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Synergistic Biochar–Nitrogen Application Enhances Soil Fertility and Compensates for Nutrient Deficiency, Improving Wheat Production in Calcareous Soil

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Abstract: Nutrient deficiencies, low organic matter content, and a limited soil–water saturation percentage in calcareous soils hinder plant growth and crop production. To address these challenges, sustainable and green-based farming practices have been introduced. This study investigates the synergistic effects of biochar and nitrogen levels as sustainable solutions for improving soil fertility and supporting wheat growth in calcareous soils. A pot experiment assessed the effects of biochar (5-, 10-, and 15-tons ha^{-1}) and nitrogen levels (60, 90, and 120 kg ha^{-1}) on soil physicochemical properties, nutrient availability, and wheat growth. The randomized complete block design included three replicates and a control. The results highlight that the highest biochar rate (15 tons ha^{-1}) combined with the highest nitrogen level (120 kg ha^{-1}) significantly ($p \leq 0.05$) improved soil physicochemical properties and nutrient status. Notably, soil pH increased by 2.8%, electrical conductivity by 29.8%, and soil organic matter by 185%, while bulk density decreased by 22.3%. Soil total nitrogen surged by 163.7%, soil–water saturation percentage by 27.2%, plant-available phosphorus by 66.8%, and plant-available potassium by 96.8%. Wheat growth parameters also showed marked improvement, with plant height up 29.7%, spike length by 20.7%, grains per spike by 41.5%, thousand-grain weight by 24.7%, grain yield by 81.3%, and biological yield by 26.5%. There was a strong positive correlation between enhanced soil properties and improved wheat growth, except for soil bulk density, which showed a negative correlation. This underscores the role of biochar in boosting soil fertility and crop productivity. A principal component analysis further validated these findings, suggesting that integrating biochar with appropriate nitrogen fertilization offers a sustainable strategy to enhance soil health, manage nutrient availability, and strengthen crop yields in calcareous soil. Biochar application combined with elevated nitrogen levels significantly enhances soil fertility and wheat productivity in semi-arid regions, offering a sustainable solution for improving calcareous soils. Future studies should explore the long-term impacts and scalability of this approach.

Keywords: biochar; nutrient-deficient soil; nutrient availability; semiarid climate; crop yield

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Academic Editor: Jan Hopmans

Received: 20 January 2025
Revised: 3 March 2025
Accepted: 5 March 2025
Published: 6 March 2025

Citation: Ahmad, B.; Rahim, H.U.; Mian, I.A.; Ali, W. Synergistic Biochar–Nitrogen Application Enhances Soil Fertility and Compensates for Nutrient Deficiency, Improving Wheat Production in Calcareous Soil. *Sustainability* **2025**, *17*, 2321. https://doi.org/10.3390/su17052321

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1. Introduction

Maintaining appropriate soil fertility and nutrient balance is a key factor for plant growth and agricultural productivity [1], particularly in semi-arid regions where soils

are predominantly alkaline, calcareous, low in organic matter, low in water content, and deficient in the essential nutrients necessary for optimal plant growth [2]. Enhancing the fertility of these soils is crucial to maximizing food production in the face of climate change and rapid population growth [3]. Researchers have explored various strategies and amendments for managing alkaline and calcareous soils in arid and semi-arid climates. These include site-specific nutrient management [4], balanced fertilizer applications [5], foliar sprays of nutrients [6], mulching [7], conservation agriculture practices [8], compost application [9], integrated nutrient management [10], the use of biofertilizers and beneficial microorganisms [11,12], organic manures [13], crop residue incorporation [14], tillage and intercropping [15], and the cultivation of tolerant crop varieties [16].

Calcareous soils with low soil organic carbon are commonly found in dry and semi-arid regions. Human activities such as tillage, fertilization, and irrigation rapidly alter biogeochemical cycles, exacerbating the challenge of maintaining soil fertility. However, organic matter additions can mitigate these issues by enhancing soil properties, increasing CO_2 concentrations, and promoting the solubility of calcium carbonate and other calcic minerals, thereby improving nutrient availability [17]. Organic and inorganic amendments improve the chemical and physical characteristics of calcareous soils by enhancing nutrient cycling, soil structure, and water retention, contributing to sustainable nutrient management and increased soil fertility [18].

One particularly promising organic amendment is biochar, a carbon-rich material produced from different kinds of feedstocks at various temperatures. Biochar is applied as a soil amendment, biofertilizer, or adsorbent to remove potential toxic elements from environmental components [19,20]. However, its effects are largely determined by the pyrolysis process (temperature and time) and the type of biomass used [21]. In calcareous soils, phosphorus (P) availability is often limited due to P fixation, a process in which P becomes bound to calcium and made unavailable to plants. However, certain types of biochar can function as a liming agent, raising soil pH and improving P availability [22,23].

Research has demonstrated the effectiveness of biochar in improving soil fertility across different regions. For example, the application of biochar along with compost significantly enhanced soil fertility and increased wheat yields in Australia [24]. In Pakistan, woodchip biochar combined with reduced nitrogen and phosphorus (NP) fertilizers improved nutrient accessibility and organic carbon content in calcareous soils [25]. Similarly, applying maize biochar to calcareous soils in China increased soil nutrient concentrations and microbial activity [26]. In Kimberly, Idaho, the United States of America, co-applying biochar with manure improved soil water status—particularly beneficial in rainfed areas—and increased soil-extractable zinc levels, addressing the zinc deficiencies commonly found in calcareous soils [27].

While numerous studies have investigated the combined effects of biochar and nitrogen fertilization on nutrient availability in calcareous soils, the impact of biochar produced from woodchips at moderate pyrolysis temperatures, combined with varying nitrogen levels (low, medium, and high), on soil fertility and wheat production in semi-arid nutrient-deficient calcareous soil remains underexplored. Therefore, this study hypothesizes that a combination of woodchip biochar and nitrogen fertilization will improve nutrient availability, soil fertility, and wheat yield in calcareous soils.

2. Materials and Methods

2.1. Synthesis of Biochar and Physicochemical Characteristics

The biochar used in this study was commercially sourced and produced from wood chips at a pyrolysis temperature of 500 °C in kilns. The biochar had a particle size of less

than 2 mm, with a pH of 8.61, an electrical conductivity of 1.40 dS m^{-1}, an organic carbon content of 76%, and an ash content of 27%.

2.2. Execution of Pot Experiment

Soil samples were collected from the research farm of the University of Agriculture Peshawar, Pakistan (34°21′ N, 71°28′5″ E), at a depth of 0–20 cm. The soil was crushed, air-dried, and sieved through a 2 mm screen to create a composite sample, from which three subsamples were collected for the analysis of physicochemical characteristics. A pot experiment, following a completely randomized design, was conducted in a greenhouse. During the growing season, the soil temperature ranged from 10.09 °C to 33.12 °C, with an average of 22.64 °C. Meanwhile, the air temperature ranged from 9.47 °C to 31.11 °C, with an average of 21.50 °C. The monthly mean relative humidity was 53.08%, and the average rainfall was 12.66 mm [12]. Each pot kept in the open atmosphere was filled with 20 kg of soil, and the experiment consisted of ten treatments, each replicated three times. The details of the treatments are provided in Table 1. Biochar was thoroughly mixed with the soil in each pot, and the pots were irrigated using canal water and kept for ten days of stabilization. Ten seeds of the wheat variety Pir-Sabaq-2013, recommended for its better performance under stress conditions in calcareous soils of the semi-arid region of Khyber Pakhtunkhwa province of Pakistan [28], were sown in each pot. After three weeks of germination, the seedlings were thinned to seven plants per pot. The pots were irrigated regularly to maintain 70% moisture content throughout the growing season, from the start of planting to the maturity of the wheat plants. The irrigation rate was adjusted as necessary to ensure consistent moisture levels. Single superphosphate, Muriate of Potash, and urea were applied as basal fertilizers to all pots, including control. The recommended NPK fertilizer used as a basal dose was 120:90:60 (kg ha^{-1}). As per the treatment plan, the required amount of nitrogen fertilizer (urea) was applied before the first irrigation, following the experimental plan. The plants were harvested at maturity, and data on agronomic parameters were collected. Pre-harvest soil was air-dried, sieved through a 2 mm screen, and stored for subsequent analysis of soil fertility attributes.

Table 1. Details of applied treatments.

T. No	Treatment Name	Description
1	CK	Control (no treatments)
2	5-BC+60-N	5 tons ha^{-1} biochar (BC) with 60 kg ha^{-1} Urea (N)
3	10-BC+60-N	10 tons ha^{-1} BC with 60 kg ha^{-1} N
4	15-BC+60-N	15 tons ha^{-1} BC with 60 kg ha^{-1} N
5	5-BC+90-N	5 tons ha^{-1} BC with 90 kg ha^{-1} N
6	10-BC+90-N	10 tons ha^{-1} BC with 90 kg ha^{-1} N
7	15-BC+90-N	15 tons ha^{-1} BC with 90 kg ha^{-1} N
8	5-BC+120-N	5 tons ha^{-1} BC with 120 kg ha^{-1} N
9	10-BC+120-N	10 tons ha^{-1} BC with 120 kg ha^{-1} N
10	15-BC+120-N	15 tons ha^{-1} BC with 120 kg ha^{-1} N

2.3. Wheat Harvesting and Measurement of Agronomic Attributes

At the maturity stage of wheat plants, several agronomic attributes were measured. Plant height, from the soil surface to the tip of the spike, was recorded by averaging the heights of three representative plants from each pot. Spike length was similarly measured using three representative spikes per pot and then averaged. To determine grains per spike, three spikes were selected, threshed, and the number of grains were counted, with the average calculated. The 1000-grain weight was obtained by weighing 100 grains from each

pot and converting the weight to a 1000-grain equivalent. The biological yield was recorded by harvesting, air-drying, and weighing the total biomass from each pot. Finally, the grain weight was determined by weighing the grains from each plant in each pot using a balance, with the total recorded in grams.

2.4. Measurement of Post-Harvest Soil Fertility Attributes

Soil pH and electrical conductivity were measured using a 1:5 soil-to-water suspension following the procedure outlined by Rhoades, J. [29]. Soil organic matter content was determined using the protocols of Nelson and Sommers [30], while soil bulk density was measured according to the method described by Walter, K. [31]. Total nitrogen in the soil was analyzed using the procedure of Bremner, J. [32]. Soil saturation percentage was assessed following the protocols of Gardner, W. H. [33]. Extractable phosphorus and potassium were determined using the method described by Soltanpour, P. [34].

2.5. Statistical Analysis

A one-way analysis of variance (ANOVA) was conducted to test the significance of the treatments at $p \leq 0.05$. A Least Significant Difference (LSD) test was applied for multiple means comparison. The statistical analyses were performed using MS Excel-2016 and Statistix 8.1. The Principal Component Analysis (PCA) was conducted using the Factoextra and FactoMineR packages in the R studio (version: 2024.12.1+563). The figures were created using GraphPad Prism 8.

3. Results

3.1. Pre-Physicochemical Characteristics of Experimental Soil

The soil at the experimental site was silty loam in texture and alkaline in nature, with a pH of 7.81. It was classified as calcareous, with a calcium carbonate ($CaCO_3$) content of 15%. The soil had low organic matter (0.54%) and total nitrogen (0.17 mg kg^{-1}), as well as low available phosphorus (2.45 mg kg^{-1}). However, the potassium content (86.3 mg kg^{-1}) was sufficient for optimum plant growth. The low fertility status of the soil can be attributed to its high carbonate content and alkaline pH, which contribute to its calcareous nature and limit the availability of nutrients to plants.

3.2. Effect of Treatments on Post-Harvest Soil Fertility Attributes

The data regarding soil fertility attributes such as soil pH, electrical conductivity, soil bulk density, soil organic matter, soil total nitrogen, soil-water saturation percentage, plant-available phosphorus, and plant-available potassium in soil are presented in Figure 1. All soil fertility attributes were significantly affected by the treatments at $p \leq 0.05$.

Biochar and nitrogen treatments significantly influenced soil pH compared to the control (7.73 $\pm$ 0.015), with the highest pH (7.96 $\pm$ 0.029) observed in the 15-BC+120-N treatment. This indicates that higher biochar levels, especially when combined with elevated nitrogen rates, increase soil pH. A consistent pattern of increasing pH was observed across all nitrogen levels with increasing biochar application, particularly at the 120-N rate. In contrast, treatments with lower biochar rates, such as 5-BC+60-N and 5-BC+90-N, resulted in only slight pH increases, remaining close to control levels. These findings suggest that biochar application, particularly at 15-BC combined with 120-N, enhances soil pH, potentially improving nutrient uptake and overall soil quality (Figure 1A). Similarly, all treatments significantly affected soil electrical conductivity compared to the control. The maximum soil electrical conductivity was observed in the 15-BC+90-N treatment (0.213 $\pm$ 0.003), as opposed to the control (0.161 $\pm$ 0.013). While the effect of other treatments was statistically similar to each other (Figure 1B). Soil bulk density was

significantly reduced by the biochar treatments, with the highest reduction observed in the 15-BC+120-N treatment (1.010 ± 0.010) compared to the control (1.300 ± 0.006). This reduction is likely due to the increased biochar application rates (15 tons and 10 tons/ha), which enhance soil structure (Figure 1C). Soil organic matter was also significantly increased, particularly in the 15-BC+120-N treatment, which recorded a value of 1.615 ± 0.089 compared to the control (0.567 ± 0.033). Other treatments had similar effects, but were not as pronounced (Figure 1D). Similarly, soil total nitrogen was highest in the 15-BC+120-N treatment (0.131 ± 0.0012), followed by the 10-BC+120-N treatment (0.122 ± 0.0013), while the control had the lowest value (0.050 ± 0.008) (Figure 1E). The soil saturation percentage also increased significantly with higher biochar rates, with the 15-BC+120-N treatment showing the maximum value (43.2 ± 0.53) compared to the control (34.0 ± 0.34) (Figure 1F). Regarding soil-available phosphorus, the 15-BC+120-N treatment recorded the highest value (6.11 ± 0.07), while the control had a mean value of 3.66 ± 0.032 (Figure 1G). Similarly, soil-available potassium was significantly higher in the 15-BC+120-N treatment (146.827 ± 2.882) compared to the control (74.603 ± 2.854), with other treatments showing similar trends (Figure 1H).

Overall, the data indicate that higher biochar rates (15-BC) combined with elevated nitrogen levels (120-N) consistently resulted in improved soil fertility attributes. The 15-BC+120-N treatment had the most pronounced positive effect on the soil's properties, suggesting that optimizing biochar and nitrogen application can enhance soil fertility, nutrient retention, and water availability. These findings underscore the effectiveness of the 15-BC+120-N treatment for maximizing wheat production by improving post-harvest soil quality.

3.3. Effect of Treatments on Growth and Yield Attributes of Wheat

The growth and yield attributes of wheat, including plant height, spike length, grains per spike, thousand-grain weight, grain yield, and biological yield, were all significantly influenced by the treatments at $p \leq 0.05$ (Figure 2).

The highest plant height was observed with the 15-BC+120-N treatment (86.9 ± 1.18), followed by the 15-BC+90-N treatment (81.5 ± 1.82), while the control recorded the lowest plant height (67.0 ± 0.58). The effects of the other treatments were statistically similar to each other (Figure 2A). A similar trend was seen for spike length, where the maximum value (12.20 ± 0.00) was recorded for the 15-BC+120-N treatment, compared to the control (10.10 ± 0.20). The differences between the other treatments were not statistically significant (Figure 2B). The number of grains per spike was also significantly affected by the treatments. The 15-BC+120-N treatment recorded the highest number of grains per spike (58.00 ± 0.58), followed closely by the 15-BC+90-N treatment (56.67 ± 0.88). Other treatments had similar effects, while the control recorded the lowest value (41.00 ± 1.53) (Figure 2C). The maximum thousand-grain weight (47.26 ± 0.35) was also observed in the 15-BC+120-N treatment, while the control treatment had the lowest value (37.89 ± 0.37) (Figure 2D). Similarly, grain yield was highest with the 15-BC+120-N treatment (46.94 ± 0.36), followed by the 15-BC+90-N treatment (45.39 ± 0.22). The control had a significantly lower grain yield (25.90 ± 0.49), while the other treatments showed statistically similar results (Figure 2E). Biological yield followed a similar pattern, with the highest value (104.67 ± 0.19) recorded for the 15-BC+120-N treatment and the lowest value being found in the control (82.71 ± 2.90) (Figure 2F).

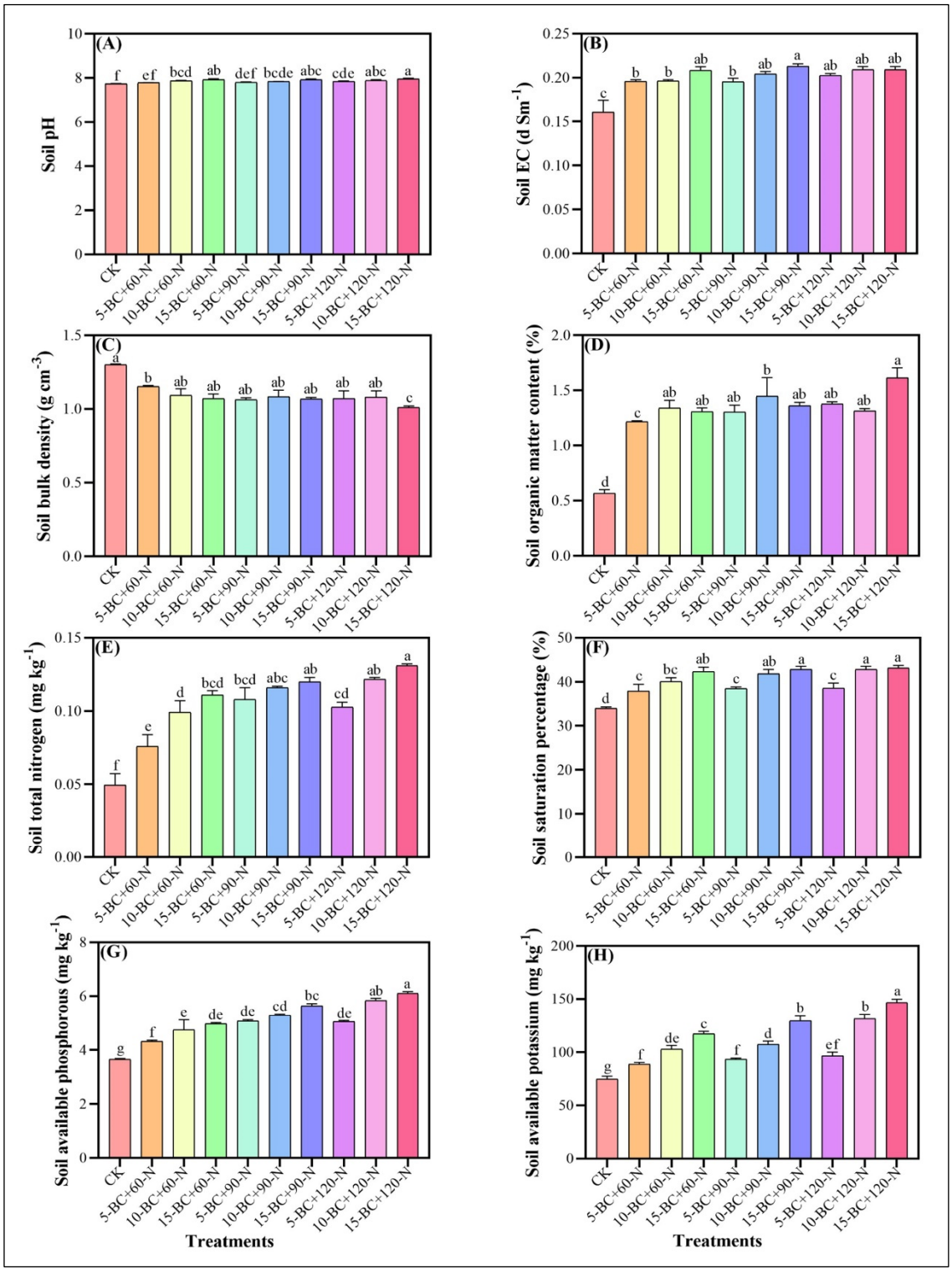


Figure 1. The influence of treatments on soil fertility parameters, (**A**) soil pH, (**B**) soil EC, (**C**) soil bulk density, (**D**) soil organic matter, (**E**) soil total nitrogen, (**F**) soil saturation percentage, (**G**) soil available phosphorus, (**H**) soil available potassium. The presented values represent the means of three replicates (n = 3) and include standard error of means. Different letters on each bar indicate significant differences between values at $p \leq 0.05$.

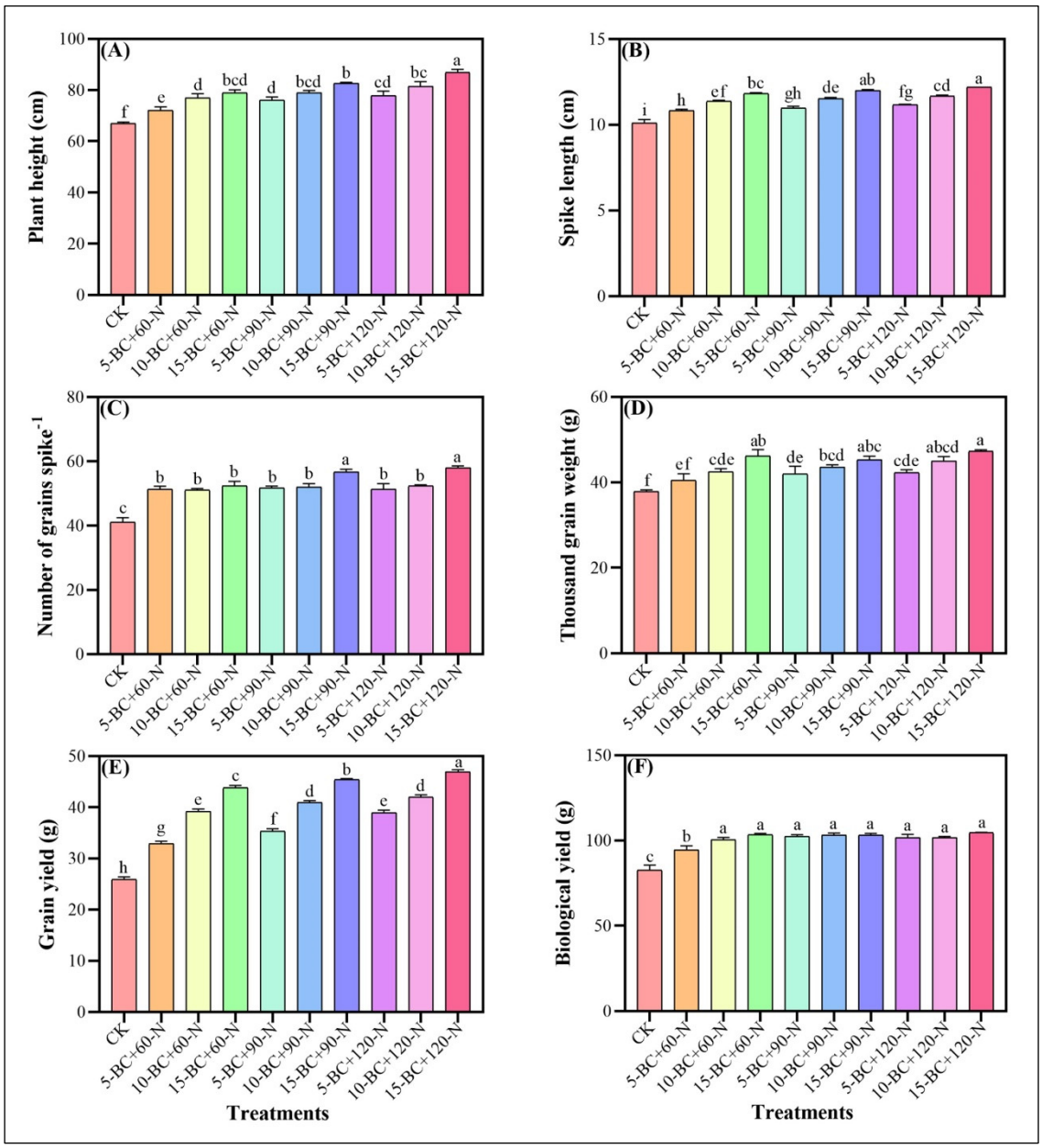


Figure 2. The influence of treatments on the growth and yield attributes of wheat, (**A**) plant height, (**B**) spike length, (**C**) number of grains spike^{-1}, (**D**) thousand-grain weight, (**E**) grain yield, (**F**) biological yield. The presented values represent the means of three replicates (n = 3) and include standard error of means. Different letters on each bar indicate significant differences between values at $p \leq 0.05$.

In summary, the results show that the 15-BC+120-N treatment consistently outperformed other treatments across all growth and yield attributes, indicating that the combination of higher biochar and nitrogen levels positively influences wheat growth and productivity. The control treatment consistently recorded the lowest values, further highlighting the beneficial effects of biochar and nitrogen applications.

3.4. Correlation Among the Studied Variables/Parameters

The relationships between soil fertility attributes and wheat growth attributes are presented in Table 2. The analysis revealed a strong positive correlation among all the

studied soil fertility and wheat growth parameters, except for soil bulk density showing a strong negative correlation.

Table 2. Correlation among soil fertility attributes and wheat agronomic parameters.

	Soil pH	***Soil EC***	***SOM***	***SBD***	***SP***	***STN***	***Avai. P***	***Avai. K***	***Ph***	***Sl***	***G. spike^{-1}***	***TGW***	***GY***	***BY***
Soil pH	1.0													
Soil EC	0.8	1.0												
SOM	0.7	0.9	1.0											
SBD	−0.8	−0.9	−1.0	1										
SP	0.9	0.9	0.8	−0.83	1.00									
STN	0.9	0.9	0.9	−0.94	0.93	1.00								
Avai. P	0.8	0.9	0.8	−0.87	0.90	0.97	1.00							
Avai. K	0.9	0.8	0.7	−0.74	0.92	0.87	0.92	1.00						
Ph	0.9	0.9	0.9	−0.89	0.93	0.96	0.97	0.95	1.00					
Sl	1.0	0.9	0.8	−0.86	0.97	0.92	0.89	0.94	0.96	1.00				
G. spike^{-1}	0.8	0.9	0.9	−0.92	0.87	0.89	0.87	0.83	0.91	0.90	1.00			
TGW	1.0	0.9	0.8	−0.85	0.96	0.92	0.89	0.94	0.95	0.98	0.86	1.00		
GY	1.0	0.9	0.9	−0.88	0.96	0.94	0.90	0.92	0.96	0.99	0.90	0.97	1.00	
BY	0.8	0.9	0.9	−0.98	0.86	0.95	0.85	0.71	0.87	0.86	0.88	0.85	0.89	1

Two-tailed test of significance used. SOM, soil organic matter; SBD, soil bulk density; SP, soil saturation percentage; STN, soil total nitrogen; Avai. P, available phosphorous; Avai. K, available potassium; Ph, plant height; Sl, spike length; G. spike^{-1}, grains per spike; TGW, thousand-grain weight; GY, grain yield; BY, biological yield.

The positive correlation suggests that the application of biochar, particularly when combined with elevated nitrogen levels, significantly enhances soil fertility, which in turn positively impacts wheat growth and yield. Notably, the increase in soil pH, organic matter, and nutrient availability (such as nitrogen, phosphorus, and potassium) due to biochar and nitrogen treatments correlated with improved wheat attributes, including plant height, grain yield, and biological yield.

The negative correlation of soil bulk density with other soil properties and plant growth attributes and yield could be due to the application of biochar that reduces the soil bulk density, owing to its porous and lightweight nature, enhancing the structure, aeration, and water retention capacity. These underlying mechanisms explain the negative correlation of soil properties (pH, electrical conductivity, soil organic matter, soil–water saturation percentage, soil total nitrogen, plant-available phosphorus, and plant-available potassium), which increased with biochar application.

These findings highlight the beneficial role of biochar in combination with nitrogen in nutrient-deficient alkaline soils typical of semi-arid climates. The strong correlations observed between soil fertility attributes and wheat growth indicate that improving soil health through biochar amendments directly supports enhanced crop productivity in challenging environments.

3.5. Principal Component Analysis (PCA) Among the Studied Variables/Parameters

The results of the PCA confirmed a positive association between soil fertility attributes and wheat productivity attributes (Figure 3). The first principal component (PC1) explained 89.80% of the total variation. The second principal component (PC2) accounted for an additional 5.4%, indicating that these two components captured most of the variability in the dataset.

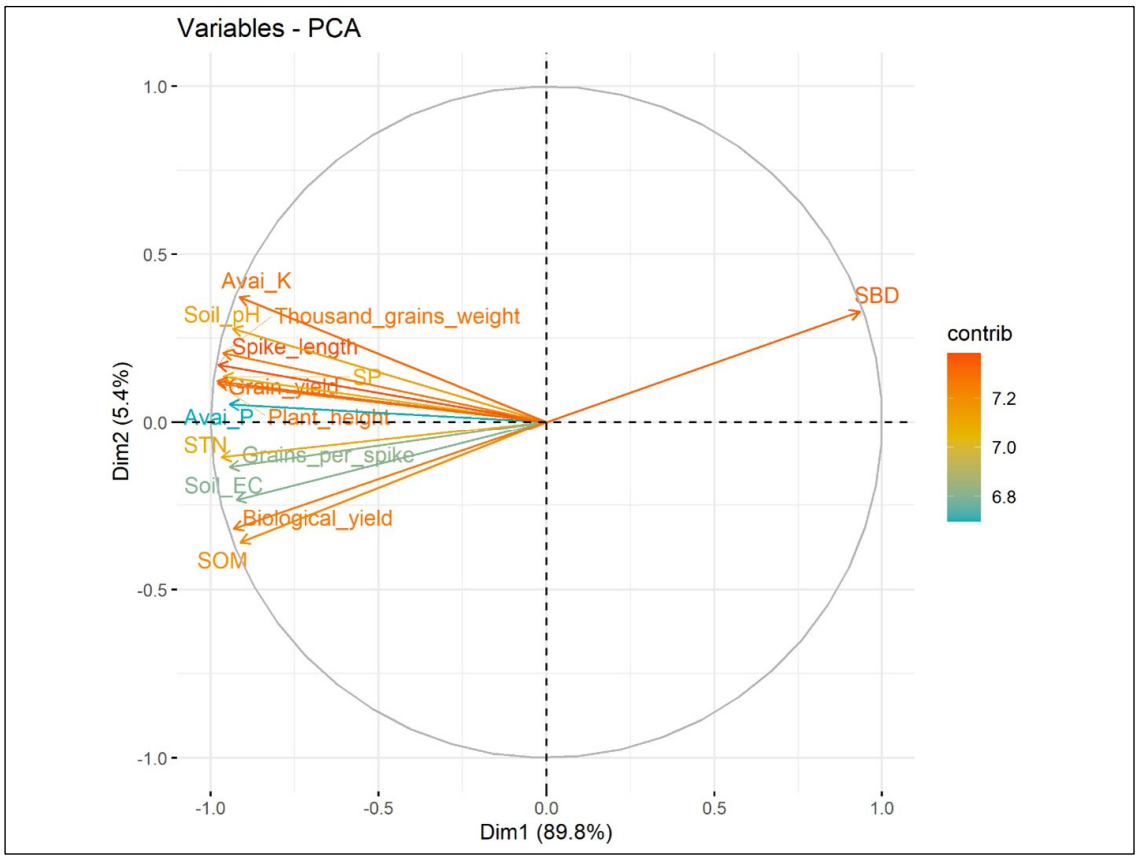


Figure 3. Principal component analysis among the soil fertility and agronomic attributes. SOM, soil organic matter; SBD, soil bulk density; SP, soil saturation percentage; STN, soil total nitrogen; Avai. P, available phosphorous; Avai. K, available potassium; Ph, plant height; Sl, spike length; G. spike^{-1}, grains per spike; TGW, thousand-grain weight; GY, grain yield; BY, biological yield.

PC1 was strongly influenced by soil fertility parameters such as soil organic matter, available phosphorus, potassium, and total nitrogen, which were positively correlated with key wheat growth attributes like plant height, grain yield, and thousand-grain weight. This suggests that improvements in soil fertility, particularly through the application of biochar and nitrogen, have a direct and substantial impact on wheat productivity.

PC2 contributed to distinguishing minor variations (soil bulk density), possibly related to biochar influence on soil bulk density and more subtle differences among treatments or environmental factors. Overall, the PCA highlights the dominant role of biochar and nitrogen in enhancing soil health and wheat performance, underscoring the significance of soil fertility improvements for sustainable crop production in semi-arid nutrient-deficient soils.

4. Discussion

4.1. Effect on Soil Fertility Attributes

Our study reveals that the addition of biochar combined with nitrogen effectively increased soil pH, with the effect being more pronounced at higher biochar (15 tons ha^{-1}) and nitrogen levels (120 kg ha^{-1}) (Figure 1A). This increase in pH could be directly due to the alkaline nature of biochar (8.61). Moreover, biochar application in soil enhances ammonium (NH^{+4}) retention and reduces nitrate (NO^{-3}) leaching, indirectly influencing soil pH by favoring NH^{+4} over NO^{-3}, thereby mitigating soil acidification caused by nitrification. In calcareous soils, this mechanism can further contribute to increased soil pH [35]. Moreover, Jien and Wang observed that adding 2.5% and 5% (*w*/*w*) biochar increased soil pH from 3.9 (control) to 5.1 with 5% biochar made from waste wood (*Leucaena*

leucocephala) [36]. Similarly, biochar produced from poplar leaves at 650 °C increased soil pH by 0.4 units, from 7.3 to 7.7 [37]. The increase in soil pH following biochar addition is likely due to the significant amount of ash (27%) and base cations present in biochar. In this regard, Masud and colleagues demonstrated that biochar with a high ash content and alkaline nature raised soil pH through the release of base cations such as Ca^{2+} and K^{+}. These cations can replace exchangeable Al^{3+} and H^{+} on negatively charged soil sites, further contributing to pH elevation [38]. Additionally, biochar's negatively charged functional groups, including phenolic, carboxylic, and hydroxyl groups, may bind excess H^{+} ions in the soil solution, thereby increasing soil pH [39]. Soil electrical conductivity also increased significantly with the addition of biochar combined with nitrogen, with the highest increase observed at the maximum biochar rate (15 tons ha^{-1}) and elevated nitrogen level (120 kg ha^{-1}) (Figure 1B). These findings are consistent with previous studies that reported significant increases in soil electrical conductivity with higher biochar application rates [40,41]. The increase in electrical conductivity can be attributed to the release of cations such as Ca^{2+}, Mg^{2+}, and Na^{+2} from the biochar, which raises the salt content in the soil [42]. Moreover, the increased content of soil total nitrogen, available phosphorus, and available potassium under the synergistic application of biochar and nitrogen could explain the rise in soil electrical conductivity. Previous studies have reported that biochars derived from nutrient-rich feedstocks or biomass can increase soil electrical conductivity when these nutrients dissolve into the soil upon biochar application [43,44]. Soil bulk density was significantly reduced with the higher application rate of biochar (Figure 1C). This finding is consistent with Burrell et al. [45], who reported that biochar application improved soil aggregate stability and reduced bulk density. Similarly, Quin and colleagues found that biochar made from woody residues had a significant effect on bulk density in coarse-textured soils compared to soils with higher clay content [46]. Additionally, a significant reduction in bulk density was observed in another study after 500 days of biochar application, even at lower rates. This could be due to the porous morphological nature of the biochars [47]. Studies have shown that biochar may increase the mineralization rates of native soil organic matter. For instance, Wardle et al. [48] reported that biochar application stimulated soil microbial activity, leading to the loss of boreal forest humus over 10 years. Similarly, refs. [49,50] observed the positive priming effects of biochar on native soil organic matter in incubation experiments. Consistent with these findings, our study reveals that higher doses of biochar can increase soil organic matter content (Figure 1D). Soil total nitrogen was also enhanced with higher biochar rates (15 tons ha^{-1}) and elevated nitrogen levels (120 kg ha^{-1}), Figure 1E. Similarly, ref. [51] reported that applying biochar at 5 tons ha^{-1} increased soil total nitrogen. This effect can be attributed to biochar's ability to stimulate both the immobilization and release of nitrogen and phosphorus through various biotic and abiotic mechanisms. For instance, biochar can enhance microbial nitrogen mineralization, as compost high in labile carbon supports microbial nitrogen transformation [52]. Soil saturation percentage also increased with higher biochar application rates (Figure 1F). These results are supported by [53], who found that biochar application can enhance soil water content at field capacity, particularly in coarse-textured soils. This effect can be explained by the increased microporosity of biochar, which contributes to higher soil water retention. Smaller biochar particles can fill the gaps between coarse soil particles, reducing average pore size and increasing the number of small pores [54]. These smaller pores are more effective at holding water against gravity than larger ones [55]. Soil-available phosphorus increased with higher biochar application rates and elevated nitrogen levels (Figure 1G). This effect can be attributed to biochar's ability to stimulate phosphorus-solubilizing microorganisms and increase soil microbial biomass and activity, which enhances phosphorus availability [56]. Additionally, biochar

may bond with soil aluminum (Al) and iron (Fe), reducing phosphorus fixation and thereby increasing its availability [57]. Soil-available potassium increased with higher biochar application rates and elevated nitrogen levels (Figure 1H). This increase can be attributed to biochar's enrichment with exchangeable potassium, which boosts soil potassium levels for plant uptake [58]. Additionally, biochar can enhance potassium availability through various mechanisms. These include direct contributions from potassium-rich biochar sources, designed using specific production methods and indirect mechanisms such as improved potassium retention due to biochar's high cation exchange capacity, porosity, and specific surface area [59].

4.2. Effect on Wheat Growth

In this study, the application of biochar combined with nitrogen significantly improved wheat growth compared to the control (Figure 2). This improvement can be attributed to several synergistic mechanisms of biochar and nitrogen application. Biochar can regulate nitrogen dynamics in soil by adsorbing NH^{+4} and NO^{-3} and reducing losses from volatilization and leaching. This can ensure the long-term supply of nitrogen in the soil for plant absorption, hence increasing crop output. For example, it was found that 20 tons of biochar with 150 kg N/ha as poultry manure significantly increased wheat quality, growth, and yield [60]. Biochar enhances soil structure, increases nutrient use efficiency, and improves nutrient uptake by plants. Additionally, biochar stimulates microbial activity in the soil, which regulates nutrient availability, ultimately promoting plant growth [61]. According to Hossain and coworkers, biochar enhances the soil's ability to retain nutrients, a feature largely determined by its porosity and surface charge. Biochar improves soil nitrogen retention by reducing leaching and gaseous losses. It also increases phosphorus availability by slowing the leaching process. While biochar can have variable effects—both positive and negative—on the availability of potassium and other minerals, it consistently reduces bulk density while increasing porosity, aggregate stability, and water retention in the soil. Furthermore, biochar raises soil pH, influencing nutrient availability for plants. The biological properties of soil are also modified by biochar, as it promotes microbial populations, enzyme activity, soil respiration, and microbial biomass [62]. These results align with the findings of our present study, as confirmed by the correlation and principal component analysis (Table 2; Figure 3), which further support the positive effects of biochar on wheat growth.

5. Conclusions

Biochar applied with elevated nitrogen levels significantly improved various soil fertility attributes, including soil pH, electrical conductivity, soil organic matter, saturation percentage, and available nutrients such as total soil nitrogen, plant-available phosphorus, and plant-available potassium while reducing bulk density. These enhancements in soil properties contributed to improved wheat growth and yield, as seen in plant height, spike length, grains per spike, thousand-grain weight, grain yield, and biological yield. The effects were most pronounced with higher biochar application rates (15 tons ha^{-1}) and elevated nitrogen levels (120 kg ha^{-1}). Our study confirms that high rates of biochar combined with elevated nitrogen levels can significantly improve soil fertility and crop performance in calcareous soils in semi-arid regions. Further research is needed to explore the potential of these treatment combinations under natural field conditions.

Author Contributions: Conceptualization, H.U.R. and I.A.M.; Methodology, B.A. and W.A.; Software, H.U.R. and W.A.; Validation, I.A.M.; Formal analysis, B.A. and H.U.R.; Investigation, B.A. and I.A.M.; Resources, I.A.M.; Data curation, B.A., I.A.M. and W.A.; Writing—original draft, H.U.R.; Writing—review & editing, H.U.R., I.A.M. and W.A.; Visualization, H.U.R. and W.A.; Supervision,

I.A.M.; Project administration, I.A.M.; Funding acquisition, I.A.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data will be made available upon request from the corresponding author.

Acknowledgments: The authors would like to acknowledge the Department of Soil and Environmental Sciences, The University of Agriculture Peshawar, Pakistan, for providing financial and technical assistance for the completion of this work.

Conflicts of Interest: The authors declare no conflicts of interest.

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