Research Article

Assessment of Soil Physico-Chemical Characteristics in Response to Biochar and Inorganic Fertilizers in Maize Field

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Abstract | A field experiment was conducted during the Kharif season, 2017 at The University of Agriculture, Peshawar, to examine the impact of biochar and inorganic fertilizers on soil physico-chemical properties in a maize field. The experiment followed a two-factor randomized complete block design (RCBD) with three replications. Factor A comprised three biochar levels: control, 5 t ha^{-1}, and 10 t ha^{-1}. Factor B included two application rates of inorganic fertilizers i.e., Nitrogen, Phosphorus and Potassium (NPK): 100% and 50% of the recommended doses. Statistical analysis revealed the application of 10 t ha^{-1} biochar resulted in the highest values for soil organic matter, pH, electrical conductivity, total soil nitrogen, extractable phosphorus, and potassium, followed by 5 t ha^{-1} biochar, compared to control plots. The bulk density of soil was significantly reduced with 10 t ha^{-1} biochar. For inorganic fertilizer doses, the application of full-dose NPK, significantly enhanced total soil nitrogen, extractable phosphorus, and potassium compared to half-dose treatments. However, soil organic matter, bulk density, and pH did not show differences at the 5% significance level for NPK doses. The interaction between biochar and inorganic doses was insignificant for all soil parameters. The lack of significant interaction between biochar and NPK suggests that biochar can independently enhance soil quality, making it a promising soil amendment for sustainable agricultural practices.

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Keywords | Soil properties, Biochar, Inorganic fertilizers, Maize crop

Introduction

Soil quality refers to the dynamic interactions between soil and plants in growth processes. To optimize agronomic crop production, soil fertility assessment is typically carried out. Within agricultural systems, soil quality includes factors such as soil pH, electrical conductivity (EC), the availability of essential minerals, moisture levels, soil air composition, and biotic elements. Both organic and inorganic amendments can significantly affect each of these aspects, either directly or indirectly (Mays *et al*., 1973; Pagliai *et al*., 1981; Tester, 1990).

Organic farming minimizes the use of artificial fertilizers. To sustain soil fertility, organic fertilizers play a continuous role, mitigating the adverse environmental impacts resulting from extensive chemical fertilizer use (Ghafoor *et al.*, 2015). Biochar, an organic substance rich in carbon, is made by heating biomass without oxygen. It is being applied increasingly as a soil amendment to enhance physical, chemical, and biological soil attributes, decrease greenhouse gas emissions, and contribute to soil properties in beneficial ways. Beyond being a carbon source, biochar has shown potential for modifying soil characteristics, improving plant growth when used as an organic amendment. Numerous studies, including field experiments, have highlighted biochar's ability to decrease soil bulk density, as reported by Laird *et al.* (2010), with Obia *et al.* (2016) further confirming this effect in sandy loam soils. Furthermore, applying biochar at rates between 0–20 $g \cdot kg^{-1}$ was found to significantly enhance the specific surface area, increasing it from 130 to 150 m^2/g (Laird *et al.*, 2010).

Amending soil with biochar notably influences soil hydrological characteristics, including moisture levels, water-holding and retention capacities, and infiltration rate, which are closely related to bulk density, surface area, porosity, and aggregate stability (Laghari *et al.*, 2015). Research has shown that biochar can enhance soil aeration, increase soil pH, improve nutrient and water accessibility for crops, and shift soil microbial communities, thereby promoting plant growth and yield (Woo, 2013; Lee *et al.*, 2018; Wu *et al.*, 2020). The incorporation of biochar into soil can also change chemical properties, raising nutrient availability for plants. Biochar has been shown to enhance various soil properties, including higher levels of carbon (C), nitrogen (N), and available phosphorus (P), as well as improvements in pH, cation exchange capacity (CEC), and the availability of exchangeable cations such as calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K) (Chan *et al.*, 2008). Studies have also found that biochar, derived from green waste, can raise pH and organic carbon, and increase levels of exchangeable Na, K, and Ca, while reducing exchangeable aluminum (Al) in soil (Chan *et al.*, 2008). The extent of these changes correlates with biochar application rates. Soil organic carbon (SOC) is a core indicator of soil quality, potentially enhancing degraded soils that are nutrient-poor. Recent studies have validated biochar's efficacy as an amendment to raise soil organic carbon and total nitrogen (Han *et al.*, 2016; Wang *et al.*, 2015). Biochar can either directly supply nutrients or improve nutrient accessibility indirectly. The ash content of biochar is rich in essential nutrients, including nitrogen (N), calcium (Ca), phosphorus (P), sulfur (S), magnesium (Mg), manganese (Mn), potassium (K), iron (Fe), and zinc (Zn), which are crucial for supporting plant growth. Research by Smider and Singh (2014) demonstrated that adding biochar, with a high ash content derived from tomato waste, to soil increased corn shoot dry matter, attributed to nutrient release and liming effects.

Inorganic fertilizers are pivotal in modern agriculture, providing essential nutrients such as nitrogen, phosphorus, and potassium to enhance crop productivity. However, excessive use can lead to adverse effects, including soil acidification and increased electrical conductivity, which degrade soil quality and reduce fertility. These fertilizers are vital for sustaining crop yields but must be managed judiciously to avoid environmental consequences such as nutrient runoff and greenhouse gas emissions (Kang *et al.*, 2022). In Pakistani soils, nitrogen is 100% deficient, with phosphorus showing a 90% deficiency, and potassium tends to be deficient due to fixation (Laghari *et al.*, 2015). Relying solely on inorganic fertilizers disrupts soil surfaces by damaging structure, increase soil EC and reduce soil pH and (Kang *et al.*, 2022), worsening plant growth, soil quality, fertility, and speeding up acidification (Wu *et al.*, 2020; Wang *et al.*, 2020). Organic fertilizers provide ongoing nutrient supply, enhancing soil structure, pH, and EC (Chauhan and Bhatnagar, 2014). Despite their benefits, organic fertilizers are not preferred alone because labor-intensive and lack of quick results (Yang *et al.*, 2020).

The co-application of biochar and inorganic fertilizers synergistically improves soil physical and chemical properties. Biochar enhances soil structure and water retention, while inorganic fertilizers supply essential nutrients. This combination improves nutrient use efficiency, reduces nutrient leaching, and mitigates the adverse effects of excessive fertilizer use. Additionally, biochar's ability to increase cation exchange capacity and stabilize nutrients complements inorganic fertilizers, fostering sustainable soil fertility management (Zhang *et al.*, 2021; Kang *et al.*, 2022). Combining organic and inorganic fertilizers has proven effective for soil fertility improvement and erosion reduction (Negassa *et al.*, 2007), making it an ideal solution for enhanced soil health and crop productivity. Therefore, this study was proposed to evaluate the soil quality parameters in response to biochar and inorganic fertilizers alone and in combination under maize crop at the research farm, The University of Agriculture, Peshawar.

Materials and Methods

Site description

During the kharif season of 2017, a field experiment was conducted to assess soil physicochemical parameters in response to biochar and inorganic fertilizers on a maize field at The University of Agriculture, Peshawar's research farm. The Azam maize variety was sown at a row spacing of 70 cm, with plants spaced 15 cm apart. Prior to seeding, the soil was amended with biochar and NPK fertilizers. All suggested cultural practices were followed throughout the growth period.

Treatments and experimental design

The experimental design consisted of a randomized complete block design (RCBD) with two treatment factors, each replicated three times. Factor A included biochar application rates (control, 5, and 10 t ha^{-1}), whereas Factor B included two levels of NPK fertilizer: 50% of the recommended dose (75, 45, 30 kg ha^{-1}) and 100% of the recommended dose (150, 90, 60 kg ha^{-1}). Nitrogen was supplied through urea, phosphorus through Di-ammonium phosphate (DAP), and potassium through sulphate of potash (SOP).

The treatment combination were following:

Treatments	Factor (A): Biochar (ton ha^{-1})	Factor (B): N. P. K. (kg/ha)
1	0	75-45-30, respectively
2	0	150-90-60, respectively
3	5	75-45-30, respectively
4	5	150-90-60, respectively
5	10	75-45-30, respectively
6	10	150-90-60, respectively

Soil sample collection

Pre-planting and post-harvest soil samples were collected from each plot to a depth of 0–15 cm. The samples were then packaged in labeled bags and transported to the soil science laboratory for further analysis. Twigs or stone were taken out of the samples and grinded after they had air-dried at room temperature. Following a 2 mm mesh sieve, the samples were stored for subsequent physico-chemical examination.

Soil parameter recorded

The pH of the soil was assessed using a pH meter, with a 1:5 soil-to-water suspension prepared according to McLean's (1982) method. Electrical conductivity (EC) was also measured in the same suspension using an EC meter, following the procedure described by Rhoades (1982). Soil organic matter (SOM) was assessed by oxidizing soil samples with $K_2Cr_2O_7$ and H_2SO_4, followed by titration with $FeSO_4$, according to Nelson and Sommers (1996). Bulk density was measured by drying soil samples taken from core samplers and calculating the mass per unit volume (Blake and Hartge, 1984). Total nitrogen content was measured using the Kjeldahl method (Bremmer, 1996), which involved acid digestion, distillation, and titration to determine nitrogen concentration. Phosphorus (P) and potassium (K) were extracted with AB-DTPA solution; P was measured spectrophotometrically at 880 nm, while K was analysed by flame photometer, following the method of Soltanpour and Schwab (1977).

Statistical analysis

The collected data were subjected to analysis of variance (ANOVA) using MS Excel and the Statistix 8.1 software package. Treatment means were compared using the LSD test at a 0.05 probability level, as described by Jan *et al.* (2009).

Results and Discussion

A field experiment was undertaken at the research farm of The University of Agriculture, Peshawar, to investigate the impact of biochar and inorganic fertilizers on soil physico-chemical properties in a maize cropping system. The findings are detailed and critically analyzed in the subsequent sections.

Table 1: *Soil physico-chemical characteristics prior to biochar and NPK application.*

Properties	Unit	Concentration
Clay	%	11
Silt	%	63.4
Sand	%	25.6
Textural class	--	Silt-loam
Soil $pH_{(1:5)}$	--	7.5
Soil $EC_{(1:5)}$	dS/m	0.126
Soil organic matter	%	0.34
Bulk density	gcm^{-3}	1.45
Extra. P	mg kg^{-1}	2.1
Extra. K	mg kg^{-1}	48.5

Soil pH

Soil pH responses to the combined application of biochar and inorganic fertilizers are summarized in Table 2 and Figure 1. The statistical analysis indicated that biochar and NPK fertilizers had a profound effect on soil pH. The highest soil pH (7.61) was recorded at 10 t ha^{-1} application of biochar followed by pH of 7.56 at 5 t ha^{-1}. Inorganic fertilizers application had no significant effect on soil pH and the interaction was also found non-significant.

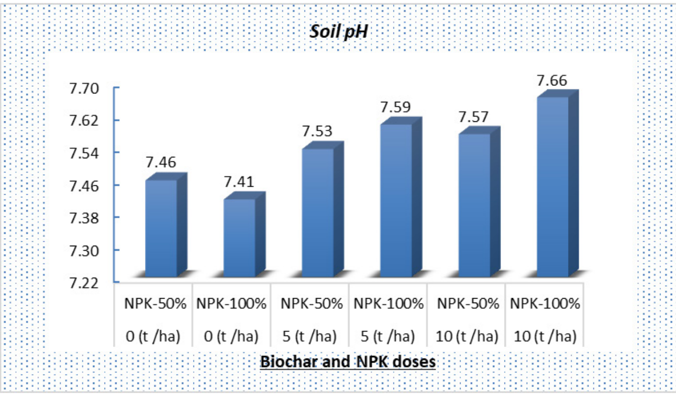

Figure 1: *Graphical representation of soil pH, influenced by biochar and NPK fertilizers under maize crop.*

Soil EC (dSm^{-1})

Soil EC responses to the combined application of biochar and inorganic fertilizers are summarized in Table 2 and Figure 2. The statistical analysis indicated that biochar and NPK fertilizers had a profound effect on soil EC. Soil EC showed a statistically significant increase with escalating biochar application rates. The maximum EC value of 0.140 dS/m was recorded in plots treated with 10 t ha^{-1} biochar, with the 5 tha^{-1} treatment ranking second. Among the NPK doses the soil EC was also significantly influenced. Application of full recomended dose resulted higher EC (0.137 dS/m). The interactive effect of both factors was found non-significant for soil EC.

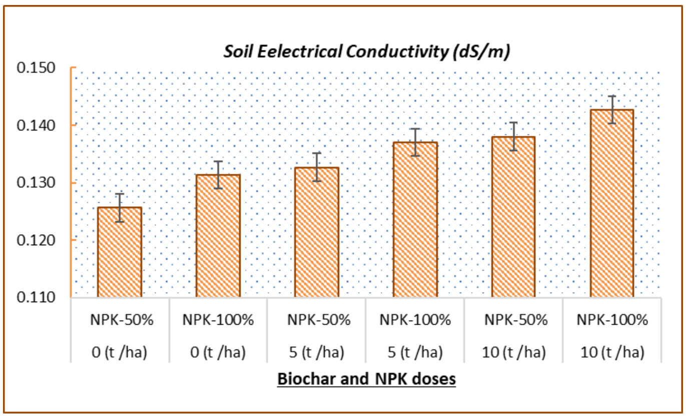

Figure 2: *Graphical representation of soil electrical conductivity (dS/m), influenced by biochar and NPK fertilizers under maize crop.*

Bulk density of soil

Soil bulk density (g cm^{-3}) responses to the combined application of biochar and inorganic fertilizers are summarized in Table 2 and Figure 3. The statistical analysis indicated that biochar and NPK fertilizers had a profound effect on soil bulk density. Application of 10t ha^{-1} biochar decreased soil bulk density (1.38 gcm^{-3}), followed by 5 t ha^{-1} over no treatment plots. Notably, the application of NPK fertilizer, with or without biochar, failed to induce significant changes in soil bulk density.

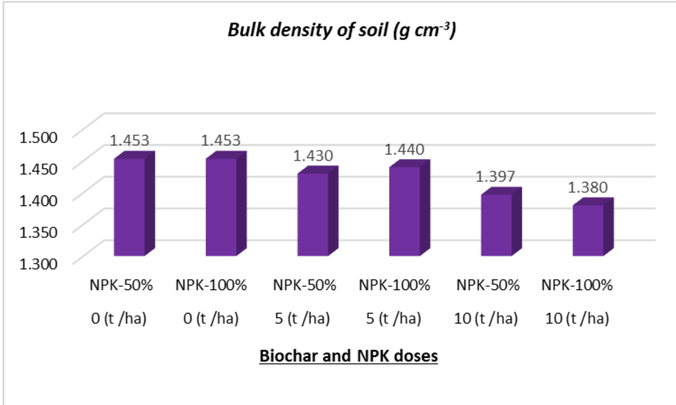

Figure 3: *Graphical representation of bulk density of soil (gcm^{-3}), influenced by biochar and NPK fertilizers under maize crop.*

Table 2: *Effect of biochar with NPK fertilizers on soil pH, EC (dS m^{-1}) and bulk density (g cm^{-3}).*

Treatments	pH	EC (dS m^{-1})	Bulk density (g cm^{-3})
Biochar (t ha^{-1})			
0	7.43 b	0.128 c	1.45 a
5	7.56 a	0.134 b	1.43 a
10	7.61 a	0.140 a	1.38 b
LSD (0.05)	0.005	0.0042	0.039
NPK (kg ha^{-1})			
Half NPK (75, 45, 30)	7.52	0.132 b	1.42
Full NPK (150, 90, 60)	7.55	0.137 a	1.42
LSD (0.05)	ns	0.0034	ns
Interaction			
Biochar × NPK	ns	ns	ns

Soil organic matter (%)

Soil organic matter (%) responses to the combined application of biochar and inorganic fertilizers are summarized in Table 3 and Figure 4. The statistical analysis indicated that biochar and NPK fertilizers had a profound effect on soil organic matter. Highest organic matter (0.60%) was found in the plot, where 10t ha^{-1} biochar were applied, and then 5t ha^{-1} (0.56%). Inorganic fertilizer levels had no significant effect on soil organic matter however an increasing trend were recorded from half to full NPK doses. The interaction between biochar and NPK application was found insignificant.

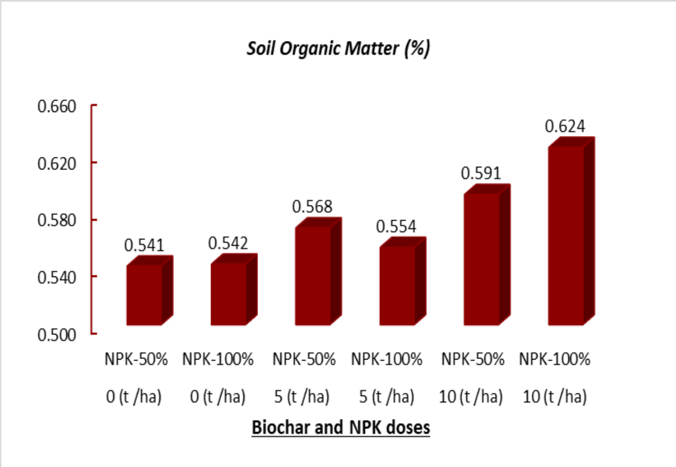

Figure 4: *Graphical representation of soil organic matter (%), influenced by biochar and NPK fertilizers under maize crop.*

Table 3: *Effects of biochar and NPK fertilizer application on soil organic matter and total nitrogen contents.*

Treatment	SOM (%)	Total Nitrogen (%)
Biochar (t ha^{-1})		
0	0.54 b	0.123 c
5	0.56 ab	0.126 b
10	0.60 a	0.136 a
LSD (0.05)	0.04	0.0027
NPK (kg ha^{-1})		
Half NPK (75, 45, 30)	0.56	0.124 b
Full NPK (150, 90, 60)	0.57	0.132 a
LSD (0.05)	ns	**0.0025**
Interaction		
Biochar × NPK	ns	ns

Soil total nitrogen (%)

Soil total nitrogen (%) responses to the combined application of biochar and inorganic fertilizers are summarized in Table 4 and Figure 5. The statistical analysis indicated that biochar and NPK fertilizers had a profound effect on soil total nitrogen. With increasing the biochar level total nitrogen content were increased over control plots. Highest soil nitrogen (0.136 %) was found on 10 t ha^{-1} followed by 5 t ha^{-1} (0.126 %). Among the inorganic fertilizer levels, maximum total soil nitrogen (0.132 %) was recorded by full recommended NPK dose (150, 90, 60 kg ha^{-1} NPK, respectively). The interaction between biochar and NPK doses were found non-significant.

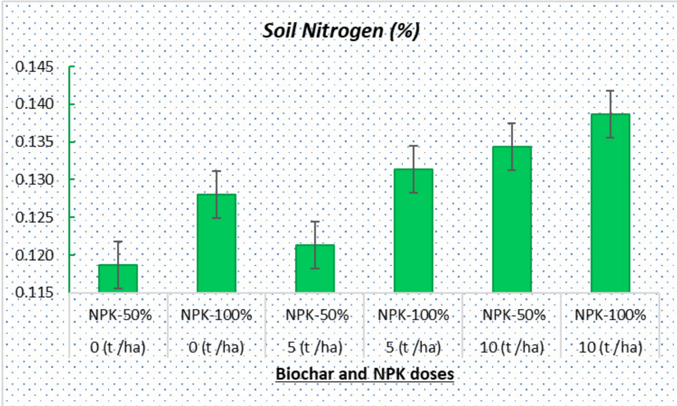

Figure 5: *Graphical representation of soil total nitrogen (%), influenced by biochar and NPK fertilizers under maize crop.*

Extractable phosphorus (mg kg^{-1})

Soil extractable phosphorus (mg kg^{-1}) responses to the combined application of biochar and inorganic fertilizers are summarized in Table 4 and Figure 6. The statistical analysis indicated that biochar and NPK fertilizers had a profound effect on soil extractable phosphorus. With increasing the biochar level phosphorus content were increased over control plots. Highest AB-DTPA extractable phosphorus (2.70 mg kg^{-1}) was found on 10 t ha^{-1} followed by 5 t ha^{-1} (2.64 mg kg^{-1}). Among the inorganic fertilizer levels, maximum soil phosphorus (2.68 mg kg^{-1}) was recorded by full recommended NPK dose. The interactive effect between both factors were found insignificant for soil phosphorus.

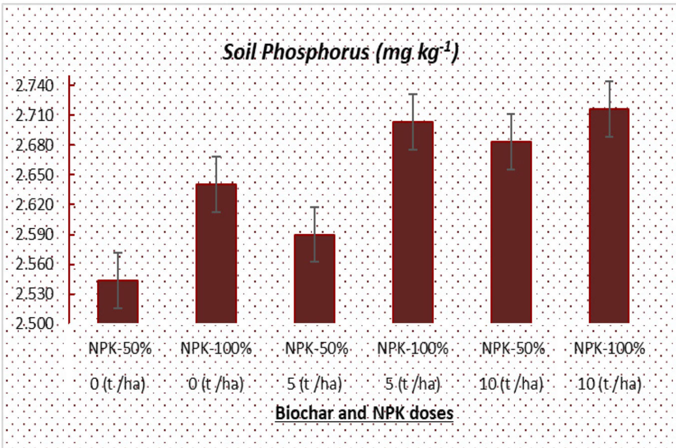

Figure 6: *Graphical representation of Extr. soil phosphorus (mg kg^{-1}), influenced by biochar and NPK fertilizers under maize crop.*

Extractable soil potassium (mg kg^{-1})

Soil extractable potassium (mg kg^{-1}) responses to the combined application of biochar and inorganic fertilizers are summarized in Table 4 and Figure 7. The statistical analysis indicated that biochar and NPK fertilizers had a profound effect on soil extractable potassium. With increasing the biochar level potassium content were increased over control plots. Highest AB-DTPA extractable potassium (73.65 mg kg^{-1}) was found on 10 t ha^{-1} followed by 5 t ha^{-1} (72.45 mg kg^{-1}). Among the inorganic fertilizer levels, maximum extractable soil potassium (72.76 mg kg^{-1}) was recorded by full recommended NPK dose. The interaction between biochar and NPK doses were found non-significant.

Table 4: *Effects of biochar with NPK fertilizer on extractable soil phosphorous and potassium (mg kg^{-1}).*

Treatment	Phosphorous (mg kg^{-1})	Potassium (mg kg^{-1})
Biochar (t ha^{-1})		
0	2.59 b	70.51 c
5	2.64 ab	72.45 b
10	2.70 a	73.65 a
LSD (0.05)	0.09	1.07
NPK (kg ha^{-1})		
Half NPK (75, 45, 30)	2.60 b	71.64 b
Full NPK (150, 90, 60)	2.68 a	72.76 a
LSD (0.05)	0.07	0.88
Interaction		
Biochar × NPK	ns	ns

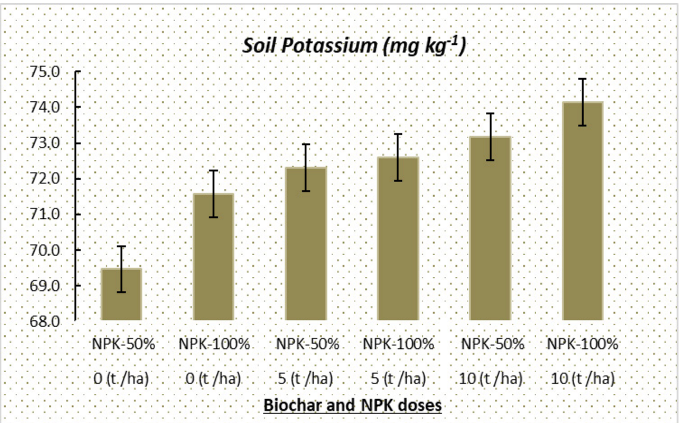

Figure 7: *Graphical representation of Extr. soil potassium (mg kg^{-1}), influenced by biochar and NPK fertilizers under maize crop.*

The beneficial influence of biochar on soil's physical and chemical attributes has been well-documented. The current findings correspond with Laird *et al.* (2010), who noted reductions in soil bulk density with biochar incorporation, and were later substantiated by Obia *et al.* (2016) for sandy loam soils. Similarly, Mukherjee and Lal (2013) concluded from their literature review that a biochar application rate of approximately 2% (w/w) is sufficient to achieve a measurable soil bulk density decrease. Similar findings were also reported by Pandian *et al.* (2016) and Yuan *et al.* (2011), highlighted that biochar not only lowers soil bulk density but also improves moisture retention, increases soil pH, and boosts soil organic carbon content. Lehmann and Joseph (2009) also reported similar results and suggested that soil nutrient retention and its availability might be due to biochar application. Chan *et al.* (2008) similarly reported increases in available phosphorus, soil organic carbon, nitrogen, pH, and exchangeable potassium, along with a reduction in exchangeable aluminum, by the application of biochar from green waste. Organic carbon (SOC) is a key indicator of soil quality, particularly in degraded or nutrient-poor soils. Studies by Han *et al.* (2016) and Wang *et al.* (2015) found parallel results and reported that biochar application increases SOC and total nitrogen. Several other studies also confirmed biochar's capacity to enhance total nitrogen levels in the soil (DeLuca et al ., 2006; Smider and Singh, 2014; Zhao *et al.*, 2014). These findings emphasize the role of biochar in improving soil fertility, particularly through its ash content, which supplies essential plant nutrients, including nitrogen, phosphorus, potassium, sulfur, calcium, magnesium, manganese, iron, and zinc. Inorganic fertilizer also has great impact in nutrient availability alone as well with Biochar. Fagbenro et al. (2015) found similar results that increasing biochar and NPK levels improve nutrient availability specifically N, P and K, enhancing tree growth, stem length, and dry matter in moringa, though biochar-fertilizer interaction was non-significant. Overall, the literature highlights biochar's potential to improve various soil properties, including bulk density, moisture retention, pH, CEC, nutrient availability, and SOC. These improvements contribute to enhanced crop performance and soil health, making biochar a valuable tool for sustainable soil management and agricultural productivity.

Conclusions and Recommendations

The study concludes that integrated application of biochar and NPK fertilizers significantly improves soil physico-chemical properties. The highest biochar level (10 t ha^{-1}) showed the most pronounced effects, enhancing soil organic matter, nitrogen, phosphorus, and potassium, while also reducing bulk density. The full recommended dose of NPK fertilizers improved soil nitrogen, phosphorus, and potassium levels, though its effects on organic matter, bulk density, and pH were not statistically significant. Enhanced levels of ABDTPA phosphorus and potassium were observed when 10 t ha^{-1} biochar was combined with the full NPK fertilizer dose (150, 90, 60 kg ha^{-1}), indicating a positive interaction between the two treatments. Biochar at 10 t ha^{-1} or higher can be effectively used to amend soil characteristics and improve soil health and quality.

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Novelty Statement

This study examines the independent and combined effects of biochar and inorganic fertilizers on soil physico-chemical properties in a maize cropping system under the agro-ecological conditions of Peshawar. It demonstrates that biochar has the potential to improve soil parameters both independently and in combination with inorganic fertilizers, enhancing key soil quality attributes such as organic matter content, bulk density, and nutrient availability. These findings highlight biochar as a sustainable soil amendment for improving soil health in intensive agricultural systems.

Author's Contribution

Mujeebur Rahman: Wrote original draft, resources, Methodology, Investigation, Formal analysis.
Muhammad Ilyas: Writing – review & editing, software, Resources, Investigation, Data curation, Conceptualization.
Arshad Ullah: Contributed in composition of review manuscripts and paraphrasing the literature data.
Rooh Ullah: Contributed in collecting and tabulating the data and proof reading of review manuscript.
Sanam Zarif: Contributed to the critical review and editing of the manuscript.

Conflict of interest
The authors have declared no conflict of interest.

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