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Original Research

Evaluation of Biochar for Increasing Maize Growth and Phosphorus Use Efficiency in an Alkaline Calcareous Soil with Different Inorganic Phosphorus Sources

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Abstract

The efficiency of different inorganic phosphorus (P) sources in an alkaline calcareous soil is significantly reduced due to elevated pH levels, which lead to phosphorus immobilization and the formation of insoluble phosphorus compounds with calcium (Ca). In this study, a greenhouse experiment was conducted to determine the efficiency of various P fertilizers using different rates of biochar. Using a completely randomized design (CRD), three levels of biochar were used: 0%, 1%, and 2% (w/w of 17 kg of soil), followed by three types of inorganic P fertilizers, i.e., single superphosphate (SSP), double superphosphate (DAP), and rock phosphate (RP). The application of biochar significantly

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increased phosphorus use efficiency (PUE). The PUE of SSP and DAP fertilizers was greatly increased by the 2% biochar application in the soil, i.e., 22.43% and 21.41%, respectively, as compared to the control (12.06%). Moreover, soil pH declined from 7.84 to 7.58 by the 2% biochar application in the soil, and a reasonable increase in soil chemical characteristics was reported, providing an optimum range for nutrient availability. Overall, soil available P, plant P contents, plant P uptake, and PUE were significantly affected by both biochar and inorganic P sources, which indicates that these findings can be valuable for understanding and optimizing agricultural practices, soil management, and plant growth in relevant ecosystems.

Keywords: inorganic amendments, plant height, phosphorus uptake, maize, physiological properties

Introduction

Phosphorus (P) is a crucial element for plant growth, and its deficiency in soil hampers plant development, leading to reduced crop yields. To fulfill the phosphorus requirements of plants, around 15 million tons of phosphorus fertilizer are applied to agricultural land worldwide each year [1, 2]. Nevertheless, only 5-30% of the phosphorus applied through fertilizers is absorbed by the crops in the year after application [3]. This obviates the frequent phosphate fertilizer applications; however, their continuous use has become both expensive and environmentally concerning [4].

In alkaline calcareous soils, calcium carbonate ($CaCO_3$) is abundant and tends to adsorb P from the soil, forming insoluble calcium phosphate compounds that make P unavailable for plant use [5]. The presence of the kaolinite clay mineral (which fixes more P than montmorillonite), low organic matter, and high pH also decrease the availability of P to plants in calcareous soils of Pakistan [6]. Hence, to overcome P deficiency, P fertilizers are added to the soil, which quickly and effectively supply significant amounts of P to plants. As a result, it is widely hypothesized that Pakistan's predominantly calcareous soils have a high potential to bind phosphorus.

Biochar is a carbon-dense substance generated through the pyrolysis of organic biomass and is recommended as a soil amendment to enhance soil fertility and nutrient status [7]. Generally, the incorporation of biochar affects the physical and chemical properties of the soil. Biochar may improve plant development, for instance, by increasing soil water-holding capacity (WHC) and nutrient retention because of an elevation in the cation exchange capacity (CEC) and providing habitat for microorganisms [8]. In the case of P, biochar acts as a source of exchangeable and available P, ameliorates P complexing metals (Fe^{3+}, Fe^{2+}, Al^{3+}, and Ca^{2+}, etc.), changes soil pH, and promotes P mineralization and microbial activity. Additionally, it also acts as a reservoir of phosphorus; it is retained on surface sites via anion exchange capacity [9], which increases P availability to plants [10].

In a natural ecosystem, P is frequently the limiting mineral nutrient for biomass formation. In Vertisols, the pH exceeds 7.0, and most of the mineral phosphorus is found as insoluble calcium mineral phosphates. Only a small proportion is taken up by plants, and the remainder is quickly transformed into insoluble complexes in the soil. This makes it necessary to apply phosphate fertilizers or organic amendments often in order to improve the availability of P in the soil [11]. However, organic inputs, such as compost and manure, decompose rapidly, especially in arid and hot climates. Therefore, it is recommended to add stable organic amendments such as biochar to provide nutrients to the soil for the long term.

Maize is used as a food and fodder crop in Pakistan, with an estimated stock of ten million tons, most of which is used in feed mills and wet milling industries [12]. Moreover, maize is an efficient crop for predicting P deficiency due to the short period of growth. In this study, we hypothesized that biochar application would improve soil properties and enhance phosphorus (P) availability in alkaline calcareous soil. We also hypothesized that different inorganic phosphorus fertilizers (RP, SSP, and DAP) would differ in their effectiveness due to variations in solubility, and that the combined application of biochar with inorganic P fertilizers would result in greater P availability, improved maize growth, higher yield, and increased phosphorus use efficiency (PUE) compared to the application of inorganic P fertilizers alone. It was further hypothesized that an optimum combination of biochar rate and inorganic P fertilizer source would maximize maize productivity and PUE. Accordingly, the present study was conducted to evaluate the individual and combined effects of biochar and inorganic P fertilizers on soil phosphorus availability, maize growth, yield, and phosphorus use efficiency in alkaline calcareous soil, and to identify the most effective biochar rate and inorganic P source for improving maize productivity and P use efficiency.

Materials and Methods

Biochar Production and Characterization

Vineyard prunings were collected from the horticulture garden (square no. 9), University of Agriculture (31.4303°N, 73.0672°E), Faisalabad, Pakistan. Biochar feedstock containing dust and other soil particles was washed to remove soil particles and then dried in sunlight. The prunings were then further dried using a forced-air oven at 65ºC until the moisture content ranged from 10-15%. After that, the dried samples were crushed into small pieces (2-5 mm) and stored in airtight plastic bags. In a laboratory setup, 200 g of the crushed feedstock were pyrolyzed at 400ºC in a muffle furnace (Gallonhop, England), following the procedure outlined by Sanchez et al. (2009) [13]. For pyrolysis, Pyrex flasks having a capacity of 2 L were used; for the removal of gases, a glass rod was used. To prevent oxygen from entering the chamber, silicone grease was applied to seal the Pyrex flask and the glass rod. After the completion of the reaction, the furnace was cooled, and the biochar was collected.

After shaking in deionized water for 90 min using a mechanical shaker, the pH and ECe of the biochar were measured at a 1:20 solid-to-solution ratio with a portable pH and ECe meter. Values represent the mean of three replicates ± standard deviation. Different letters within a column denote significant differences between treatments at $\alpha = 0.05$, as determined by the LSD test. The vanadate-molybdate method and Kjeldahl distillation [14] were used to measure total nitrogen (N) and available P concentrations in biochar. By using a standard curve on a flame photometer, extractable potassium (K) was also determined (Table 1).

Greenhouse Study

A pot study was established in a warehouse at the Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan (31.4303°N, 73.0672°E). Faisalabad has a semi-arid climate, characterized by hot summers, mild winters, and low to moderate rainfall, bordering a humid subtropical climate. The average maximum and minimum temperatures in June are 45.5ºC and 26.9ºC, while the average minimum and maximum in January are 19.4ºC and 4.1ºC. Soil (0-15 cm depth) from the Institute of Soil and Environmental Sciences research station was gathered in order to conduct a greenhouse experiment. Before the pot experiment, the soil was air-dried and put through a 2-mm sieve to measure basic soil parameters (Table 2). Soil pH, ECe, total N, available P, and extractable K were measured using the standard methods described in section 2.1. The CEC and $CaCO_3$ content of the soil were measured according to the methods proposed by Sumner and Miller (1996) [15]. To determine the total soil organic carbon (TOC) and soil texture, the Walkley-Black method [16] and the hydrometer method were employed [17].

Treatments included three levels of biochar (B0: 0.0%; B1: 1.0%; B2: 2.0% w/w of soil) along with various types of inorganic P fertilizers, i.e., P0 (control), P(SSP) (single superphosphate), P(DAP) (diammonium phosphate), and P(RP) (rock phosphate), arranged in a completely randomized design (CRD) with three replications. In each pot with a diameter of 24 inches and a depth of 12 inches, 17 kg of soil was added. Additionally, the respective calculated amount of biochar was added according to the treatment plan. In all treatments at 250 kg ha^{-1}, 160 kg ha$^{-1,}$ and 110 kg ha^{-1} N, P in the form of diammonium phosphate and K

Table 1. Biochar composition after pyrolysis at 400ºC.

Parameter	Unit	Value	Parameter	Unit	Value
pH	---	7.67	Available P	mg kg^{-1}	0.0104
ECe	dSm^{-1}	1.27	Extractable K	mg kg^{-1}	0.0186
N	%	0.0129	--	--	--

Note: ECe = electrical conductivity, N = Total Nitrogen.

Table 2. Determination of soil basic properties before sowing of maize.

Parameter	Unit	Value	Parameter	Unit	Value
Sand	%	56.3	$CaCO_3$	%	3.43
Silt	%	22.5	ECe	dS m^{-1}	0.51
Clay	%	21.2	CEC	cmol$_c$ kg^{-1}	13.0
Texture	--	Sandy clay Loam	OC	g kg^{-1}	4.0
pH	--	7.85	Total N	%	0.06
Available P	mg kg^{-1}	5.2	Extractable K	mg kg^{-1}	109

Note: TOC: total organic carbon; $CaCO_3$: calcium carbonate; ECe = electrical conductivity, OC = organic carbon of the soil, CEC = cation exchange capacity.

in the form of sulphate of potash were uniformly applied, but N fertilizer in the form of urea was used as a split dose, the first dose at sowing and the remainder at 15-day intervals. Five healthy pre-soaked maize hybrid (CLIPS-cultivar) seeds were put in each pot during plant establishment, and after a few weeks, seedlings were thinned to one plant per pot. During the whole experimental duration, plants were appropriately irrigated, keeping in mind the moisture level (30%) of the soil used. Regular monitoring of pest populations was done, and pesticides were applied when necessary. The plants were harvested after 12 weeks of germination.

Maize Agronomic Measurements

Shoot samples were air-dried and then further dried in a forced-air oven at 65ºC until a consistent weight was achieved (Eyela WFO-600ND, Tokyo Rika Kikai, Tokyo, Japan). The dry weight of the shoot samples was recorded once the weight had stabilized.

Maize Physiological Measurements

Photosynthetic rate, vapor pressure deficit, stomatal conductance, and water use efficiency were assessed after full leaf development, in the morning (between 9:00 and 10:00 am) using the combined infrared analysis system (CIRAS). The second completely expanded leaf of each plant was used to measure the above-mentioned parameters.

Maize Nutritional Characteristics after Harvesting

Plant samples were ground finely using a Wiley mill with a stainless-steel chamber and blades. A 0.2 g portion of the ground material was then digested in a digestion chamber using a mixture of nitric acid and perchloric acid. After digestion, the final volume was made up to 50 mL with deionized water for measuring N and P concentrations. The following formula was used to determine each nutrient's individual total absorption of N, P, and K.

$$\text{Nutrient uptake (mg pot}^{-1}) = \frac{\text{Nutrient concentration (\%)} \times \text{Dry matter (g pot}^{-1})}{100} \times 1000$$

The total uptake of nitrogen (N), phosphorus (P), and potassium (K) was determined individually for each nutrient using the following formula:

$$\text{NR (\%)} = \frac{\text{NUT} - \text{NUC}}{\text{NAF}}$$

Whereas NR = Nutrient recovery, NUT = Nutrient uptake in treatment, NUC = Nutrient uptake in control treatment, NAF = Nutrient added through fertilizer.

Statistical Analysis

The results were presented as the means ± standard errors (SE) of three replicates. One-way analysis of variance (ANOVA) and Duncan's multiple comparison test were employed to determine the differences between the various treatments. To identify significant differences among treatments, the test was conducted at a 5% probability level ($p = 0.05$) using SPSS 17.0 statistical software. Microsoft Excel 2013® (Microsoft Corporation, Redmond, WA, USA) was used for basic data computation and graph preparation.

Results

Determination of Basic Soil Properties after Harvesting

The effect of biochar addition on soil pH is shown in Fig. 1. In all the treatments, it was observed that pH decreased as the rate of biochar increased. Control treatment B0P0 showed the highest pH value, which was significantly decreased in biochar applications (1% and 2%) to the soil. Small effects of inorganic fertilizers were also observed on soil pH; for example, treatments of B0P(SSP) and B0P(RP) indicated pH 7.77 and pH 7.81, respectively, which was slightly lower than the control. Biochar 2% with the recommended dose of SSP showed the minimum value of pH, while B0P0 indicated the maximum pH value, i.e., 7.58 and 7.84, respectively (Fig. 1).

Data with respect to soil CEC are exhibited in Fig. 1 and reveal a large increase in soil CEC with various rates of biochar in soil. It shows that the peak value of CEC was (35.33 cmolc kg^{-1}) when 2% biochar was incorporated in the soil in treatment B2P(SSP), and the lowest (13.33 cmolc kg^{-1}) CEC was observed with no application of biochar in treatment B0P0.

As the rate of biochar incorporation into the soil increased, a noticeable increase in soil N content was observed (Fig. 2). The highest N content percentage was observed in B2P(RP), while the lowest percentage was observed in B0P(RP), which showed a significant effect of mineral fertilizers on N concentration in the soil when applied with biochar amendment. There was an increase of 59% in soil N content in B2P(RP) (0.105%) as compared with the control B0P0 (0.06%). Furthermore, the soil available P content increased up to 46%, providing a clear indication of the positive influence of biochar on soil nutrient concentration (Fig. 3). The available P content increased from 4.93 mg kg^{-1} (B0P0) to 10.77 mg kg^{-1} (B0P(DAP)) in the soil, which showed the suitability of biochar application to the soil along with inorganic fertilizer sources.

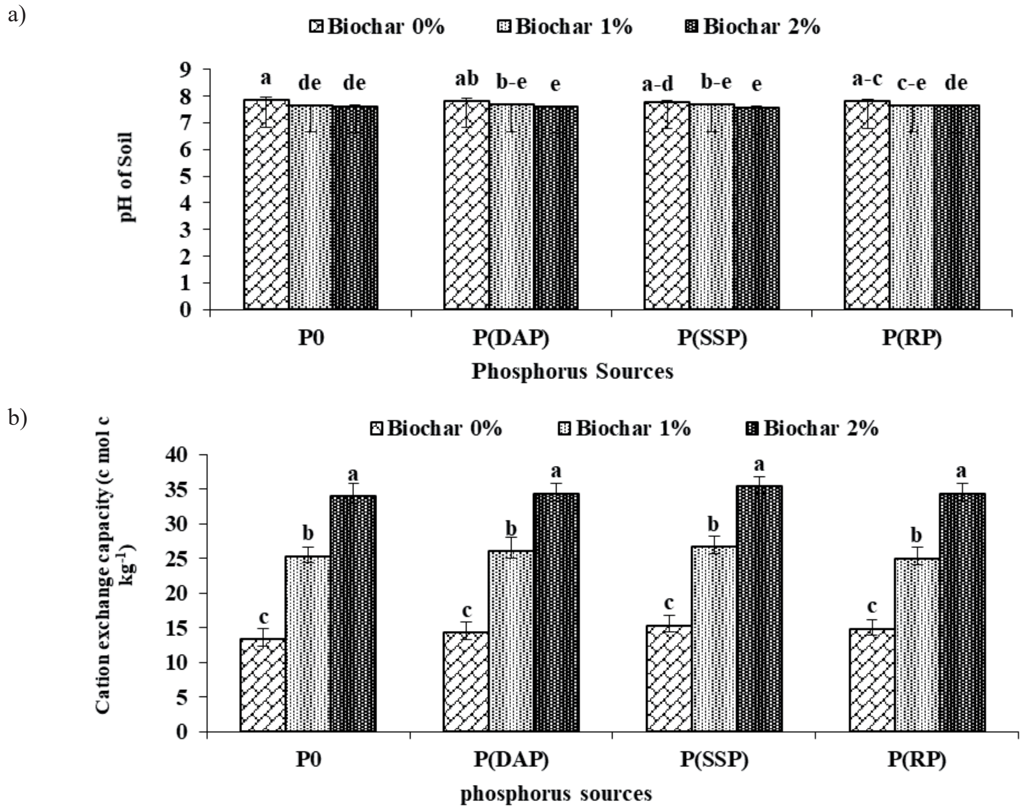

Fig. 1. Impact of various biochar and phosphorus fertilizer rates on a) soil pH and b) CEC after maize harvest.
P0 = No biochar or phosphorus, P(DAP) = biochar + DAP, P(SSP) = biochar + SSP, P(RP) = biochar + RP. Different letters show significant differences among treatments at p≤0.05, n = 3.

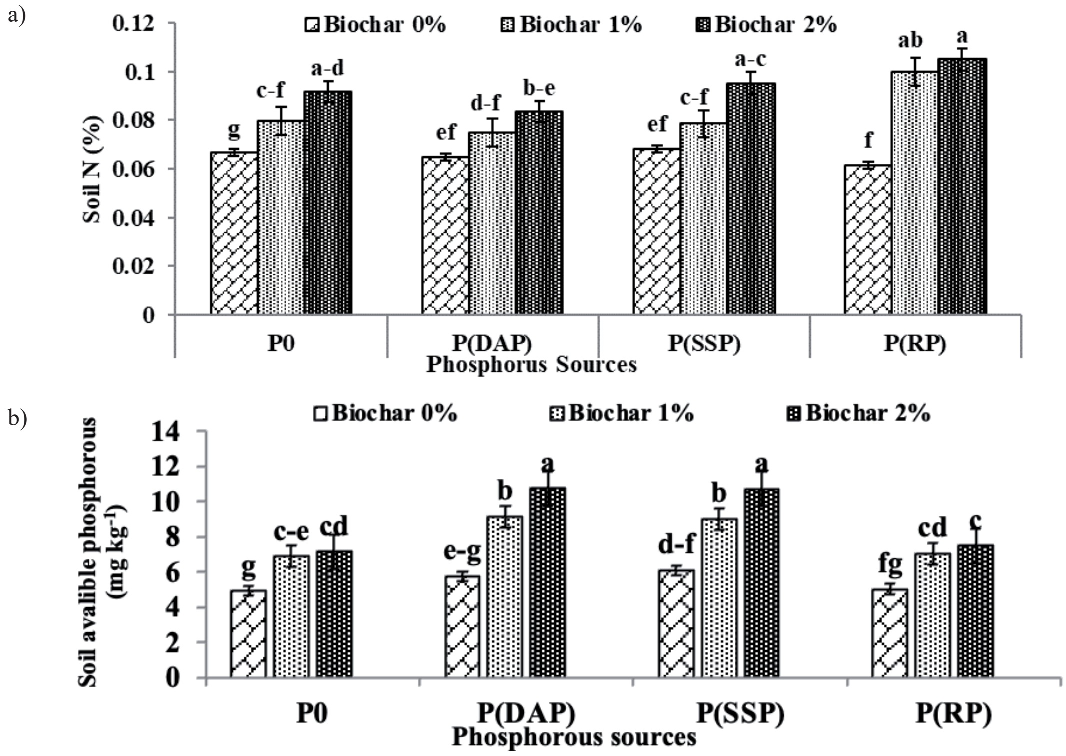

Fig. 2. Impact of various biochar and phosphorus fertilizer rates on a) soil nitrogen concentration and b) soil available phosphorus concentration after maize harvest.
P0 = No biochar or phosphorus, P(DAP) = biochar + DAP, P(SSP) = biochar + SSP, P(RP) = biochar + RP. Different letters show significant differences among treatments at p≤0.05, n = 3.

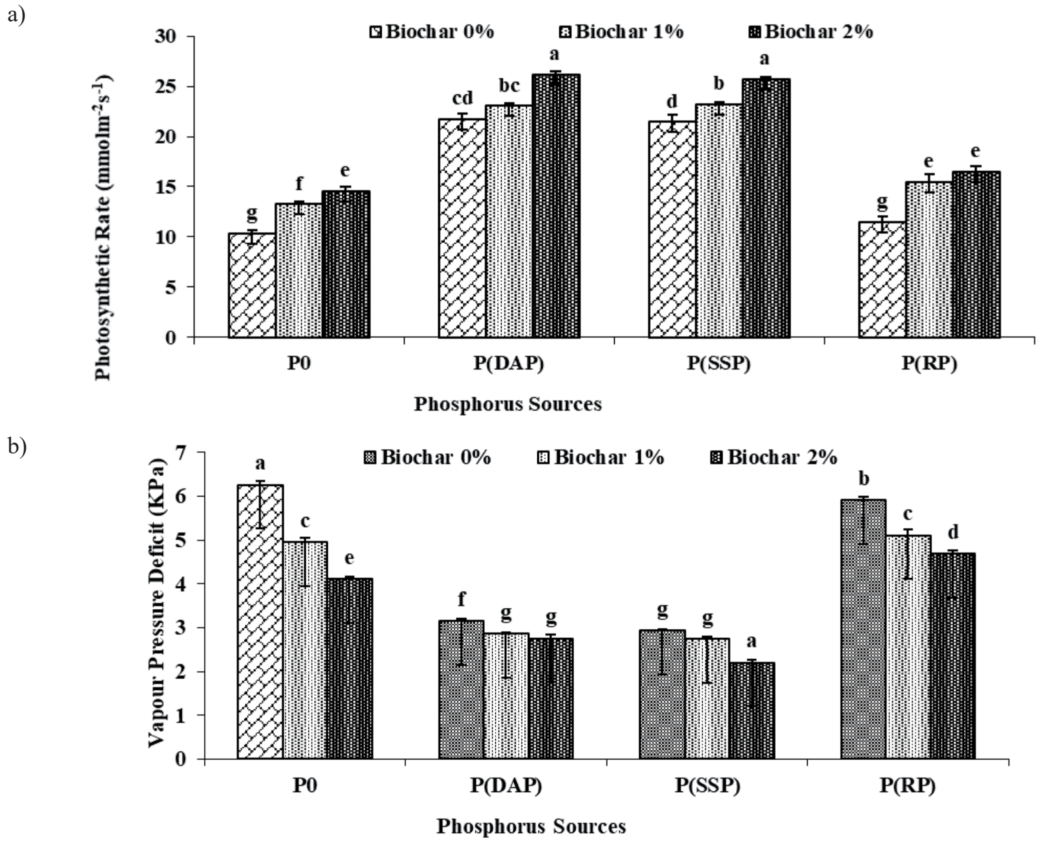

Fig. 3. Impact of various biochar and phosphorus fertilizer rates on a) plant photosynthetic rate and b) vapor pressure deficit of maize plants at the maximum vegetative growth stage.
P0 = No biochar or phosphorus; P(DAP) = biochar + DAP; P(SSP) = biochar + SSP; P(RP) = biochar + RP. Different letters show significant differences among treatments at $p \leq 0.05$, n = 3.

Determination of Maize Physiological Parameters

The photosynthetic rate showed a significant response to the increasing application rates of biochar and inorganic phosphorus sources (DAP and SSP). The highest value was recorded in B2P(DAP), with a mean of 26.16 µmol m^{-2} s^{-1}, followed by B2P(SSP), B1P(SSP), and B1P(DAP) treatments, with mean values of 25.71 µmol m^{-2} s^{-1}, 23.31 µmol m^{-2} s^{-1}, and 23.03 µmol m^{-2} s^{-1}, respectively (Fig. 3). A similar trend was observed in stomatal conductance, where again B2P(DAP) showed the highest conductance (Fig. 4). In the case of stomatal conductance (gs) of maize plants at maximum vegetative growth, B0P0 showed the minimum value (104.33 mmol m^{-2} s^{-1}), while B2P(SSP) showed the maximum value (275.66 mmol m^{-2} s^{-1}) as shown in Fig. 4. RP showed the least effect on photosynthetic rate as well as stomatal conductance. Biochar application significantly increased the physiological parameters of maize, but the combined application of biochar and inorganic P sources resulted in much improved parameters as compared with the control, i.e., 10.3 µmol m^{-2} s^{-1} and 104.33 mmol m^{-2} s^{-1} in the case of photosynthetic rate and stomatal conductance, respectively. In the case of vapor pressure deficit (VPD), the highest mean value (6.26 kPa) was recorded in B0P0 treatment. Fig. 3 revealed that VPD was less affected by RP, followed by the control treatment. Water use efficiency of maize plants was maximum in B2P(SSP) (6.936 mmol CO_2 mol^{-1} H_2O). The lowest mean value of WUE (3.263 mmol CO_2 mol^{-1} H_2O) was recorded in the B0P0 treatment (Fig. 4).

Determination of Maize Agronomic Parameters

Dry biomass was significantly enhanced by increasing biochar amendment. B2P(SSP) yielded the highest plant dry biomass value (75.86 g), followed by B2P(DAP), B1P(SSP), and B1P(DAP), respectively. Our experimental results showed that biochar amendment in the soil significantly increased dry biomass of maize plants (Fig. 5).

Plant Nutritional Analysis after Harvesting

Nitrogen (N) content of maize plants measured after harvesting is shown in Fig. 5. The results showed that increasing biochar rates had a significant effect on plant N content, but the effects of different treatments on P sources were different. In comparison with RP, DAP and SSP showed a paramount effect on N content of maize.

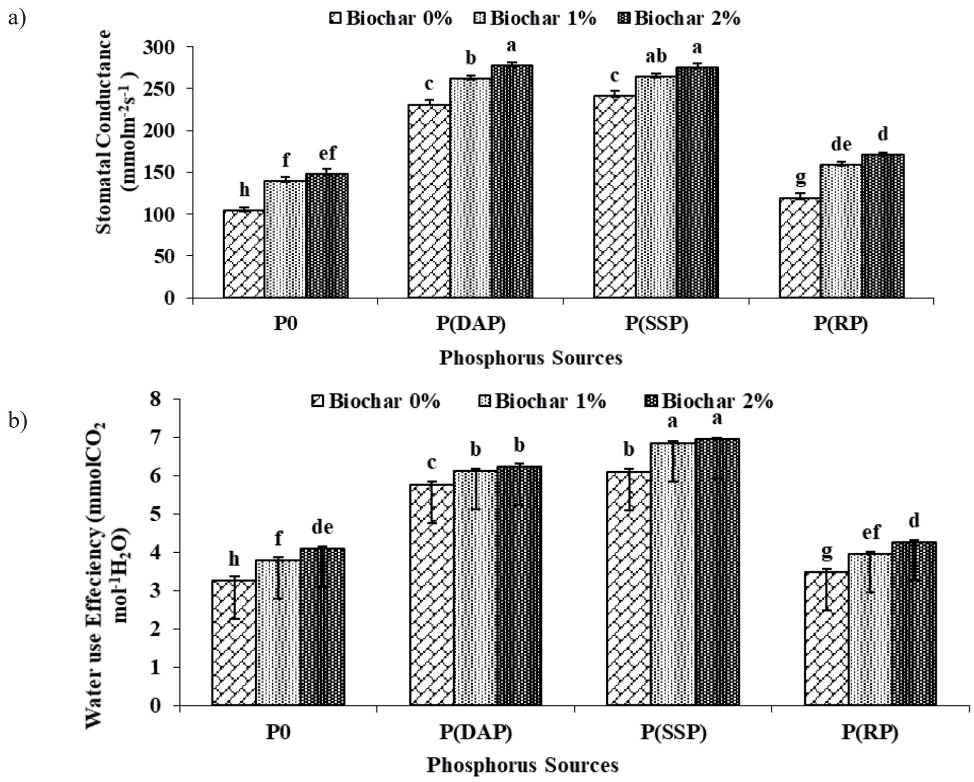

Fig. 4. Impact of various biochar and phosphorus fertilizer rates on maize a) plant stomatal conductance and b) plant water use efficiency (WUE) at maximum vegetative growth stage.

P0 = No biochar or phosphorus, P(DAP) = biochar + DAP, P(SSP) = biochar + SSP, P(RP) = biochar + RP. Different letters show significant differences among treatments at $p \leq 0.05$, n = 3.

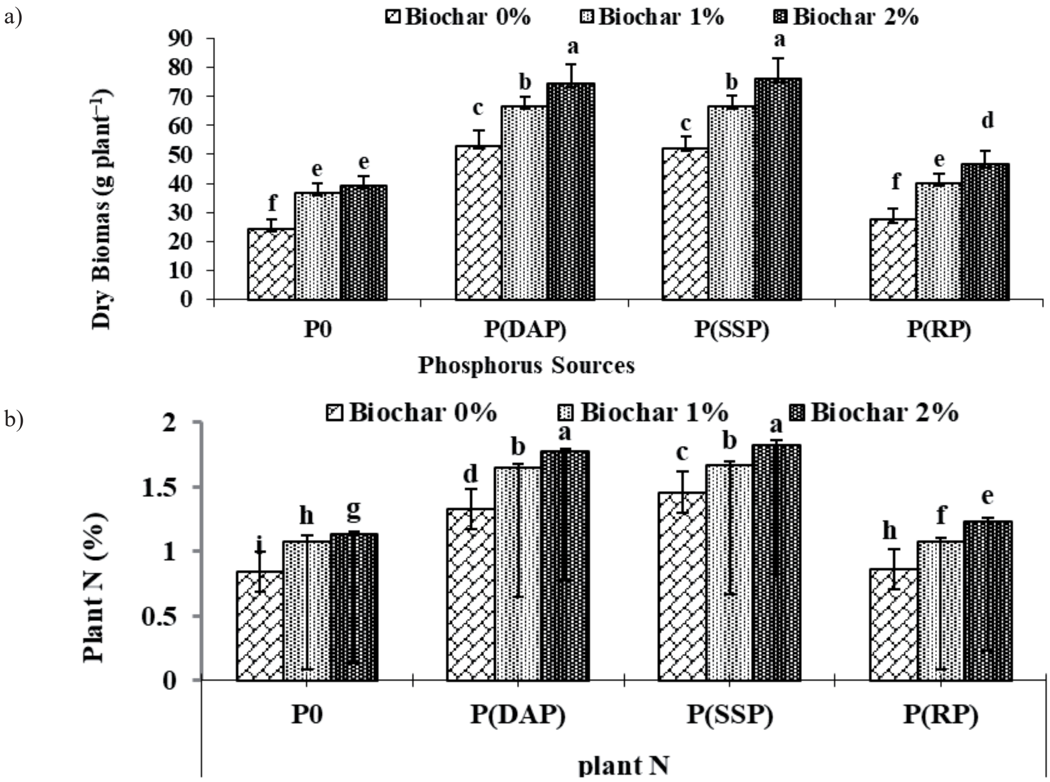

Fig. 5. Impact of various biochar and phosphorus fertilizer rates on maize plant a) dry biomass and b) nitrogen concentration.

P0 = No biochar or phosphorus, P(DAP) = biochar + DAP, P(SSP) = biochar + SSP, P(RP) = biochar + RP. Different letters show significant differences among treatments at $p \leq 0.05$, n = 3.

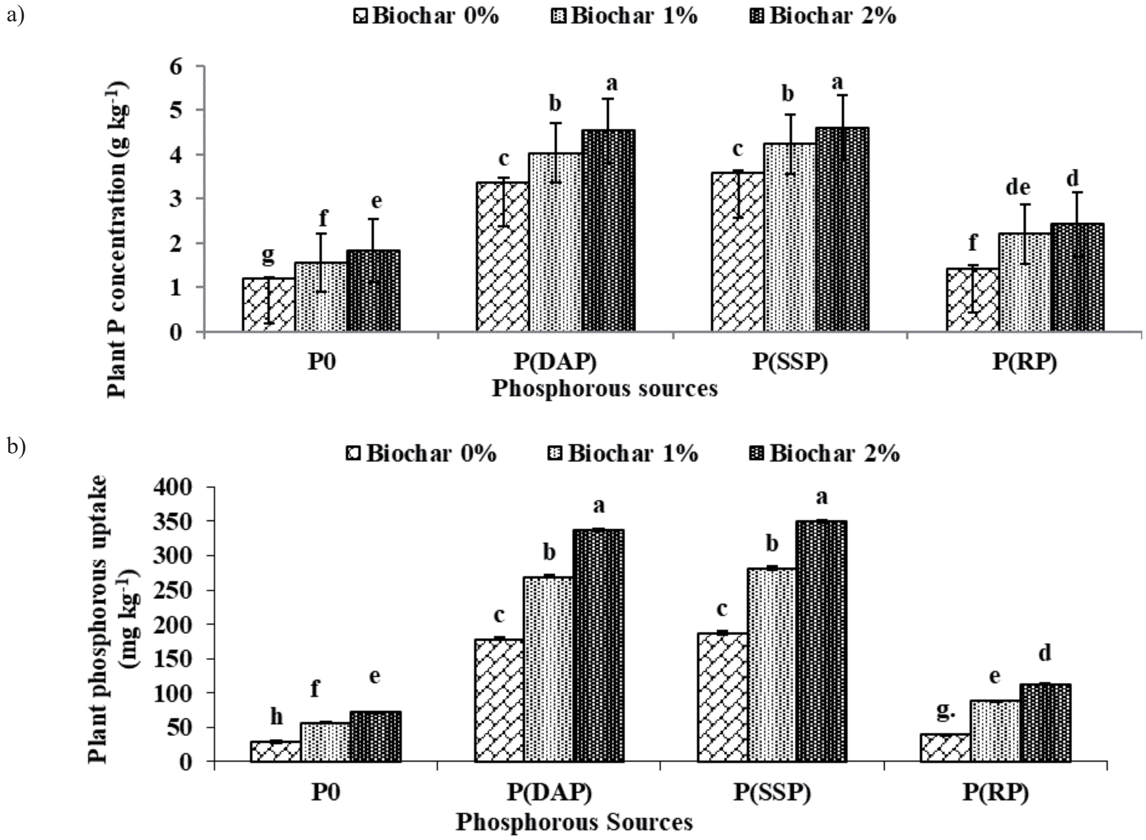

Fig. 6. Impact of various biochar and phosphorus fertilizer rates on a) maize plant phosphorus concentration and b) phosphorus uptake in maize plants.
P0 = No biochar or phosphorus; P(DAP) = biochar + DAP; P(SSP) = biochar + SSP; P(RP) = biochar + RP. Different letters show significant differences among treatments at p≤0.05, n = 3.

The mean nitrogen concentration in the plant was recorded as 1.82% in the B2P(SSP) treatment and 1.77% in the B2P(DAP) treatment, respectively. As compared to inorganic P fertilizer, the treatment with biochar has a significant influence on the P concentration of maize plants. Among P fertilizer sources, DAP and SSP showed significant effects as compared to the control and RP (Fig. 6). The data indicated that the highest mean phosphorus concentrations in maize plants (4.60 g kg^{-1} and 4.52 g kg^{-1}) were observed in the B2P(SSP) and B2P(DAP) treatments, respectively. In contrast, the lowest mean phosphorus concentrations

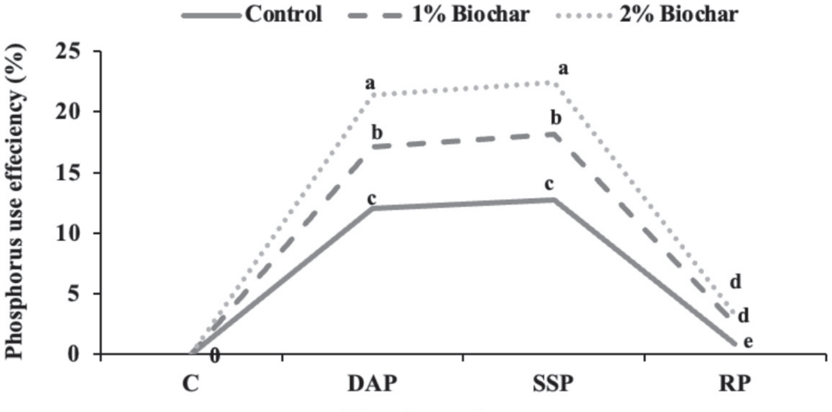

Fig. 7. Impact of various biochar and phosphorus fertilizer rates on phosphorus use efficiency.
P0 = No biochar or phosphorus; P(DAP) = biochar + DAP; P(SSP) = biochar + SSP; P(RP) = biochar + RP. Different letters show significant differences among treatments at p≤0.05, n = 3.

(1.18 g kg^{-1} and 1.42 g kg^{-1}) were recorded in the B0P0 and B$_0$RP treatments, respectively. In the case of plant P uptake, a significant effect of biochar treatments was found. The maximum mean values of P uptake were observed in B2P(SSP) and B2P(DAP) treatments (349.06 mg kg^{-1} and 336.46 mg kg^{-1}, respectively) (Fig. 6).

Phosphorus Use Efficiency (PUE)

PUE was observed to increase among the treatments amended with inorganic P sources along with biochar in the soil, as shown in Fig. 7. The results indicated significant effects on PUE of biochar application in combination with P fertilizers. B2P(SSP) and B2P(DAP) showed the maximum mean values of PUE (22.43% and 21.41%, respectively), while B0P0 and B0P(RP) treatments showed the minimum mean values (12.06% and 12.71%, respectively). Increasing rates of biochar along with P fertilizers showed positive impacts on the PUE of the soil. Fig. 7 also indicated that SSP and DAP showed a significant difference in PUE when different rates of biochar were applied among treatments, whereas RP did not show any significant difference in PUE with various rates of biochar application in soil.

Discussion

The use of biochar in agriculture has gained considerable attention because of its potential to improve soil fertility and boost crop productivity. In alkaline calcareous soils, the efficient utilization of phosphorus (P) remains a challenge, often necessitating the exploration of alternative strategies such as biochar application. Understanding the synergistic effects of biochar and various inorganic phosphorus sources on maize growth and phosphorus use efficiency is crucial for sustainable agricultural practices in alkaline soils. To date, a great deal of research has demonstrated that soil physicochemical properties, such as soil pH, CEC, and nutrient status, are improved by biochar input [18, 19]. Correspondingly, our results also demonstrated that biochar alone or with P fertilizers contributed to neutralizing soil pH (Fig. 1), which is consistent with previous findings [8, 20]. The possible explanation is that after application to the soil, biochar gets oxidized through chemical and microbial activities [21]. In addition, slow oxidation of biochar produces carboxylic functional groups that result in soil pH neutralization. In alkaline soil, biochar reduces soil pH and maximizes nutrient availability for plants, especially in the pH range of 6.5-7.5. Hence, biochar amendment can be an effective approach for enhancing nutrient availability, especially P for plants, by maintaining soil pH [8]. Increased CEC of soil is attributed to the fine and porous structure of biochar, which can hold nutrients for a longer period [22]. Furthermore, a high surface area of biochar determines the rate of supply of nutrients to the plants [23]. Our results regarding CEC showed a reverse trend compared to pH under biochar plus phosphate fertilizers, while only fertilizers slightly modified the soil CEC. Various studies have demonstrated that physicochemical soil attributes, such as pH and CEC, directly affect P availability to plants [11, 24]. Briefly, to improve soil CEC and neutralize soil pH to enhance P availability for crops in alkaline soils, a high dose of biochar (2%) should be applied with phosphate fertilizers instead of the sole application of biochar.

The improvement in soil physicochemical properties is attributed to biochar input, which is a source of micro- and macronutrients, such as N and P [25, 26]. The P contents in biochar are likely to persist longer than N, as P is resistant to high temperature. When applied to the soil, biochar improves the soil structure, which avoids erosion of clay particles containing P by runoff [27]. Hence, regarding the nutritional status of soil, biochar is found to enhance N and P contents of the soil more effectively than other fertilizers. Biochar is a potential source of nutrients for plant uptake and soil fertility [28]. These factors influence the agronomic parameters of maize plants, showing a remarkable increase in plant biomass (Fig. 5). Consistently, maize plant growth has increased under biochar amendment, which may be attributed to a better supply of limiting nutrients for plants [29]. Concerning the impact of biochar along with phosphate fertilizers, fresh and dry biomass of maize plants were significantly increased under DAP and SSP along with biochar application (1% and 2%), while RP showed a less significant effect on biomass increase compared to the control. Similarly, Zwieten et al. (2015) reported an increase in biomass of plants after biochar amendment along with fertilizer applications [30]. On the contrary, improvements in photosynthetic pigments and chlorophyll content can be significant factors for developing the physiological characteristics of maize plants. Consistently, as reported by Tarin et al. (2018), biochar input led to improvements in soil structure, which may increase gaseous exchange and photosynthetic rate [23].

Moreover, studies have indicated that the CEC of biochar can retain NH^{4+} [28], thereby increasing N contents in the plants. Sarfraz et al. (2017) also reported elevated N levels in biochar-treated alkaline soils. The possible explanation is that enhanced plant N contents could be due to high N content in the soil, which was attributed to a high dose of biochar along with P sources [18]. The phosphorus use efficiency (PUE) of SSP and DAP increased by up to 79% compared to the control treatment, which did not receive any biochar amendment. This enhancement in PUE could be attributed to the increased phosphorus availability in the soil and its subsequent uptake by the plants [29]. In alkaline calcareous soils, P is likely to form bonds with Ca, becoming stable and unavailable for plant uptake; thus, when biochar is applied, it decreases soil pH, facilitating maximum uptake of P for plant use. Our results showed a significant effect of inorganic P sources combined with biochar application, indicating a significant correlation between soil pH and biochar application across various inorganic fertilizers [5].

Conclusions

Biochar addition to an alkaline calcareous soil resulted in improved chemical properties of the soil. Our results suggested that biochar application at the rate of 2% provided optimum conditions for plant growth. The decrease in soil pH, as well as the increase in soil CEC is attributed to an increased concentration of nutrients as well as their uptake. Application of biochar in an alkaline calcareous soil along with various inorganic P fertilizers (SSP and DAP) showed significant positive results on soil P contents, PUE, and maize physiological parameters as compared to the control. Therefore, we conclude that the combined application of biochar amendment along with inorganic P fertilizers can be an alternative strategy for long-term sustainable agriculture in the future.

Authors' Contributions

Conceptualization: Z.A.; Data curation: A.A., R.S.; Formal analysis: A.A., A.S.; Funding acquisition: A.M.I.; Software: H.S.E, H.M.D.; Validation: Visualization; Writing - original draft: A.A. , R.S.; Writing - review and editing.

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Conflict of Interest

There declare no conflicts of interest.

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