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Cattle-Urine-Enriched Biochar Enhances Soil Fertility, Nutrient Uptake, and Yield of Maize in a Low-Productive Soil

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Abstract: Poor soil fertility, imbalanced fertilization, and limited use of organic fertilizer by farmers are significant limitations contributing to lower crop productivity in Nepal. Biochar-based organic fertilizers have been identified as efficient soil amendments to improve soil fertility and boost crop yields. In this study, we investigated the effects of biochar-based organic fertilizers on soil properties, fertilizing efficiency, and maize yields in low-productivity Nepalese soil. A field trial was conducted using a randomized complete block design comprising four treatments with three replications: (1) control without biochar (CK), (2) biochar (BC), (3) biochar + manure (BC+M), and (4) urine-enriched biochar + manure (BU+M). Recommended NPK fertilizers were applied to all plots, including the control. Urine-enriched biochar (BU+M) significantly improved soil pH, organic carbon, and soil nutrient levels (N, P, and K) compared to the control (CK). Total N, available P, and K were significantly higher ($p < 0.05$) in BU+M treatments compared to the other two biochar amendments (BC and BC+M). A similar trend was observed in the NPK uptake by plants, with BU+M outperforming CK, BC, and BC+M. Moreover, BU+M increased ($p < 0.05$) the partial factor of productivity of N (PFPN) and P (PFPP) compared to CK. The application of urine-enriched biochar resulted in a 62% increase in maize yield compared to the CK. These findings suggest that farmers can improve soil fertility and increase grain production with the use of urine-enriched biochar, which can be easily produced by farmers themselves using locally available feedstocks and cattle urine.

Keywords: biochar; nutrient-enriched biochar; productivity; maize; Nepal

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1. Introduction

In Nepal, maize (*Zea mays* L.) is the second-most important crop following rice (*Oryza sativa* L.). Maize is mostly grown in hills (ranging from subtropical to temperate zones) under rainfed conditions by farmers for food, feed, and fodder [1]. However, maize productivity in Nepal is lower with a national average of 2.8 t ha^{-1}. This lower productivity could be attributed to declining soil fertility characterized by low pH, organic carbon levels, base saturation, and available nutrients. Additionally, poor nutrient management practices and dependence on rainfed agriculture are other crucial factors affecting productivity [2]. Farmers have deviated from the recommended practices by applying higher amounts of nitrogen fertilizer (urea) compared to phosphorous and potassium fertilizers. Moreover, the inappropriate time and method of nitrogen (N) fertilization in addition to imbalanced N rate among farmers has led to reduced N use efficiency and larger N losses into the environment, thereby contributing to water pollution and global warming [3]. The reduced

NUE due to inefficient fertilization techniques and declining crop productivity has resulted in a large yield gap (difference between the potential yield and actual crop yields) in maize.

Biochar, a carbon-rich material, mixed with organic and mineral fertilizers, has shown promising effects on improving soil fertility, available nutrients, and nutrient use efficiency (NUE) in low-productivity soils [4–7]. Several studies have confirmed the positive effect of biochar in improving soil chemical properties such as soil pH, organic carbon (OC), and cation exchange capacity (CEC) [4,8,9]. Soil pH increased from 3.6 to 4.7 [10] and from 3.9 to 5.1 [8] upon biochar addition to highly weathered acidic soils. Similarly, soil OC, CEC, and exchangeable K were found to be significantly higher with the use of biochar [9,11]. Biochar, with its highly porous structure, surface area, and CEC assures strong sorption capacity that can retain nutrients for a prolonged period, thereby increasing nutrient availability, recovery fraction, and NUE [12–15]. In addition to improving soil properties, biochar, due to its inert nature, remains stable in soil for several years and helps mitigate climate change [16].

The benefits of using biochar in combination with mineral or organic nutrients on crop productivity are well documented in previous studies [4,17]; however, some studies have shown nonsignificant or even negative yield effects of biochar amendment [18,19]. Increased crop productivity was mainly attributed to improved soil physicochemical properties such as pH, OC, CEC, and available NPK [8,9], as well as increased nutrient use efficiency (NUE) [12,15] upon biochar addition. However, the exact mechanism of biochar in improving crop productivity, nutrient cycling, and NUE is poorly understood [20,21].

In recent years, biochar enriched with mineral or organic fertilizers (compost or cattle urine) has illustrated higher fertilizing efficiency compared to nonenriched biochar (separate addition of biochar and fertilizers to the soil) [22,23]. Maize production increased by 105% when biochar was loaded with mineral fertilizers in an aqueous solution, compared with the same amount of biochar and fertilizer added separately [23]. Similarly, another study revealed that biochar enriched with cattle urine increased pumpkin yield by up to 300% compared to a nonbiochar plot receiving an equal amount of urine [24]. The enhanced agronomic performance of nutrient-enriched biochar was due to the restriction of water movement in biochar micro- and nanopores. This allows retention of nutrients for a longer period and acts as a slow-release fertilizer, enabling synchrony between soil nutrient supply and plant demand [24–26]. The slow-release mechanism of nutrient-enriched biochar improves nutrient use efficiency (NUE) and reduces nutrient losses from the soil through leaching and emissions [13,15].

In Nepal, due to depleted soil fertility (low pH, organic carbon, and available nutrients such as N, P, and K) and limited fertilizer inputs by farmers, the majority of crops are grown under nutrient-deficit conditions [27,28]. As a result, crop productivity has decreased. Thus, it is crucial to identify the efficient soil nutrient management practices that include the judicious use of both organic and inorganic fertilizers. The use of balanced fertilization through organic and inorganic sources improves soil health and nutrient use efficiency, and boosts crop productivity. Urine-loaded biochar has been found to be one of the most efficient biochar-based organic fertilizers and its application has shown dramatic increments on vegetable yields [7,24]. We assume a similar beneficial effect of urine-enriched biochar on maize crop production in this study. We conducted a field experiment to assess the effect of biochar and urine-enriched biochar (BU) on maize productivity in a subtropical silty loam acidic soil in Nepal. The underlying hypothesis is that the urine-enriched biochar with its high fertilizing efficiency [22] enhances soil chemical properties (pH, OC), nutrient availability (N, P, and K), plant nutrient uptake, and boosts maize productivity compared with nonbiochar-fertilized plots (control) and nonenriched biochar (biochar added separately with organic and inorganic fertilizers) receiving the same quantity of nutrient supplements.

2. Materials and Methods

2.1. Study Site

The field trial was conducted in Lubhu, Lalitpur (27°35′ N 85°23′ E). The study site was located at an altitude of 1298 m above sea level with a mean annual temperature of 18.3 °C. Annual precipitation ranges from 1600–2000 mm, with higher rainfall during the monsoon period (from June to September). The dominant cropping system is maize–vegetables–wheat and rice–wheat in the study site.

2.2. Biochar and Urine-Enriched Biochar

The invasive, ubiquitous, and nonpalatable forest weed "*Eupatorium adenophorum*" (locally named "Banmara"), also known as *Ageratina adenophora* (Spreng), was used as a feedstock for biochar production. Biochar (BC) was produced using a novel flame curtain soil pit Kon-Tiki kiln with a pyrolysis temperature ranging from 450–700 °C [22]. Sundried feedstock weighing 250 kg was used for biochar production. After a pyrolysis time of about 2 h, the biochar was snuffed with soil and kept overnight (12–18 h) before collection. Biochar yield was 20% of the dry feedstock (50 kg). Biochar produced from Eupatorium using Kon-Tiki was characterized by a high pH (10.4), organic carbon (70%), CEC (72 cmolc kg^{-1}), and surface area (74.6 m^2 g^{-1}) [23]. For the preparation of urine-enriched biochar (BU), 1 kg biochar was added in a bucket containing 5 L cattle urine (approximately 1:1 volume ratio of biochar and urine) and stirred thoroughly to prepare the urine–biochar slurry. The next day, the urine-enriched biochar slurry was collected and applied to the respective experimental plots.

2.3. Experimental Setup and Cultivation Practices

A field experiment was conducted for four months, from April to August 2018. In a randomized complete block design, four treatments with three replications were used: (1) fertilized control without biochar (CK); (2) biochar (BC), (3) biochar + manure (BC+M), and (4) urine-enriched biochar + manure (BU+M). The size of the treatment plot was 2 m^2, keeping 50 cm spaces between each plot. In all treatment plots, including the control, the recommended dosage of mineral fertilizers was applied (180:60:40 kg N P_2O_5 K_2O ha^{-1} in the form of urea, diammonium phosphate (DAP), and muriate of potash (MOP), respectively) to ensure sufficient nutrients for optimum growth and development of maize. Biochar, manure, and urine-enriched biochar substrate were applied at the rate of 10 t ha^{-1} (2 kg per plot). The application rate of manure was determined according to the recommended dosage for maize cultivation in Nepal, while the rate of biochar was established based on our earlier study, which showed that applying biochar at 10–15 t ha^{-1} resulted in optimum agronomic, economic, and environmental benefits. For urine-enriched biochar (10 t ha^{-1}), 1.6 t ha^{-1} of biochar was mixed with 8400 L of fresh cattle urine (1 L urine weighs 1 kg) i.e., 0.33 kg biochar was mixed with 1.67 L of urine per plot. In treatments 3 and 4, nutrient levels in cattle manure and urine were determined based on the study conducted by Schmidt et al. [24], involving cattle of comparable breed and reared in the same agroecological zone (mid-hills). This information was used to calculate the available NPK rates in the respective treatments during the maize growing period.

The cattle manure had a total nitrogen (TN), phosphate, and potassium content of 14 g kg^{-1}, 7 g kg^{-1}, and 18 g kg^{-1}, respectively. According to a research study by Schmidt et al. [24] and Kammann et al. [29], 15% of manure TN and 30% of each of the manure phosphate and potassium are in a plant-available form in the first year. Based on this assumption, approximately 7 kg N ha^{-1}, 7 kg P_2O_5 ha^{-1}, and 35 kg K_2O ha^{-1} would be available in plant-available form from manure during the maize growing period. Similarly, the fresh cattle urine contained a TN, phosphate, and potassium content of 9.5 g L^{-1}, 0.35 g L^{-1}, and 9.2 g L^{-1}, respectively, corresponding to approximately 79 kg ha^{-1} TN, 3 kg ha^{-1} P_2O_5, and 77 kg ha^{-1} K_2O, respectively. According to the study by Ramirez-Sandoval et al. [30], 35% of fresh cattle urine nitrogen is assumed to be in a plant-available form in the first year. Thus, approximately 9.5 kg N ha^{-1}, 0.3 kg P_2O_5 ha^{-1}, and 7.7 kg K_2O ha^{-1} would be available with the cattle urine during maize growing period. Using the nutrient levels from organic sources (manure and cattle urine) and inorganic NPK fertilizer input, the available NPK contributions in each treatment were computed. In treatments 1 and 2, NPK input from inorganic fertilizer was 180:60:40 kg N P_2O_5 K_2O ha^{-1}. In treatment 3, NPK input from inorganic fertilizer and organic fertilizer (manure) was 187:67:58 N P_2O_5 K_2O ha^{-1}. Similarly, in treatment 4, NPK input from inorganic fertilizer, cattle manure, and urine was 196:67:66 kg N P_2O_5 K_2O ha^{-1}.

During land preparation, the full dosage of DAP, MOP, 1/3rd amount of urea, biochar (BC), cattle manure (M), and urine-enriched biochar (UB) were broadcast uniformly, followed by tillage (15–20 cm soil depth) and harrowing in the respective treatment plot. The remaining 2/3rd amount of urea was top-dressed in two equal splits, i.e., 60 kg N ha^{-1} (24 g per plot) each at 45 and 60 days after sowing (DAS). Two maize seeds (Arun-2 variety) were sown at a depth of 5 cm with a spacing of 30 cm × 30 cm following line sowing methods. Maize was grown under rainfed conditions. Terracing and drains were built on the sides of each plot to conserve the topsoil and prevent erosion. Upon germination and the emergence of two leaves after 2 weeks, the seedling was thinned, keeping one healthy plant in the field. Insecticide was applied after two weeks to control cutworm infestations after sowing. Hand-weeding was carried out as and when needed in all the plots to control the weeds.

2.4. Soil and Plant Analysis

Three soil samples from each treatment plot at a depth of 0–15 cm were collected with a soil auger in the month of April 2018 before maize sowing. Samples were pooled into one composite sample for each treatment plot and analyzed for soil texture, pH, organic carbon, total nitrogen (N), available phosphorous (P), and potassium (K) at the Agriculture Technology Center laboratory (ATC). Soil samples were oven-dried at 40 °C for three days, passed through a 2 mm sieve, and grounded before analysis. Soil texture was analyzed through the hydrometer method [31]. Soil pH was measured in a 1:2.5 water suspension using a digital pH meter (buffering at pH 7 and 4). Organic carbon was determined as per the Walkley and Black method [32]. Total N was analyzed through Kjeldahl's method. Available P was determined through modified Olsen's bicarbonate [33] and available K through the neutral ammonium acetate method using a flame photometer. Details about the soil analytical process are shown in the Supplementary Information (Description S1).

Three flag leaf samples from each plot were collected before the silk turned brown for plant nutrient analysis. Plant samples were oven-dried, milled, and digested with sulfuric acid prior to analysis. Nitrogen content was determined using Kjeldahl's method, where digested solution was treated with alkali, zinc, and thiosulphate. Liberated ammonia was collected in the boric acid solution and titrated with standard acid using a mixed indicator. Phosphorus content was analyzed using the vanadomolybdophosphoric yellow method, in which the digested solution was treated with vanadomolybdophosphoric acid for yellow color development, using a spectrophotometer at 400 nm wavelength. The potassium content in the digested solution was measured using a flame photometer.

2.5. Grain Yield and Nitrogen Use Efficiency

Harvesting was performed manually upon physiological maturity (grain moisture of 15–20%) by cutting stems at 5 cm above the soil surface. During harvest, three plants were selected randomly from each plot and averaged to record the mean value for each treatment replication. During harvest, a thousand grain weight and grain yield were measured. Moisture-corrected grain yield was recorded by adjusting the moisture content at 12%.

For all treatments, nutrient use efficiency (NUE) was calculated as partial factor productivity (PFP) of nitrogen (PFPN), phosphorus (PFPP), and potassium (PFPK) using the equation given by Fixen et al. [34]. PFP refers to the production efficiency, i.e., units of crop yield per unit of nutrient applied. Equation (1):

$$\text{PFP} = \frac{\text{Y}}{\text{F}}(\text{kg maize yield per kg nutrient applied}), \quad (1)$$

where Y is maize yield (kg ha^{-1}) and F is the amount of fertilizers applied (kg ha^{-1}).

2.6. Statistical Analysis

The data were analyzed using R version 4.1.2 statistical software. One-factor ANOVA was used to assess the effect of biochar and urine-enriched biochar on soil chemical properties (pH, OC, total N, available P and K), plant nutrient uptake (total N, P, and K), PFP, and maize yield. In addition, for maize yield response, two-factor ANOVA was performed, keeping manure as the second variable, to see if there was a manure effect (confounding) on yield in both biochar and urine-enriched biochar plots. The post hoc Tukey test (p = 0.05) was used to determine the significant differences in maize yield between treatments. The difference between various treatments was significant at $p < 0.05$ unless stated otherwise. Linear regression was used to assess the relationship between soil chemical properties (pH, OC, total N, available P and K), nutrient uptake (total N, P, and K), and crop yield.

3. Results

3.1. Soil Properties

The soil was characterized as a moderately acidic silty loam, Dystrochrepts, Inceptisol (Table 1). Biochar amendments (BC, BC+M, BU+M) showed a significant positive effect ($p < 0.05$) on soil chemical properties and nutrient availability (pH, OC%, total N, available P, and available K).

Table 1. Effect of biochar (BC), biochar mixed with manure (BC+M), and urine-enriched biochar (BU+M) along with nonbiochar control (CK) treatments on soil chemical properties. Letters in the table represent significant difference between the treatments at 5% probability level (post hoc Tukey test, $p < 0.05$).

Properties	Treatments			
	CK	**BC**	**BC+M**	**BU+M**
pH	5.19 ± 0.09 a	5.35 ± 0.05 b	5.51 ± 0.24 bc	5.63 ± 0.04 c
OC%	1.12 ± 0.04 a	1.23 ± 0.04 b	1.48 ± 0.08 c	1.64 ± 0.01 d
Total N%	0.10 ± 0.01 a	0.10 ± 0.01 a	0.13 ± 0.01 b	0.14 ± 0.00 c
Available P (mg kg^{-1})	17.41 ± 0.11 a	19.06 ± 0.26 b	22.07 ± 1.27 b	26.92 ± 0.86 c
Available K (mg kg^{-1})	76.60 ± 4.32 a	88.75 ± 4.48 b	120.13 ± 2.47 c	140.47 ± 6.71 d
Texture	Silty loam	Silty loam	Silty loam	Silty loam
Sand	27.33 ± 5.03 a	25.67 ± 3.21 a	20.67 ± 3.06 a	20.33 ± 4.04 a
Silt	56.40 ± 4.58 a	56.73 ± 2.52 a	60.07 ± 2.52 a	60.07 ± 1.53 a
Clay	16.27 ± 1.53 a	17.60 ± 1.00 a	19.27 ± 2.08 a	19.60 ± 4.58 a

Soil pH was significantly increased with the addition of BC (5.35), BC+M (5.51), and BU+M (5.63) compared to the control (CK) plot (5.19). Similarly, soil OC was increased from 1.12% (CK) to 1.23%, 1.48%, and 1.64% with the application of BC, BC+M, and BU+M, respectively. Soil nitrogen was significantly increased with the use of BC+M (0.13%) and BU+M (0.14%) over CK (0.1%).

Biochar amendments increased plant available phosphorous (P), which was increased from 17.4 mg kg^{-1} (CK) to 19.1, 22.1, and 26.9 mg kg^{-1} with the application of BC, BC+M, and BU+M, respectively. A similar trend was observed for available potassium where biochar amendments increased available K from 76.6 mg kg^{-1} (CK) to 88.7 mg kg^{-1} (BC), 120 mg kg^{-1} (BC+M), and 140 mg kg^{-1} (BU+M). The magnitude of increment on soil OC, total N, available P, and K was significantly higher with the use of urine-enriched biochar compared to the BC+M treatments (Table 1).

3.2. Nutrient Uptake by Plants

Biochar amendments showed a significant positive effect on nutrient uptake (N, P, and K) by maize (Figure 1). N uptake was increased by 71% (18.73 ± 0.75 g kg^{-1}), 88% (20.63 ± 0.55 g kg^{-1}), and 125% (24.60 ± 0.61 g kg^{-1}) with BC, BC+M, and BU+M, respectively, compared to the CK (10.93 ± 0.06 g kg^{-1}) (Figure 1a). P uptake was increased by 34% with BC+M (1.17 ± 0.11 g kg^{-1}) and by 60% with BU+M (1.40 ± 0.10 g kg^{-1}) over CK (0.87 ± 0.06 g kg^{-1}) (Figure 1b). Biochar amendment had a similar positive effect on K uptake, which was increased by 38%, 45%, and 58% with BC (10.50 ± 0.50 g kg^{-1}), BC+M (11.07 ± 0.06 g kg^{-1}), and BU+M (12.01 ± 0.50 g kg^{-1}), respectively, compared to the CK (7.67± 0.29 g kg^{-1}) (Figure 1c). Plant nutrient uptake (N, P, and K) was found to be significantly higher with urine-enriched biochar (BU+M) compared with (BC+M) treatment (Figure 1a–c).

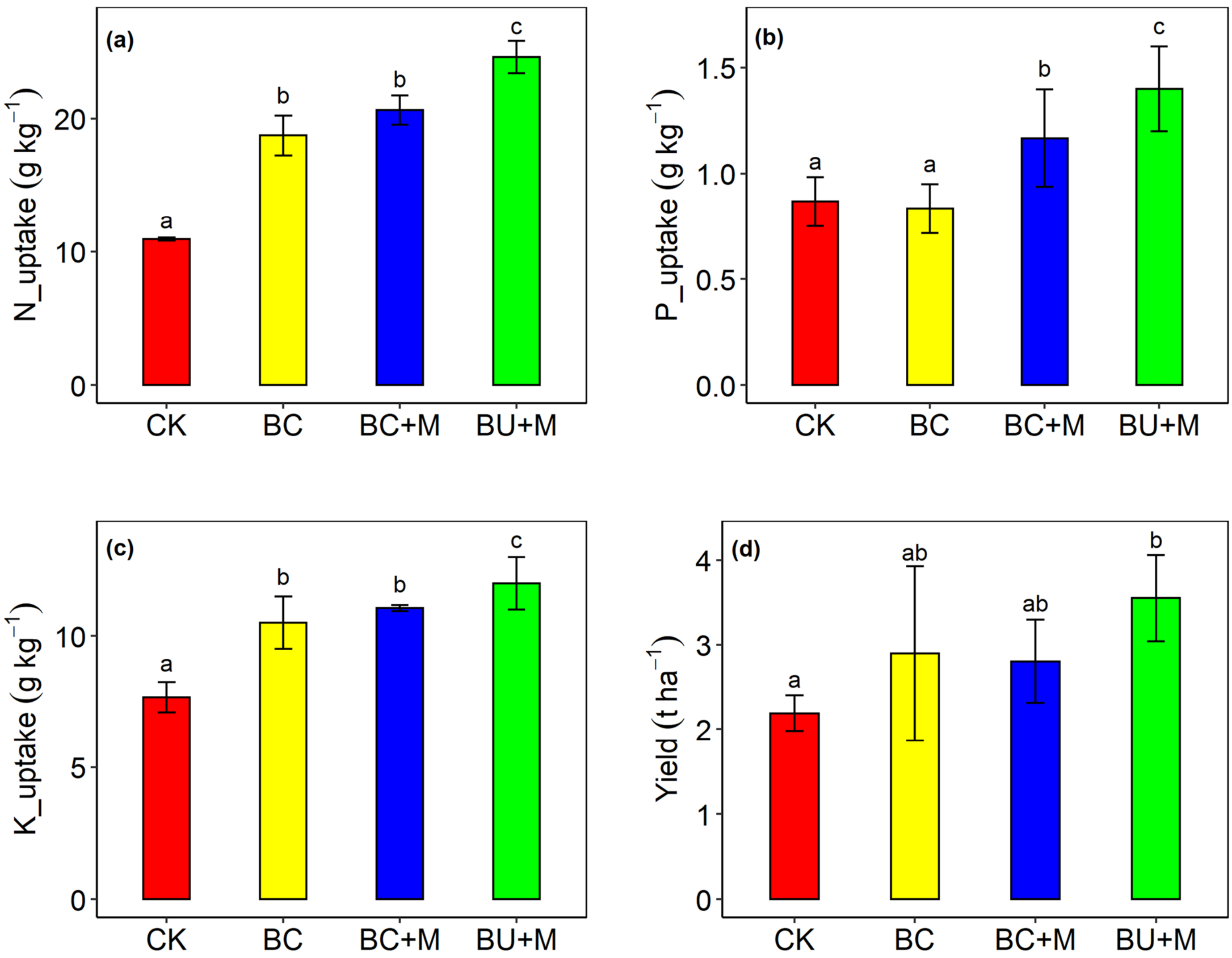

Figure 1. Effect of urine-enriched biochar (BU+M) over control (CK), biochar (BC), and biochar + manure (BC+M) on plant uptake of N (**a**), P (**b**), K (**c**), and maize yield (**d**) (mean ± SD). Different letters inside a bar represent significant difference between the treatments at 5% probability level (post hoc Tukey test, $p < 0.05$).

3.3. Maize Productivity and PFP

Urine-enriched biochar (BU+M) showed a significant positive effect on maize yield (Figure 1d). BU+M increased maize yield by 62% (3.55 ± 0.14 t ha^{-1}) compared to the CK

(2.19 ± 0.06 t ha^{-1}) (Figure 1d). However, the other two biochar amendments, i.e., BC and BC+M, did not show a significant variation in maize yield compared with CK.

Partial factor productivity of nitrogen (PFPN) and phosphorous (PFPP) was significantly higher with urine-enriched biochar (BU+M) compared to the CK (Figure 2). BU+M increased PFPN by 48% and PFPP by 45% over CK. PFPK was observed to be the highest with the use of BC (Figure 2).

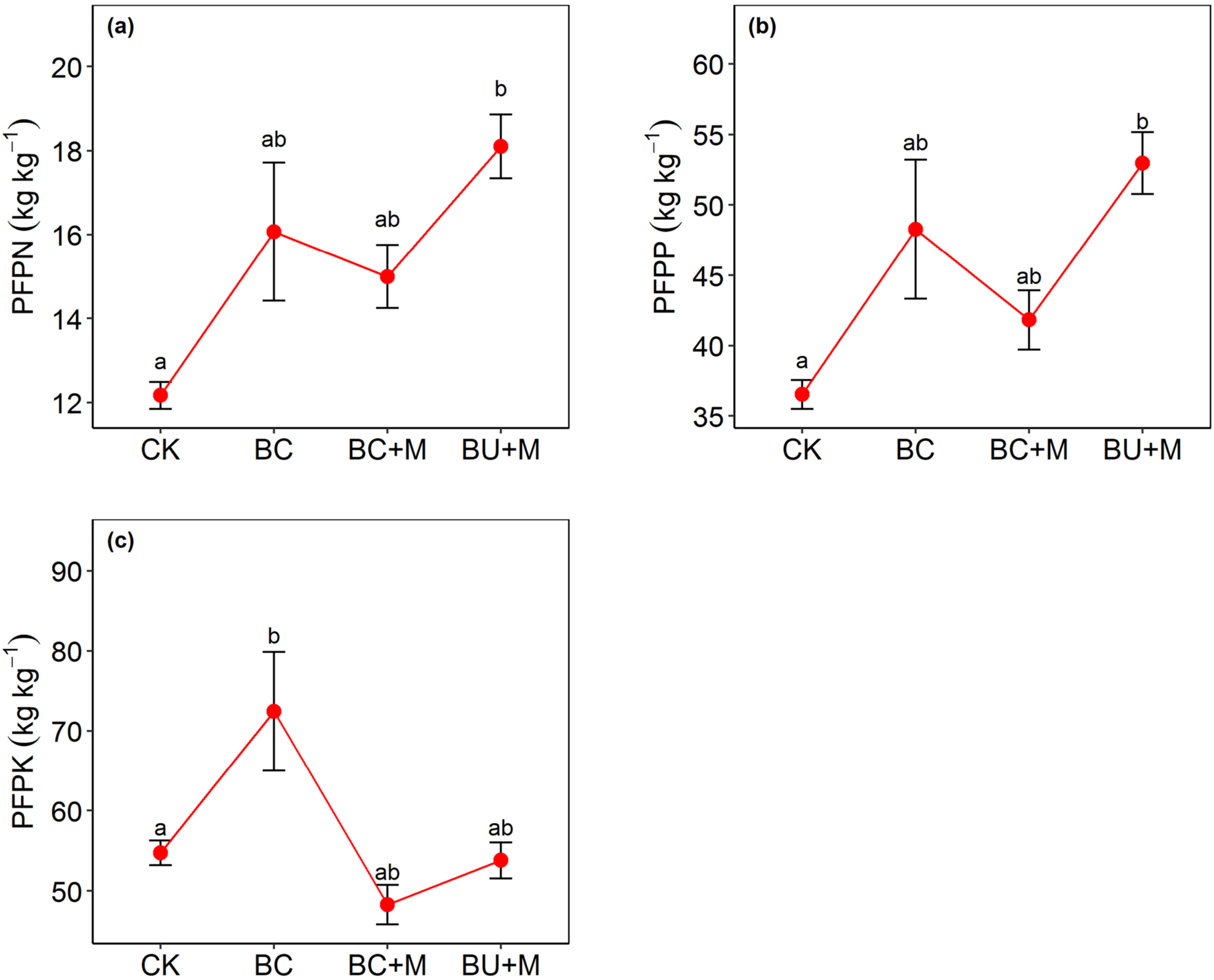

Figure 2. Effect of urine-enriched biochar on partial factor productivity of N (**a**), P (**b**), and K (**c**) nutrients (mean ± SE). Different letters above the mean plots represent significant difference between the treatments at 5% probability level (post hoc Tukey test, $p < 0.05$).

3.4. Relationship between Soil Chemical Properties, Plant Nutrient Uptake, and Yields

A significant positive relationship was observed between soil nitrogen and plant nitrogen uptake (R^2 = 0.78), soil available phosphorous and plant phosphorous uptake (R^2 = 0.79), and soil available potassium and plant potassium uptake (R^2 = 0.71) (Figure 3).

Similarly, soil chemical properties such as pH (R^2 = 0.49), OC (R^2 = 0.58), soil N (R^2 = 0.54), soil available P (R^2 = 0.60), and soil available K (R^2 = 0.56) showed significant positive relationship with maize yield (Figure 4a–e). Moreover, plant nutrient uptake of nitrogen, phosphorous, and potassium was linearly correlated with maize yield (Figure 4f–h).

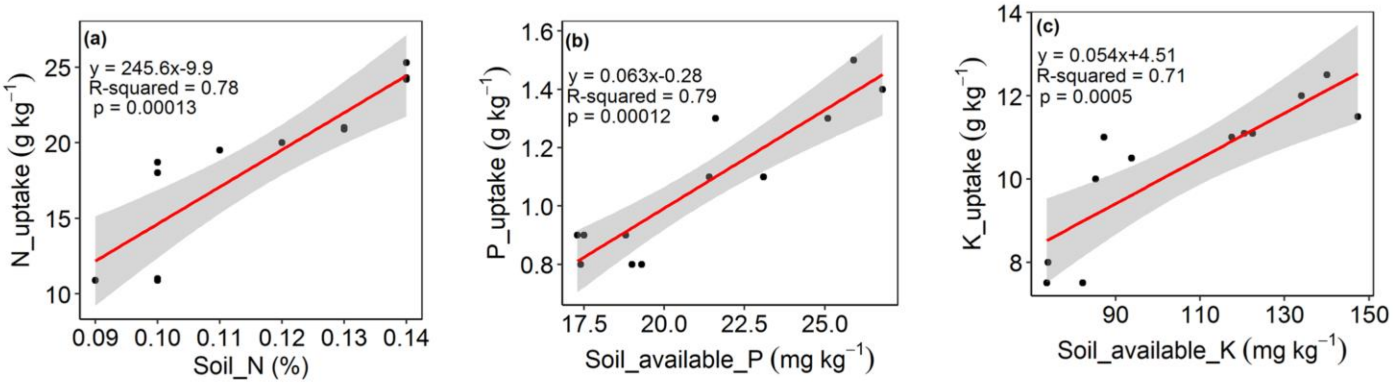

Figure 3. Relationship between soil nutrient supply and uptake by plants for N (**a**), P (**b**), and K (**c**).

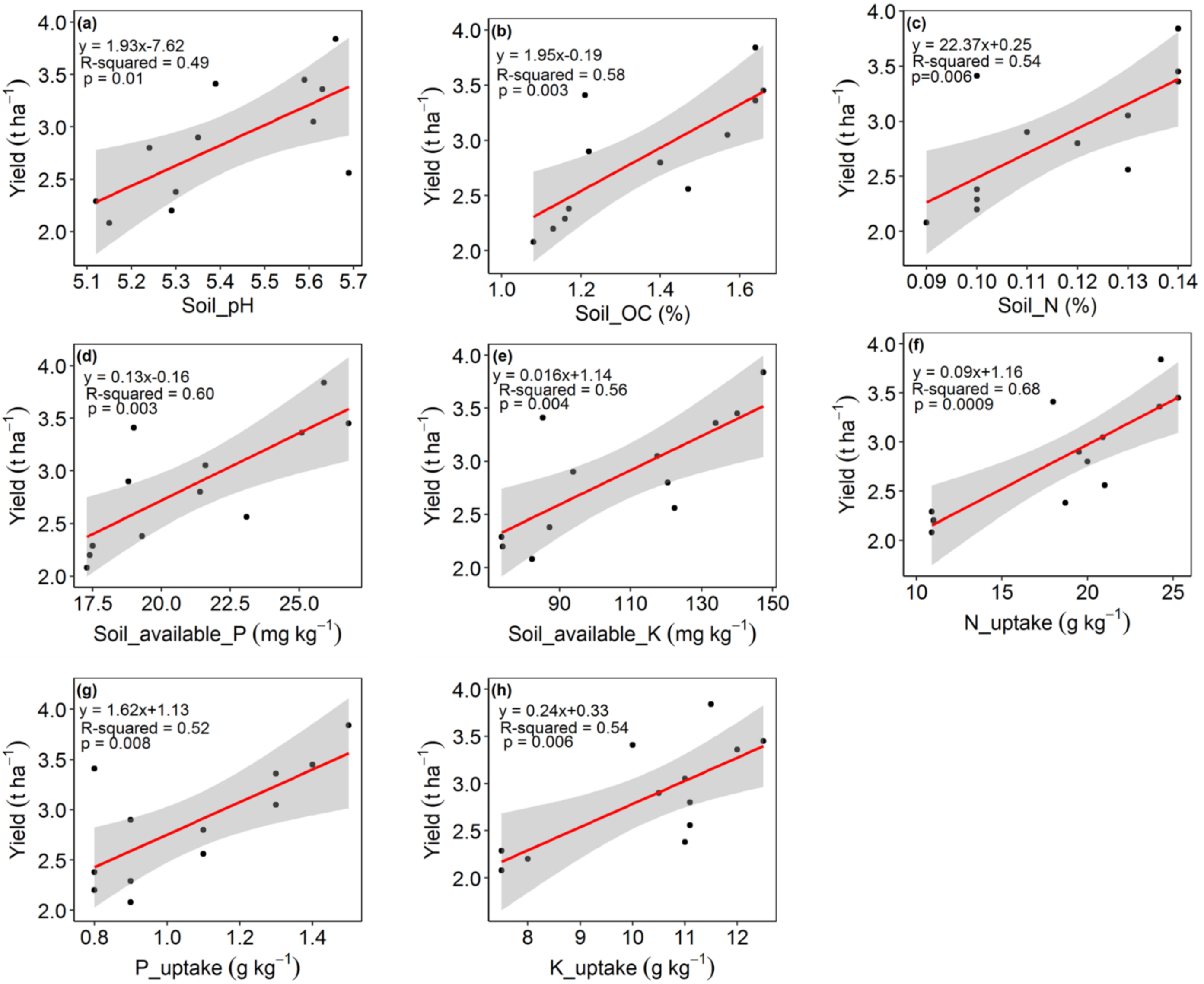

Figure 4. Relationship between (i) maize yield vs. soil chemical properties, i.e., soil pH (**a**), OC (**b**), N (**c**), available P (**d**), available K (**e**), and (ii) maize yield vs. N (**f**), P (**g**), and K (**h**) uptake by plant.

4. Discussion

Both biochar and urine-enriched biochar showed significant positive effects on soil pH and OC, with a more pronounced effect observed in urine-enriched biochar (BU+M) compared to the nonenriched biochar (BC and BC+M) (Table 1). Significant improvements on soil pH and OC upon biochar addition were in line with earlier studies conducted in acidic soils [8–10,24]. Moreover, soil nutrient content (total N, P, and available K) was found to be significantly higher with BU+M than with CK and BC+M (Table 1). This is corroborated by the study of Kammann et al. [29], where nutrient-enriched biochar increased nitrate and phosphate levels in a soil solution. Similarly, in our previous study, biochar enriched with organic nutrients (co-composted biochar) increased available P by up to 105 mg kg^{-1} compared to the nonenriched biochar (38 mg kg^{-1}) [5]. Nutrient enrichment allows penetration of available nutrients into biochar micropores and, thus, acts as a nutrient carrier medium, increasing the bioavailability [22]. Furthermore, increased P may be associated with increased soil pH (R^2 = 0.70) (Figure S1), which was significantly increased upon urine-enriched biochar amendment (Table 1).

Nutrient uptake by the plant was significantly higher with urine-enriched biochar (BU+M) compared to both control (CK) and nonenriched biochar treatments (BC+M) (Figure 1). N, P, and K uptake by plants showed a significant positive relationship ($p < 0.05$) with soil N and available P and K, respectively (Figure 3), which was increased upon urine-enriched biochar amendment (Table 1). The result implies that nutrient-enriched biochar supplies more available nutrients in the soil and increases plant nutrient uptake, which is in line with earlier studies [22,29] and accepts the hypothesis of this study. BU+M showed higher NUE expressed as PFPN (Figure 2a), indicating that biochar enriched with urine can effectively diminish a significant portion of N losses to the environment. These losses typically arise from nitrate leaching, run-off, NH_3 volatilization, and the emission of N_2O gases (biproduct of nitrification/denitrification) [3]. Elevated N losses from the agricultural areas can adversely affect the environment by causing groundwater pollution, contamination of downstream water sources, and atmospheric pollution due to N_2O emissions, which contribute to global warming and climate change [3,35]. Such losses from cropping land result in reduced yield and add to both economic and environmental costs [35]. Previous research has consistently shown that biochar blended with minerals or organic amendments leads to increased NUE and crop yields and reduces significant amount of N losses both through leaching and emissions [15,29,36].

In this study, urine-enriched biochar (BU+M) showed a significant positive effect on maize yield but not with biochar that was added separately, even after receiving the same amount of organic and inorganic supplements (BC+M), when compared to the fertilized control (CK). Thus, we accept the hypothesis that urine-enriched biochar boosts maize productivity in a silty loam subtropical Nepalese soil. The main effect of urine-enriched biochar on maize productivity could be illustrated by the nonconfounding effect of manure (Table S1), which could be further confirmed by the nonsignificant difference between treatments 2 (BC) and 3 (BC+M). Maize yield was 1.7 times higher with the use of urine-enriched biochar (an average increase of 62%) than in nonbiochar plots receiving an equal amount of NPK fertilizers (Figure 1d). In accordance with this, Schmidt et al. [22] reported an average increase of 95% in maize yield with the application of urine-enriched biochar compared with a nonbiochar (control) in an equally fertilized plot. Moreover, in another study conducted by Schmidt et al. [24] in a similar soil, urine-enriched biochar increased pumpkin yield more than twofold compared with biochar or urine added separately in the soil. Similarly, nutrient-enriched biochar increased maize production by 165% compared with a control receiving the same level of fertilizer input [23]. Increased maize productivity upon urine-enriched biochar application was possibly due to the organic coatings formed in biochar pores, which reduce hydrophobicity and improve the nutrient retention capacity of biochar [25,26]. Nutrient enrichment of biochar allows the penetration of available nutrients into biochar micro- and nanopores and they release slowly based on the synchrony between nutrient supply and plant demand [24]. The slow-release mechanism based on crop physiological requirements increases NUE, reduces leaching losses, and increases nutrient bioavailability, resulting in increased crop productivity [13,15,29]. Increased crop yield in this study could possibly be due to higher NUE (PFP of N, P, and K) upon urine-enriched biochar application (Figure 2).

Maize productivity showed a significant positive relationship with soil chemical properties and nutrient availability, such as pH, OC, soil N, and available P and K (Figure 4). Similarly, nutrient uptake (N, P, and K) by plants revealed a significant positive effect on maize yield (Figure 4), illustrating the higher internal efficiency (conversion of nutrient uptake into marketable yield) of applied nutrients. In accordance with this, earlier studies reported a strong positive relationship between soil available nutrients and plant uptake, and soil available nutrient and crop productivity as a function of biochar amendments [5,29].

A significant positive relationship between these soil chemical parameters and crop productivity was mainly attributed to urine-enriched biochar treatment. This could be confirmed by the results where urine-enriched biochar (BU+M) stood out and showed significantly higher soil available nutrients (Table 1), NPK uptake, and maize productivity (Figure 1) compared with both control (CK) and nonenriched biochar (BC and BC+M). According to this, Kammann et al. [29] discovered increased nutrient retention, supply, and uptake of nitrate and phosphate in organic-nutrient-enriched biochar (co-composted biochar), which has a significant positive relationship on crop productivity. In a previous study, biochar enriched with organic nutrient showed significantly higher available P and K, which was strongly correlated with maize productivity [5]. Moreover, the significant beneficial effects of soil available P [29,37] and K [8,9,38] on maize productivity were reported in earlier studies. In our study, soil pH showed a positive relationship with maize yield, which is in line with previous studies that reported the liming effect of biochar in acidic soil [8,10]. Furthermore, there could be a synergistic effect of P associated with pH on maize yield, as P showed a significant positive relationship with soil pH (Figure S1). In our earlier study, pH increased available P, which in turn showed a significant positive effect on maize production, illustrating nutrient stress alleviation in a similar soil [5].

5. Conclusions and Future Prospect

Urine-enriched biochar can significantly improve soil chemical properties, enhance fertilizing efficiency, and boost maize productivity in low-productive acidic soils. The finding indicates that by enriching biochar with cattle urine, farmers could significantly increase yields and reduce nutrient losses compared to nonenriched biochar (biochar added separately with organic or mineral fertilizers to the soil). However, it is important to note that this study represents a single growing season for a specific location and soil type, while the effects of organic amendments continue for longer periods. Thus, further research covering multiple seasons is recommended to investigate the agronomic effect of nutrient-enriched biochar in successive years in diverse soil types and agroecological domains. There are few studies across the globe that have assessed the agronomic potential of nutrient-enriched biochar. Therefore, this study could be of high significance to various researchers, academicians, and organizations at both the national and international levels.

In Nepal, farmers can produce biochar with invasive Eupatorium feedstock using low-cost flame curtain soil pit Kon-Tiki, thereby turning organic waste/pest into a valuable agricultural resource. Eupatorium feedstock, a species known for its invasive nature in Nepal, is readily abundant in farmlands, roadsides, forest, and riverbanks. The average household landholding size is 0.2 ha in Nepal, and requires around 320 kg biochar (1.6 t ha^{-1}) that can be produced by farmers themselves in 2–3 days. Given that most rural households in Nepal rear cattle, farmers could produce urine-enriched biochar on their own and apply it on their farm. This practice could significantly improve soil fertility, increase crop productivity and farm income, and help in addressing ongoing concerns related to global warming by effectively sequestering carbon in the soil over longer periods. This will contribute to catering to the current food insecurity, climate change, and poverty issues of the country.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/nitrogen5010002/s1: Description S1: Methods of soil analysis; Table S1: Two-factor ANOVA to assess the effect of biochar and manure on maize yield; Figure S1: Relationship between soil pH and available P.

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