroxides and carbonates, thereby reducing soil acidity [41,42]. Soil OM was observed higher in biochar-amended soils (Table 4), which could be due to high OC content in biochar, soil microbial abundance, reduced leaching, and lower mineralization rate (higher mean residence time) due to greater carbon stability [36,42–44]. On average, biochar blended with organic and mineral fertilizers increased soil OC by 70% compared to controls, which is corroborated with earlier studies that reported an 80% increase in OC in similar soils upon biochar application in combination with organic and inorganic fertilizers [22].

Soil nitrogen and available P and K were found significantly higher in both biochar-amended mineral and organic fertilizers over control (Table 4), with a superior effect observed for biochar-based organic fertilizers (BCU, BV, and BM). This is corroborated by earlier findings where N, P, and K were significantly increased upon biochar application compared with non-biochar soils [22,45]. Zhang et al. [46] reported an increase in soil N by 18.5% and 32.9% over control with the application of 1% and 5% biochar-based organic fertilizer, which is in line with our findings (Table 4). Higher soil N content upon biochar amendment could be explained by the abundance of surface functional groups and highly porous structure of biochar, leading to reduced leaching, and retaining a higher amount of nitrogen, as well as fostering microbes in biochar pores, which enhance soil biological processes such as mineralization, nitrification and other mineral solubilization activities [28,47,48].

Similarly, higher soil available P upon biochar amendment (Table 4) is in line with the findings from Mensah [49], who reported an increase in available P with the addition of biochar in combination with mineral and organic fertilizers (biofertilizer, vermicompost, and peat substrate). Increased soil P upon biochar amendment could be due to reduced leaching losses, higher P retention, and the synchronization of biochar and organic fertilizers, which enhance the P biogeochemical cycles (total P, available P) in soil [42,48,50]. Moreover, higher soil available P could be related to increased soil pH upon biochar amendment (Figure 4f). Soil PO_4^- is tightly bound in Fe and Al under acidic conditions; thus, the biochar amendment could increase pH towards neutral, thereby making more P available in the soil solution [51].

Increased available K in biochar-amended soil (Table 4) could be due to the direct addition of K from biochar and biochar ash per se, and also due to the higher surface area of biochar, which adsorbs K strongly and reduces leaching losses of K in soil [19]. This is corroborated by the earlier studies in which Mensah [49] reported higher available K with biochar in combination with 50% biofertilizer and 50% inorganic fertilizer compared with the control. The high concentration of K in biochar-amended soils could result from low exchangeable acidity due to the precipitation of Al as hydroxyl releases cations into the soil. Moreover, the K saturation percentage increases with biochar application due to the more significant effects of biochar on exchangeable K. Moreover, the increase in soluble K content could be attributed to the limited capacity of exchange sites and clay interlayers for K adsorption [49,52].

4.2. Plant Growth Parameters

Biochar enriched with mineral fertilizers showed higher efficiency in increasing the plant height (Figure 1), which is in line with the study by Utomo et al. [53], where plant height was significantly increased in nitrogen-enriched biochar compared with non-biochar treatments in 90 DAS. Sharma et al. [54] reported a significant increase in plant height of knolkhol with biochar applied in combination with vermicompost by 18.2%, and with cattle manure (FYM) by 15.8% compared to control, which corroborates our findings where biochar mixed with vermicompost, and goat manure showed a superior effect on plant height (Figure 1). The increase in plant height could be attributed to the improved soil pH, EC (electrical conductivity), and soil fertility [49], and also due to plant-promoting effects and nutrient loadings, stimulated by biochar [30].

The application of vermicompost and cow urine in combination with biochar has shown the maximum stem girth (Figure 2). A significant increase in the knob diameter of knolkhol with the application of biochar blended with vermicompost, reported by Sharma et al. [54], corroborates our findings. The ability to retain nutrients due to the low bulk density and high-water holding capacity of biochar could explain the improvement in crop performance, increasing the stem girth of the okra plant as observed in our findings [55].

4.3. Fruit Yield

Total fruit yield was found significantly higher in biochar enriched with cattle urine (BCU) and biochar blended with goat manure (BM) compared with the non-fertilized (CK) and fertilized control (F) (Figure 3). In accordance with this, Schmidt et al. [25] reported a significant increase in crop yields by 95% with cattle urine-enriched biochar compared with the control and fertilized control receiving NPK mineral fertilizer. In another study, they reported an almost two-fold increment in pumpkin yield with urine-enriched biochar compared with the control in Dhading, Nepal [24]. Similarly, Shrestha and Pandit [56] reported double pea yields with the application of urine-biochar amendments compared with the control plot receiving only NPK mineral fertilizer and only manure. Several earlier studies are well documented where urine-enriched biochar improved soil fertility and increased crop yield substantially [14,24,25]. Higher maize productivity with urine-enriched biochar application could be due to the formation of organic coatings in biochar pores, which enhance the nutrient retention capacity of biochar [28]. Nutrient-enriched biochar allows penetration of available nutrients, such as N, P, and K in biochar micro- and nano-pores, and releases slowly based on the physiological requirements of the plant over the cropping season [24,26]. In addition, urine application could promote stem growth due to cell elongation by promoting hormonal activities, resulting in the faster growth of the okra plant [57].

In our study, biochar blended with goat manure (BM) showed a greater effect on fruit yield among all the treatments, including control (CK) and fertilized control (F) (Figure 3). In accordance with this, Sanchez-Monedero et al. [58] reported significantly higher fruit yield in tomatoes by 16.4% with biochar-blended sheep manure and compost, compared with the control. Increased yield could be due to improved soil fertility (higher soil pH and OC) and a higher amount of available nutrients (soil N, P, and K) observed in goat manure blended biochar (BM) over both controls and all other biochar-amended treatments (Table 4). Moreover, a higher yield could be explained by the positive relationship between soil properties (pH, OC, N, P, and K) and total fruit yield (Figure 4), which is in line with an earlier study where a strong positive correlation between soil properties (pH, P, and K) and crop yields [59] was reported after using organic biochar amendments. Improvements in soil chemical properties and nutrient availability with BM are corroborated by a study conducted by Ingold et al. [60], who reported increased soil OC and total N with the use of biochar-blended goat manures. Higher soil N in BM could be due to higher levels of N in goat manure per se, which was reported to be around 4.9% N [61], relatively higher compared with N content in cattle manure or farmyard manure. Increased crop yield

and growth parameters (plant height, stem diameter) upon goat manure application is widespread [61,62]. Ojeniyi and Adegboyega [63] reported that the use of goat manure significantly increased the growth and yield of okra, *Amaranthus*, and *Chelosia*. However, the agronomic performance of goat manure mixed with biochar is less studied and is noticeably scarce. Our findings on soil properties, nutrient availability, and okra productivity as a function of biochar-blended goat manures could be highly significant to researchers and institutions at national and international levels.

Increased yields upon BM application could be due to a higher amount of N in goat manures that are retained in biochar pores for longer periods and released slowly based on the synchrony between soil nutrient supply and plant demand [24,30]. Similarly, higher soil available P and K in BM treatments could have increased the okra yield, which is corroborated by Pandit et al. [18], where biochar blended with organic fertilizers considerably increase soil P and K, which was positively correlated with maize yield in similar soils. Similarly, BM showed higher soil pH (Table 4) and a positive relationship with okra yield (Figure 4a), which could be due to liming effect of biochar (alleviating acid stress) in sandy loam acidic soils [17]. Jemal and Yakob [64] reported that the addition of 12 t ha⁻¹ of biochar recorded the lowest exchangeable acidity (0.39 cmol_c kg⁻¹), thus, underscoring the potential of biochar as a liming material. Moreover, there could be a compounding effect of soil N and available P on okra yield, as pH was positively correlated with soil N and P (Figure 4f,g). The increase in soil pH enhanced the availability of soil N and other essential immobile nutrients such as P and K, which increases root/shoot growth and yield of plants [48,65]. Moreover, a 13% and 43% increase in the yield of fresh eggplant in two consecutive years with the application of biochar-based fertilizers holds close links with our results [66]. Moreover, the improvement in nutrient absorption and photosynthesis activities upon biochar-based fertilizers might have increased carbohydrate synthesis, dry matter, and subsequent accumulation of fruits, leading to high yields [67,68].

5. Conclusions

The results suggest that the addition of biochar-based organic fertilizers, such as biochar enriched with cattle urine (BCU) and biochar blended with goat manures (BM) could significantly improve soil chemical properties (pH, OC, total N, and available P and K) and okra fruit yield in a sandy loam Nepalese soil. Biochar blended with goat manure was found efficient among all the organic and inorganic treatments to increase soil nutrient availability such as N, P, and K, thereby increasing okra yield. This study analyzed and presented soil chemical parameters for various organic and inorganic nutrients mixed with biochar and lacks detailed studies on the organic matter transformation and nutrient bioavailability. Therefore, more detailed spectroscopic and microbiological studies are needed to mechanistically disentangle the higher effect of biochar-goat manure formulations on increasing nutrient availability in the soil.

This is the first study in which the agronomic effects of biochar-based organic and inorganic fertilizers have been studied under controlled conditions in okra. Thus, further studies on different crops/vegetables, soil types, and agroecological zones of Nepal are recommended. In view of the shortage of fertilizers in Nepal, the promotion of biochar-based organic fertilizers should be encouraged through research and extension by the concerned authorities for wider adoption by farmers in their farmland.

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