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Application of Biochar and Poultry Manure for Enhanced Wheat Growth and Yield in Calcareous Soils of Peshawar, Pakistan

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Abstract
Soil fertility decline and poor nutrient use efficiency are major constraints to wheat productivity in calcareous soils of Peshawar, Pakistan. This study evaluated the effects of biochar (BC) and poultry manure (PM) alone and in combination with mineral phosphorus on growth, yield and phosphorus use efficiency of wheat (*Triticum aestivum* L.). A field experiment was conducted at the University Research Farm, The University of Agriculture, Peshawar, during the winter season of 2023-24 using a randomized complete block design with three replications. Twelve treatment combinations were tested using four phosphorus levels (0, 60, 90 and 120 kg P ha^{-1}), biochar at 10 t ha^{-1} and poultry manure at 10 t ha^{-1}. The experimental soil was alkaline, calcareous, non-saline and low in organic matter and available phosphorus. Results showed that phosphorus application with biochar significantly improved wheat growth, yield attributes, nutrient uptake and phosphorus use efficiency. The treatment receiving 120 kg P ha^{-1} + 10 t biochar ha^{-1} produced the highest plant height (98.4 cm), spike length (12.8 cm), grains per spike (52.4), thousand-grain weight (46.2 g), biological yield (12,845 kg ha^{-1}) and grain yield (4,872 kg ha^{-1}). The

same treatment also recorded the highest total nitrogen uptake (142.3 kg ha^{-1}), total phosphorus uptake (38.7 kg ha^{-1}) and phosphorus use efficiency (32.25). Biochar consistently outperformed poultry manure in improving wheat productivity when combined with mineral phosphorus. The findings indicate that integration of mineral phosphorus with biochar improves nutrient availability and crop performance under calcareous soil conditions. Application of 120 kg P ha^{-1} with 10 t biochar ha^{-1} is therefore recommended for improving wheat productivity and phosphorus use efficiency in the Peshawar region.
Keywords: biochar; calcareous soil; phosphorus use efficiency; poultry manure; wheat (*Triticum aestivum* L.)

1. Introduction

Wheat (*Triticum aestivum* L.) is one of the most important cereal crops globally and serves as a staple food for a large portion of the world's population. In Pakistan, wheat occupies a central position in the agricultural economy, contributing significantly to food security and rural livelihoods. The country ranks among the top wheat producers globally; however, wheat productivity remains constrained by several factors, including declining soil fertility, imbalanced nutrient management and low nutrient use efficiency (Minot et al., 2015). In the Peshawar region, the situation is further exacerbated by the prevalence of calcareous soils, which are characterized by high pH, low organic matter content and limited availability of essential nutrients, particularly phosphorus.

Phosphorus (P) is a critical macronutrient for wheat production, playing essential roles in root development, energy transfer, photosynthesis, grain formation and overall crop productivity (Balemi and Negisho, 2012). Despite the considerable total phosphorus content in many soils, only a small fraction is available to plants in the form of orthophosphate ions. In calcareous and alkaline soils, soluble phosphorus is rapidly fixed through reactions with calcium, magnesium and other soil constituents, resulting in low phosphorus availability to crops (Ryan et al., 1985). This fixation process significantly reduces fertilizer efficiency and increases production costs for farmers. The calcareous soils of Peshawar, with their high lime content (often exceeding 15%) and alkaline pH, are particularly prone to phosphorus fixation, making phosphorus management a critical challenge for sustainable wheat production.

Soil fertility decline in agricultural lands has been attributed to intensive cropping systems, shortening of fallow periods, reduced manure application, extensive use of crop residues as fuel or fodder and removal of ground cover (Amede et al., 2001). In Ethiopia and other parts of Sub-Saharan Africa, studies have indicated that most agricultural soils have low fertility due to low rates of biomass return to crop fields, continuous nutrient uptake by crops, low fertilizer use and insufficient organic matter application (Gebrekidan, 2003). Similar conditions prevail in the agricultural soils of Pakistan, where continuous cropping without adequate organic matter replenishment has led to soil degradation and declining productivity.

Integrated nutrient management, which combines mineral fertilizers with organic amendments, has emerged as a promising strategy for improving soil fertility, enhancing nutrient availability and sustaining crop productivity (Efthimiadou et al., 2010). Among various organic amendments, biochar has

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Vol. 4 No. 6 (June) (2026)

gained considerable attention in recent years due to its potential to improve soil physical, chemical and biological properties while providing long-term carbon sequestration benefits (Lehmann and Joseph, 2009).

Biochar is a carbon-rich material produced through pyrolysis of biomass under limited oxygen conditions at relatively high temperatures (400-700°C) (Lehmann and Joseph, 2009). Studies have reported the beneficial effects of biochar amendment on yield components of various crops in different parts of the world (Agboola and Moses, 2015; Haileselassie et al., 2015; Faruque et al., 2017). The positive effects of biochar on plant growth and yield parameters have been associated with improvements in soil pH, cation exchange capacity (CEC), nutrient availability and water retention (Liang et al., 2014). Biochar addition to croplands has been shown to enhance water retention, sorption capacity, nutrient availability and soil organic carbon (Laird, 2008). The increase in plant growth and yield parameters has been attributed to improved soil nutrient supply and increased uptake of plant nutrients (Lehmann et al., 2006).

In Ethiopia, Lulu et al. (2020) investigated the effect of biochar, lime and farmyard manure on growth, yield and grain nutrients of wheat in southern Ethiopia. Their study demonstrated that biochar (5 t ha^{-1}) produced the highest straw yield, grain yield and total biomass, with significant improvements in plant height, tiller number and seeds per spike. Biochar also significantly increased the concentrations of phosphorus and potassium in wheat grain. The superior effect of biochar was attributed to improvements in soil pH, CEC, nutrient availability and water retention. Similarly, Haileselassie et al. (2015) reported that mesquite biochar increased grain and straw yields of wheat in Tigray, Ethiopia.

Poultry manure is another valuable organic amendment rich in essential nutrients such as nitrogen (N), phosphorus (P) and potassium (K), which are crucial for plant growth and soil health (Tawfik et al., 2023). The high nutrient content and organic matter in poultry manure make it an excellent amendment for improving soil fertility and structure (Agbede et al., 2020). Studies have shown that poultry manure application increases soil organic matter and plant nutrients, thereby positively improving soil physical and chemical properties and crop yields (Agbede and Ojeniyi, 2009; Adekiya et al., 2019). However, the benefits of organic matter are generally short-lived because they decompose rapidly, especially under tropical and subtropical conditions with high temperature and aeration (Mekuria and Noble, 2013).

The combination of biochar with organic manure may further enhance soil properties and plant productivity. Biochar's high stability against decomposition allows it to remain in soil for longer periods, providing long-term benefits, while its porous structure and high surface area enable it to retain nutrients and improve soil physical properties. Studies have demonstrated that combining biochar with poultry manure can enhance soil aggregate stability, improve nutrient retention and significantly increase crop yield (Cai et al., 2022). In Nigeria, Agbede et al. (2020) found that this combination significantly improved soil properties and crop yield in degraded tropical sandy soils. Similarly, Ayito et al. (2023) reported that biochar application enhanced soil nutrients, crop growth and fruit yields while reducing reliance on chemical fertilizers.

The response of wheat to biochar and poultry manure application in calcareous soils of Peshawar has not been adequately investigated. While biochar represents a valuable soil ameliorant that can change the physical and chemical

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Vol. 4 No. 6 (June) (2026)

properties of soil, it might be limited as a nutrient supplier alone because of its very low nutrient concentrations and high recalcitrance to biodegradation (Partey et al., 2014). Therefore, for improved soil sustainability and wheat productivity, application of poultry manure in combination with biochar may be one of the best options. The working hypothesis of this study was that the combined application of biochar and poultry manure with mineral phosphorus would significantly improve soil properties, growth and wheat yield compared with sole application of mineral phosphorus. Therefore, this study was designed to evaluate the effects of biochar and poultry manure, alone and in combination with graded phosphorus levels, on growth, yield and phosphorus use efficiency of wheat in the calcareous soils of Peshawar, Pakistan.

2. Materials and Methods

2.1. Research Study Area

A field experiment was conducted at the University Research Farm, The University of Agriculture, Peshawar, during the winter (*Rabi*) season of 2024–2025. The experimental site is located in the Peshawar Valley, Khyber Pakhtunkhwa, Pakistan, at an altitude of approximately 359 m above sea level. The soil at the experimental site is classified as silty clay loam in texture, alkaline in reaction (pH 7.8), low in organic matter (0.85%), and medium in available phosphorus and potassium content, representative of the calcareous alluvial soils commonly found in the Peshawar Valley.

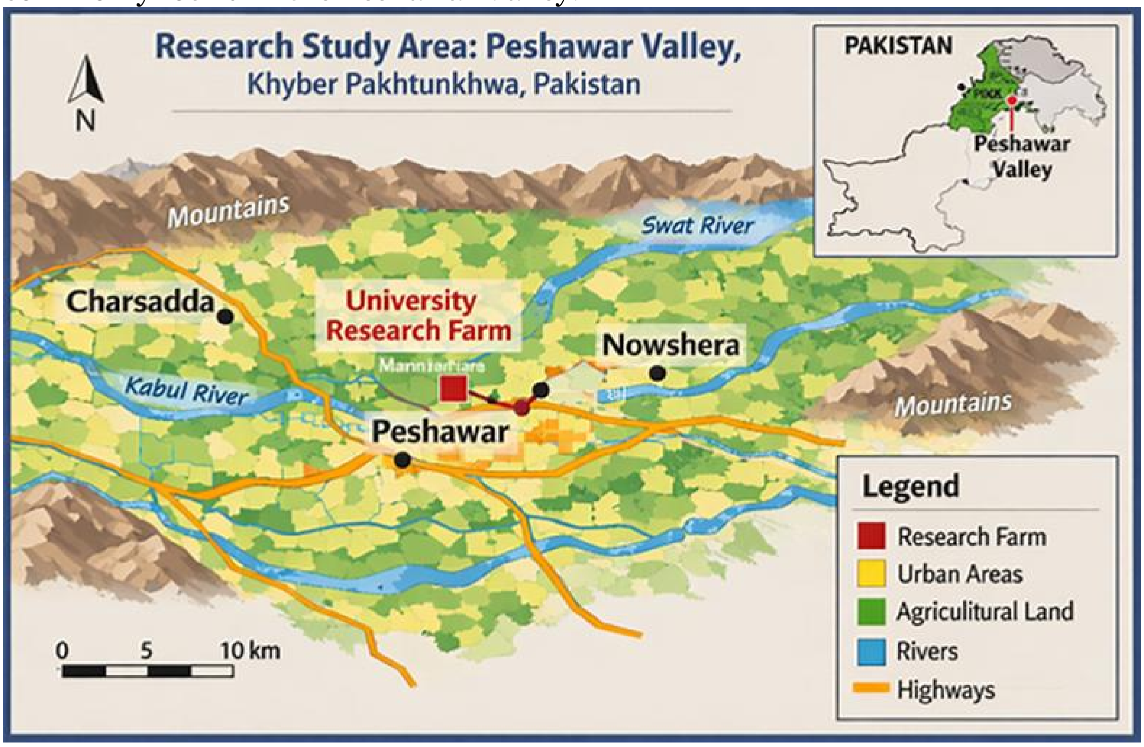

Figure 1: Climate Profile of the Peshawar Valley. Mean monthly temperature (°C) and rainfall (mm) during the 2024–2025 Rabi season, illustrating the semi-arid climate with peak temperatures in June and monsoon-driven precipitation from July to September

2.2. Soil Characteristics

Before the commencement of the experiment, composite soil samples were collected from the experimental site at 0-20 cm depth. The samples were air-

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DIALOGUE SOCIAL SCIENCE REVIEW
Vol. 4 No. 6 (June) (2026)

dried, ground and passed through a 2-mm sieve for analysis. The soil was analyzed for texture using the hydrometer method, pH (1:2 soil-water suspensions), electrical conductivity (EC), and organic matter by the Walkley-Black method, lime content and AB-DTPA extractable phosphorus following standard procedures (Soltanpour and Schwab, 1977). The physico-chemical properties of the experimental soil are presented in Table 1. The soil was silty clay loam in texture, alkaline in reaction (pH 7.76), non-saline (EC 0.28 dS m^{-1}), calcareous (16.3% lime) and low in organic matter (0.69%) and available phosphorus (3.6 mg kg^{-1}). These characteristics indicate a soil environment where phosphorus fixation can be high and crop response to phosphorus fertilizer and organic amendments is expected.

Table 1: ***Selected physico-chemical properties of the experimental soil***

Property	Unit	Value
Sand	%	15.24
Silt	%	51.51
Clay	%	33.25
Texture class	-	Silty clay loam
pH (1:2)	-	7.76
EC	dS m^{-1}	0.28
Organic matter	%	0.69
Lime content	%	16.3
AB-DTPA extractable P	mg kg^{-1}	3.6

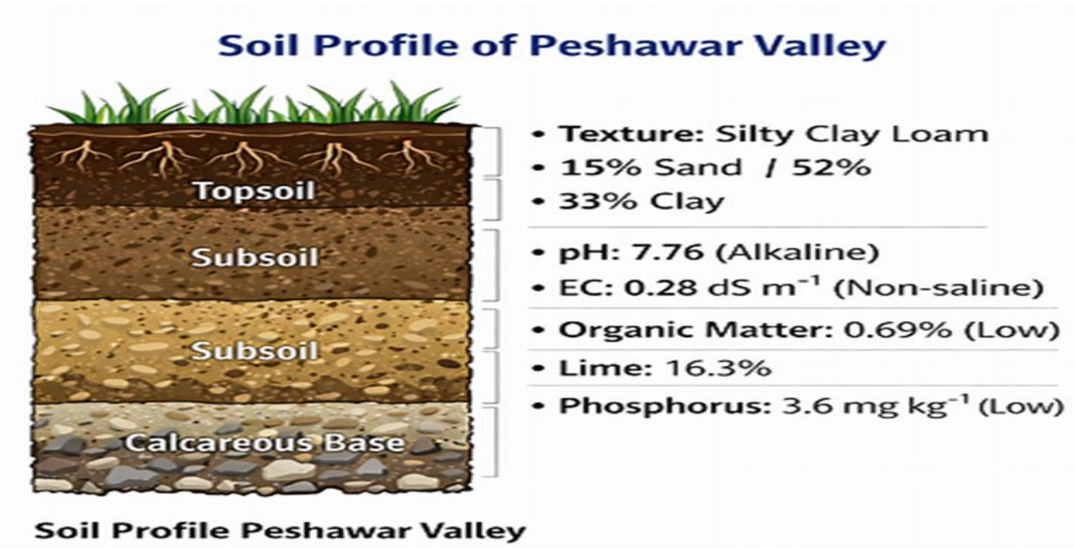

Figure 2. Soil Composition of the Peshawar Valley. Soil profile showing silty clay loam texture, alkaline pH (7.8), low organic matter (0.85%), and medium levels of available phosphorus and potassium, representative of the valley's alluvial soils.

2.3. Climate Profile

The experimental site is situated in the Peshawar Valley, which experiences a

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www.thedssr.com

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DIALOGUE SOCIAL SCIENCE REVIEW
Vol. 4 No. 6 (June) (2026)

semi-arid subtropical climate characterized by hot summers and mild winters. The region receives mean annual precipitation of approximately 360–400 mm, with the majority (about 65–70%) occurring during the monsoon season from July to September. The winter months (November to March) remain relatively dry with occasional light rainfall. The mean monthly temperature exhibits considerable seasonal variation, with minimum temperatures dropping to 5°C in January and maximum temperatures rising to 40°C in June. Relative humidity ranges from 45–60% during the winter season to 65–80% during the monsoon months. Potential evapotranspiration (PET) typically exceeds precipitation, resulting in a moisture deficit that necessitates supplemental irrigation for successful wheat cultivation.

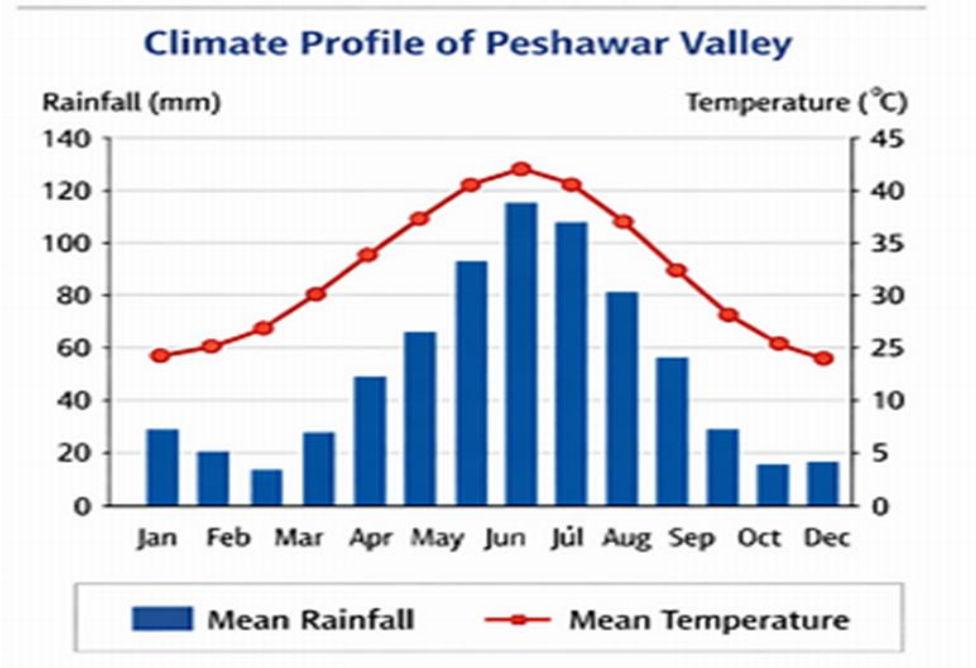

Figure 1: Climate Profile of the Peshawar Valley

2.3. Biochar and Poultry Manure Characterization

Biochar used in the experiment was produced from hardwood biomass through slow pyrolysis at approximately 450-550°C. The biochar was ground and passed through a 2-mm sieve before application. Poultry manure was collected from a local poultry farm and composted for three weeks before application to allow for mineralization. The chemical composition of biochar and poultry manure was determined following standard procedures (Table 2). Biochar was alkaline with high organic carbon content (55.7%) and a high C:N ratio (65.5), while poultry manure was slightly acidic with higher concentrations of nitrogen, phosphorus and a low C:N ratio (7.72). These characteristics indicate that poultry manure would decompose rapidly, releasing nutrients quickly, while biochar would provide long-term soil improvement benefits.

Table 2: ***Chemical composition of biochar and poultry manure***

Property	Biochar	Poultry Manure
pH (1:2)	8.2	6.8
Organic C (%)	55.7	22.3
Total N (%)	0.85	2.89

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Total P (%)	0.38	1.34
Total K (%)	1.92	1.57
Ca (%)	4.63	0.92
Mg (%)	3.78	0.46
C:N ratio	65.5	7.72

2.4. Experimental Design and Treatments

The experiment was laid out in a randomized complete block design (RCBD) with three replications. Twelve treatment combinations were developed from four phosphorus levels (0, 60, 90 and 120 kg P ha^{-1}), biochar at 10 t ha^{-1} and poultry manure at 10 t ha^{-1}. The treatment combinations are presented in Table 3. Each plot measured 3 m × 2 m (6 m^2), with 0.5 m spacing between plots and 1 m spacing between blocks. Phosphorus was applied as single superphosphate (SSP) containing 18% P_2O_5. Biochar and poultry manure were weighed and spread evenly on the plots according to the required rates and incorporated into the soil to a depth of approximately 15 cm using a spade, two weeks before sowing.

Table 3: ***Treatment combinations used in the experiment***

Treatment	Phosphorus (kg P ha^{-1})	Biochar (t ha^{-1})	Poultry Manure (t ha^{-1})
T1	0	0	0
T2	60	0	0
T3	90	0	0
T4	120	0	0
T5	0	10	0
T6	60	10	0
T7	90	10	0
T8	120	10	0
T9	0	0	10
T10	60	0	10
T11	90	0	10
T12	120	0	10

2.5. Crop Establishment and Management

Wheat variety 'Pirsabak-2013' was used as the test crop. The seed was obtained from the Cereal Crops Research Institute, Pirsabak, Nowshera. Wheat was sown at a seeding rate of 120 kg ha^{-1} in rows 20 cm apart on November 15, 2023. Nitrogen fertilizer was applied at the rate of 120 kg N ha^{-1} in the form of urea (46% N), with half applied at sowing and the remaining half as top dressing at the tillering stage (35 days after sowing). Potassium was applied uniformly at 60 kg K ha^{-1} as muriate of potash (MOP) at sowing. All recommended agronomic practices, including irrigation, weeding and pest management, were applied uniformly to all treatments. Weeds were controlled manually through hand weeding at 30 and 60 days after sowing. A total of five irrigations were applied throughout the crop season.

2.6. Data Collection

2.6.1. Growth Parameters

Ten plants were randomly selected from each plot at physiological maturity for recording growth parameters. Plant height (cm) was measured from the base to the tip of the spike excluding awns using a measuring tape and averaged. Number of total tillers and productive tillers per plant were counted from randomly selected plants and averaged. Spike length (cm) was measured excluding awns and averaged. Number of grains per spike was counted from randomly selected spikes and averaged.

2.6.2. Yield and Yield Components

The crop was harvested manually at physiological maturity from each plot. The harvested material was sun-dried and weighed to determine biological yield. After threshing, grain yield was recorded and straw yield was calculated by subtracting grain yield from biological yield. Thousand-grain weight (g) was determined by counting 1000 grains from each plot and weighing using an electronic balance. Harvest index (%) was calculated as:

Harvest Index (%) = (Grain Yield / Biological Yield) × 100

2.6.3. Plant Tissue Analysis

Plant samples (grain and straw) were collected from each plot at harvest. The samples were oven-dried at 70°C for 48 hours, ground in a stainless steel Wiley mill and sieved through a 0.5-mm sieve. Nitrogen content was determined by the Kjeldahl method (Jackson, 1958). Phosphorus and potassium contents were determined after wet digestion with H_2SO_4 and H_2O_2 (Okalebo et al., 2002). Phosphorus was measured colorimetrically using the molybdenum blue method (Murphy and Riley, 1962), while potassium was determined using a flame photometer. Nutrient uptake was calculated by multiplying nutrient concentration by dry matter yield.

2.6.4. Phosphorus Use Efficiency

Phosphorus use efficiency (PUE) was calculated using the following formula to evaluate the efficiency of phosphorus fertilizer utilization by wheat under different conservation practices and priming treatments: PUE = (P uptake in fertilized plot – P uptake in control plot) / P applied × 100, where P uptake in fertilized plot represents the total phosphorus uptake (kg ha^{-1}) in the treatment receiving phosphorus fertilizer, P uptake in control plot represents the total phosphorus uptake (kg ha^{-1}) in the treatment without phosphorus application, and P applied represents the amount of phosphorus fertilizer applied (kg ha^{-1}) to the respective treatment. This calculation provides a quantitative measure of the efficiency with which applied phosphorus is taken up by the crop, allowing for comparison of phosphorus utilization efficiency among different conservation practices and priming treatments. Higher PUE values indicate better phosphorus recovery and utilization by the wheat crop, reflecting the effectiveness of the integrated management practices in enhancing phosphorus availability and uptake from both soil and fertilizer sources. Phosphorus use efficiency (PUE) was calculated using the following formula: PUE = (P uptake in fertilized plot - P uptake in control plot) / P applied × 100

ISSN Online: 3007-3154
ISSN Print: 3007-3146
Vol. 4 No. 6 (June) (2026)

2.7. Statistical Analysis

All data were analyzed using analysis of variance (ANOVA) appropriate for a randomized complete block design using statistical software (SAS version 9.4). Treatment means were compared using Fisher's least significant difference (LSD) test at the 5% probability level where treatment effects were significant (Steel and Torrie, 1981).

3. Results

3.1. Effect of Biochar, Poultry Manure and Phosphorus on Growth Parameters

Plant height, number of total tillers, productive tillers, spike length and grains per spike were significantly influenced by the application of phosphorus, biochar and poultry manure (Figure 1). Plant height ranged from 72.4 cm in the control (T1) to 98.4 cm in T8 (120 kg P ha^{-1} + 10 t biochar ha^{-1}). Application of biochar with phosphorus significantly improved plant height compared to phosphorus alone or poultry manure treatments. T8 showed a 36% increase in plant height over the control. Poultry manure with 120 kg P ha^{-1} (T12) produced plant height of 90.2 cm, which was significantly lower than T8 but higher than phosphorus alone at the same rate (85.6 cm). The lowest plant height among amended treatments was recorded in T5 (biochar alone without phosphorus) at 73.5 cm, which was statistically similar to the control.

Total tillers per square meter followed a similar pattern, with T8 producing the highest number (335.2 m^{-2}), representing a 55% increase over the control (215.6 m^{-2}). T12 produced 305.8 m^{-2}, while T4 (120 kg P ha^{-1} alone) produced 278.3 m^{-2}. Productive tillers showed the same trend, with T8 recording 298.6 productive tillers m^{-2} compared to 182.3 in the control. Spike length was significantly improved by the treatments, ranging from 8.2 cm in the control to 12.8 cm in T8. T8 showed a 56% increase in spike length over the control. T12 produced spike length of 11.6 cm, while T4 produced 10.5 cm. The number of grains per spike was also highest in T8 (52.4), followed by T12 (46.8) and T4 (40.2). The control produced the lowest grains per spike (28.6). The results demonstrate that biochar was more effective than poultry manure in improving growth parameters when combined with the highest phosphorus level. The positive interaction between biochar and phosphorus was evident, as T8 consistently outperformed all other treatments.

Dialogue Social Science Review (DSSR)
www.thedssr.com

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Vol. 4 No. 6 (June) (2026)

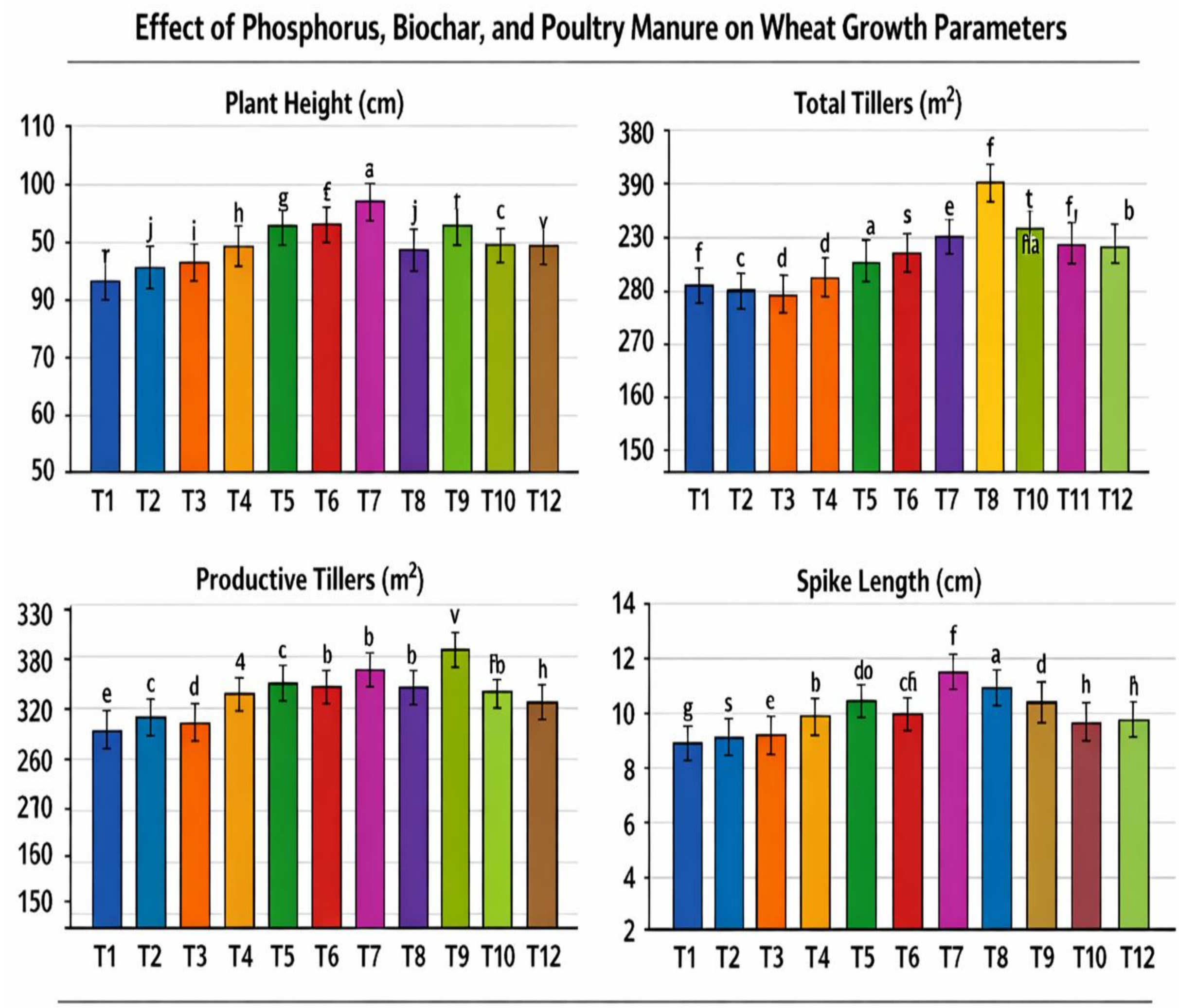

Figure 1: Effect of phosphorus, biochar and poultry manure on growth parameters of wheat

3.2. Effect on Yield and Yield Components

The effect of treatments on yield and yield components of wheat is presented in Table 5. Thousand-grain weight was significantly influenced by the treatments, ranging from 32.4 g in the control to 46.2 g in T8. T8 showed a 43% increase in thousand-grain weight over the control. T12 produced thousand-grain weight of 43.6 g, while T4 produced 40.6 g (Figure 2). Biochar with phosphorus generally produced higher thousand-grain weight than phosphorus alone or poultry manure treatments at the same phosphorus level.

Biological yield ranged from 8,450 kg ha^{-1} in the control to 12,845 kg ha^{-1} in T8. T8 showed a 52% increase in biological yield over the control. T12 produced 11,896 kg ha^{-1}, while T4 produced 10,876 kg ha^{-1}. Grain yield followed the same pattern, with T8 producing the highest grain yield (4,872 kg ha^{-1}), which was 69% higher than the control (2,876 kg ha^{-1}). T12 produced 4,568 kg ha^{-1}, while T4 produced 3,985 kg ha^{-1}. Straw yield was also highest in T8 (7,973 kg ha^{-1}), followed by T12 (7,328 kg ha^{-1}). Harvest index ranged from 33.6% to 38.4%, with T12 showing the highest value (38.4%), followed by T8 (37.9%) and T6 (37.8%). The differences in harvest index were less pronounced than other parameters, indicating that treatments influenced both

ISSN Online: 3007-3154
ISSN Print: 3007-3146
Vol. 4 No. 6 (June) (2026)

grain and straw production proportionally.

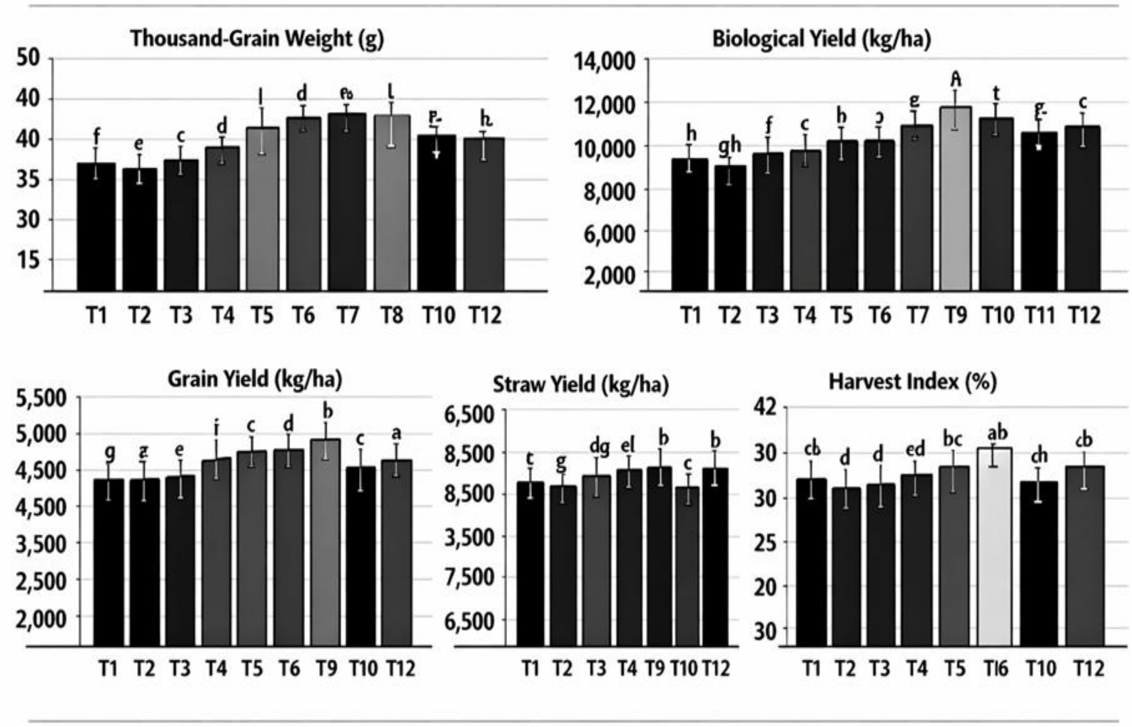

Figure 2: Effect of phosphorus, biochar and poultry manure on yield and yield components of wheat

3.3. Effect on Nutrient Concentration in Grain and Straw

Nitrogen concentration in straw ranged from 0.40% in T5 to 0.84% in T8, while grain N concentration ranged from 1.18% in the control to 1.92% in T8 (Figure 3). T8 showed a 63% increase in grain N concentration over the control. Poultry manure with 120 kg P ha^{-1} (T12) produced grain N concentration of 1.58%, which was significantly lower than T8 but higher than T4 (1.55%). Phosphorus concentration in grain ranged from 0.20% in T5 to 0.54% in T8. T8 showed a 145% increase in grain P concentration over the control (0.22%). T12 produced grain P concentration of 0.34%, while T4 produced 0.42%. Straw P concentration followed a similar pattern, with T8 recording the highest value (0.42%) and the control the lowest (0.18%).

Potassium concentration in grain ranged from 0.40% in T9 to 0.72% in T8. T8 showed a 64% increase in grain K concentration over the control (0.44%). Straw K concentration was also highest in T8 (1.12%), followed by T7 and T12 (both 0.82%). The results clearly demonstrate that the integrated application of phosphorus with biochar (T8) produced the highest nutrient concentrations in both grain and straw, indicating improved nutrient uptake and utilization by the crop.

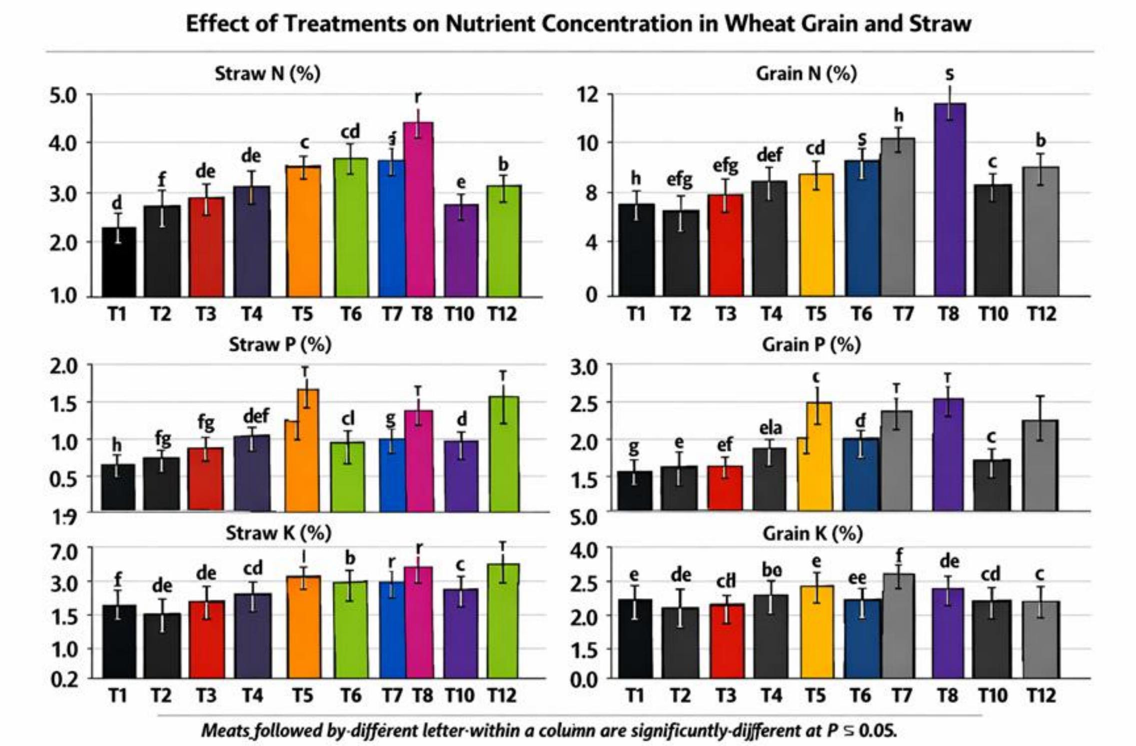

Figure 3: Effect of treatments on nutrient concentration in wheat grain and straw

3.4. Effect on Nutrient Uptake and Phosphorus Use Efficiency

Total nitrogen uptake ranged from 58.2 kg ha^{-1} in the control to 142.3 kg ha^{-1} in T8. T8 showed a 144% increase in total N uptake over the control. T12 produced 98.4 kg N ha^{-1}, while T4 produced 96.8 kg N ha^{-1}. Total phosphorus uptake ranged from 16.8 kg ha^{-1} in the control to 38.7 kg ha^{-1} in T8. T8 showed a 130% increase in total P uptake over the control. Total potassium uptake was also highest in T8 (105.8 kg ha^{-1}), followed by T12 (82.4 kg ha^{-1}) and T4 (78.6 kg ha^{-1}). Phosphorus use efficiency (PUE) ranged from 13.0% in T6 (60 kg P ha^{-1} + biochar) to 32.25% in T8 (120 kg P ha^{-1} + biochar). Interestingly, PUE decreased with increasing phosphorus rate when applied alone (from 19.3% at 60 kg P ha^{-1} to 16.7% at 120 kg P ha^{-1}). However, when biochar was applied with phosphorus, PUE increased with increasing phosphorus rate, with T8 showing the highest PUE (32.25%). Poultry manure also improved PUE compared to phosphorus alone at the same rate, but the effect was less pronounced than biochar.

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Vol. 4 No. 6 (June) (2026)

DIALOGUE SOCIAL SCIENCE REVIEW

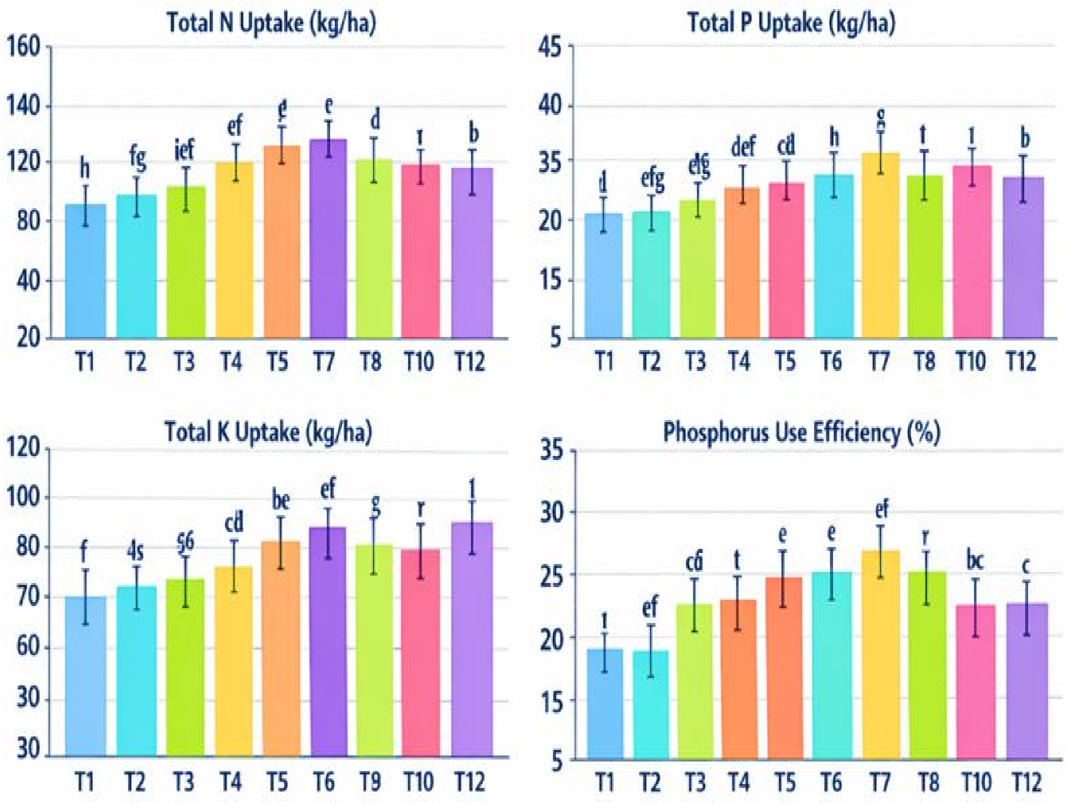

Figure 4: Effect of treatments on total nutrient uptake and phosphorus use efficiency of wheat

4. Discussion

4.1. Effect on Growth Parameters

The study demonstrated that application of biochar and poultry manure, particularly in combination with mineral phosphorus, significantly improved the growth parameters of wheat. The highest plant height, tiller number, spike length and grains per spike were recorded in the treatment receiving 120 kg P ha^{-1} with 10 t biochar ha^{-1} (T8). These findings are consistent with previous studies that reported positive effects of biochar on plant growth parameters of annual crops such as wheat, maize, tomato and rice (Dunlop et al., 2015; Haileselassie et al., 2015; Agegnehu et al., 2016). The improvement in growth parameters can be attributed to several mechanisms.

Biochar application improves soil physical properties by reducing bulk density, increasing porosity and enhancing water retention (Liang et al., 2014). In the calcareous soils of Peshawar with high bulk density and low organic matter, biochar's porous structure would have improved root penetration and aeration, facilitating better nutrient and water uptake. The increased water holding capacity of biochar-amended soils would have been particularly beneficial during dry periods, ensuring adequate moisture availability for crop growth (Laird, 2008).

Biochar also improves soil chemical properties by increasing pH (in acidic soils), CEC and nutrient availability (Lehmann et al., 2006). In the present study, the calcareous soil with pH 7.76 was already alkaline; however, biochar's high CEC and surface area would have enhanced nutrient retention and reduced

ISSN Online: 3007-3154
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DIALOGUE SOCIAL SCIENCE REVIEW
Vol. 4 No. 6 (June) (2026)

leaching losses. The high concentrations of exchangeable cations (Ca, Mg, K) in biochar would have contributed to improved nutrient availability (Lulu et al., 2020). The significant increase in plant height and tillering observed in biochar-amended treatments can be attributed to improved phosphorus availability, as phosphorus plays a critical role in tiller formation and stem elongation.

The superior performance of biochar over poultry manure in improving growth parameters can be explained by the different characteristics of these amendments. While poultry manure is rich in nutrients and decomposes rapidly, releasing nutrients quickly, its effects are relatively short-lived (Mekuria and Noble, 2013). Biochar, on the other hand, has high stability against decomposition and can stay in soil for longer periods, providing sustained benefits (Lehmann and Joseph, 2009). The high C:N ratio of biochar (65.5) compared to poultry manure (7.72) indicates that biochar would decompose slowly, providing long-term soil improvement, while poultry manure would decompose rapidly, releasing nutrients quickly but with limited residual effects.

The interaction between biochar and mineral phosphorus observed in this study is noteworthy. Biochar with 120 kg P ha^{-1} (T8) consistently outperformed phosphorus alone at the same rate (T4) and poultry manure with phosphorus (T12). This synergistic effect can be attributed to biochar's ability to reduce phosphorus fixation in calcareous soils. In calcareous soils, soluble phosphorus is rapidly fixed by calcium, forming insoluble calcium phosphates (Ryan et al., 1985). Biochar can reduce this fixation through several mechanisms: (1) by providing organic acids that chelate calcium, reducing P fixation; (2) by occupying P sorption sites on soil particles; and (3) by improving soil physical conditions that enhance P diffusion to roots (Cui et al., 2011). The improved phosphorus availability would have enhanced root development, tillering and overall plant growth.

4.2. Effect on Yield and Yield Components

The significant increase in grain yield (69% over control) and biological yield (52% over control) observed in T8 demonstrates the potential of biochar-phosphorus integration for improving wheat productivity in calcareous soils. These findings are consistent with previous studies that reported positive effects of biochar on wheat yield. Lulu et al. (2020) found that biochar (5 t ha^{-1}) produced the highest straw yield, grain yield and total biomass of wheat in southern Ethiopia. Similarly, Haileselassie et al. (2015) reported that mesquite biochar increased grain and straw yields of wheat in Tigray, Ethiopia. Solaiman et al. (2010) showed that wheat grain yield increased by application of oil mallee waste biochar.

The increase in yield can be attributed to improved growth parameters, particularly higher tiller number and grains per spike. The higher tiller number in biochar-amended treatments would have contributed to more spikes per unit area, while the higher grains per spike would have increased the sink capacity. The improved thousand-grain weight in biochar treatments indicates better grain filling, which could be attributed to improved nutrient availability, particularly phosphorus and potassium, during the grain filling period. The significant increase in thousand-grain weight with biochar application (46.2 g in T8 vs. 32.4 g in control) is consistent with findings of Lulu et al. (2020), who reported that biochar and FYM significantly affected thousand seed weight of wheat.

The improvement in grain weight can be attributed to better nutrient availability and improved water relations during grain filling. Potassium, in particular, plays a critical role in grain filling by regulating stomatal conductance and assimilate translocation (Mengel and Kirkby, 2001). The higher K concentration in grain and straw of biochar-amended treatments (Table 6) supports this explanation. The harvest index was relatively less affected by treatments, ranging from 33.6% to 38.4%. This indicates that treatments influenced both grain and straw production proportionally. The slightly higher harvest index in T12 (38.4%) compared to T8 (37.9%) suggests that poultry manure may have promoted relatively more assimilate partitioning to grains compared to biochar. However, the difference was not statistically significant.

4.3. Effect on Nutrient Concentration and Uptake

The significant increase in N, P and K concentrations in both grain and straw of biochar-amended treatments indicates improved nutrient uptake and utilization by wheat. The highest grain N concentration (1.92%) in T8 is within the sufficiency range of 1.8-2.2% reported for wheat (Barrett et al., 2017). The improvement in N concentration can be attributed to several factors. Biochar can reduce N leaching by adsorbing NH_4^+ and NO_3^- ions, thereby increasing N availability to plants (Clough et al., 2013). Biochar can also stimulate microbial activity and N mineralization, increasing the pool of available N (Lehmann et al., 2011). The high C:N ratio of biochar (65.5) may have induced N immobilization initially; however, in the presence of mineral N fertilizer, this effect would have been overcome, and the long-term benefits of improved N retention would have prevailed.

The highest grain P concentration (0.54%) in T8 represents a 145% increase over the control (0.22%). This is consistent with findings of Lulu et al. (2020), who reported that biochar significantly increased P concentration in wheat grain. The improvement in P uptake can be attributed to reduced P fixation in calcareous soils, as discussed earlier. Biochar's high surface area and functional groups can adsorb P, reducing its fixation by calcium and iron oxides (Cui et al., 2011). The organic acids released during biochar decomposition can also chelate calcium, reducing P precipitation (Wang et al., 2015). The improved P availability would have enhanced root development, tillering and grain formation, contributing to the observed yield increase.

The highest grain K concentration (0.72%) in T8 is also consistent with findings of Lulu et al. (2020), who reported that biochar significantly increased K concentration in wheat grain. Biochar is rich in potassium (1.92% in the present study), and its application would have directly contributed to soil K availability. The high CEC of biochar would have also reduced K leaching, ensuring sustained K availability throughout the crop season. Potassium plays a critical role in wheat production by regulating stomatal conductance, photosynthesis and assimilate translocation to grains (Mengel and Kirkby, 2001). The improved K nutrition in biochar-amended treatments would have contributed to the higher thousand-grain weight and grain yield.

The total nutrient uptake data clearly demonstrates the superiority of biochar-phosphorus integration over other treatments. T8 recorded the highest total N, P and K uptake, which is consistent with its highest biomass production and nutrient concentrations. The strong positive correlation between nutrient uptake and grain yield indicates that improved nutrient availability was the primary mechanism behind the yield increase.

4.4. Effect on Phosphorus Use Efficiency

The phosphorus use efficiency (PUE) data revealed interesting patterns. When phosphorus was applied alone, PUE decreased with increasing P rate (from 19.3% at 60 kg P ha^{-1} to 16.7% at 120 kg P ha^{-1}). This is expected, as the efficiency of applied P typically decreases with increasing rate due to the law of diminishing returns and increased P fixation at higher rates. However, when biochar was applied with phosphorus, PUE increased with increasing P rate, reaching a maximum of 32.25% at 120 kg P ha^{-1}. This is a remarkable finding that demonstrates the synergistic effect of biochar in improving P use efficiency.

The improvement in PUE with biochar can be attributed to several mechanisms. Biochar reduces P fixation in calcareous soils by providing alternative sorption sites and releasing organic acids that chelate calcium (Cui et al., 2011). Biochar improves soil physical conditions, enhancing root growth and P diffusion to roots (Laird, 2008). Biochar also improves the biological environment, stimulating P-solubilizing microorganisms that enhance P availability (Lehmann et al., 2011). The high surface area and functional groups of biochar can adsorb P, creating a slow-release P pool that reduces losses and improves P use efficiency (Wang et al., 2015).

The PUE values observed in this study (32.25% in T8) are higher than those reported in many studies, which typically range from 10-30% for cereal crops (Roberts and Johnston, 2015). This indicates that the combination of biochar with phosphorus fertilizer can be an effective strategy for improving P use efficiency in calcareous soils. The economic implications are significant, as improved PUE would reduce the amount of P fertilizer required to achieve target yields, reducing production costs and environmental pollution.

The lower PUE in poultry manure treatments compared to biochar treatments at the same P rate can be explained by the different characteristics of these amendments. Poultry manure decomposes rapidly, releasing P quickly, but much of this P may be fixed in calcareous soils before the crop can utilize it (Agbede et al., 2020). Biochar, on the other hand, provides a slow-release P source and reduces P fixation, resulting in higher PUE.

4.5. Comparative Performance of Biochar and Poultry Manure

Throughout this study, biochar consistently outperformed poultry manure in improving wheat growth, yield and nutrient uptake when combined with mineral phosphorus. This is consistent with findings of Lulu et al. (2020), who reported that biochar had superior effects on wheat growth and yield compared to farmyard manure in southern Ethiopia. Similarly, Ayito et al. (2023) found that biochar application enhanced soil nutrients, crop growth and fruit yields more effectively than organic manure alone.

The superiority of biochar can be attributed to several factors. First, biochar has higher stability against decomposition than poultry manure, providing longer-term benefits (Mekuria and Noble, 2013). Second, biochar has higher surface area and porosity, improving soil physical properties and nutrient retention (Lehmann and Joseph, 2009). Third, biochar is more effective in reducing P fixation in calcareous soils due to its high surface area and functional groups (Cui et al., 2011). Fourth, biochar improves soil biological properties by providing habitat for beneficial microorganisms (Lehmann et al., 2011).

However, it should be noted that poultry manure also made significant

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Vol. 4 No. 6 (June) (2026)

contributions to wheat productivity, particularly in terms of N nutrition. The highest grain N concentration was observed in T8 (1.92%), but T12 (poultry manure with 120 kg P) also produced relatively high grain N (1.58%). Poultry manure's low C:N ratio (7.72) would have resulted in rapid N mineralization, providing readily available N for crop growth (Agbede et al., 2020). This explains why poultry manure treatments generally performed better than phosphorus alone at the same P rate, particularly in terms of N uptake.

The combined application of biochar and poultry manure was not tested in this study, but based on the individual performance of these amendments, such combinations could potentially provide synergistic benefits. Biochar would provide long-term soil improvement and reduce P fixation, while poultry manure would provide readily available nutrients, particularly N. This integrated approach could be particularly beneficial for sustainable wheat production in calcareous soils. Agegnehu et al. (2016) reported that combined application of biochar and compost provided greater benefits for soil quality and crop yield than either amendment alone.

5. Conclusion

The study evaluated the effects of biochar and poultry manure, alone and in combination with graded phosphorus levels, on growth, yield and phosphorus use efficiency of wheat in calcareous soils of Peshawar, Pakistan. The following conclusions can be drawn from the results Application of phosphorus with biochar and poultry manure significantly improved growth parameters, yield attributes and grain yield of wheat compared to the control. The integrated application of 120 kg P ha^{-1} with 10 t biochar ha^{-1} (T8) produced the highest plant height, tiller number, spike length, grains per spike, thousand-grain weight, biological yield and grain yield. Biochar was more effective than poultry manure in improving wheat productivity when combined with mineral phosphorus. The superior performance of biochar was attributed to its high stability, high surface area, ability to reduce phosphorus fixation in calcareous soils and capacity to improve soil physical, chemical and biological properties. The combination of biochar with mineral phosphorus significantly improved phosphorus use efficiency, with T8 recording the highest PUE (32.25%) among all treatments. The improvement in PUE was attributed to reduced P fixation, improved soil physical conditions and enhanced root growth. Biochar application significantly increased the concentrations of N, P and K in both grain and straw, indicating improved nutrient uptake and utilization by wheat. The highest nutrient concentrations and total nutrient uptake were recorded in T8. Poultry manure also contributed to improved wheat productivity, particularly in terms of N nutrition, due to its rapid decomposition and N mineralization. However, its effects were generally lower than biochar at the same phosphorus level. Based on these findings, application of 120 kg P ha^{-1} with 10 t biochar ha^{-1} is recommended for improving wheat productivity and phosphorus use efficiency in the calcareous soils of Peshawar region. This integrated nutrient management approach has the potential to enhance food security, reduce production costs and improve environmental sustainability by reducing P fertilizer requirements. Further multi-season and multi-location trials are recommended to confirm the economic feasibility and long-term soil fertility effects of this treatment. Future research should also investigate the combined application of biochar and poultry manure to explore potential synergistic benefits for wheat production in

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Vol. 4 No. 6 (June) (2026)

calcareous soils.

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DIALOGUE SOCIAL SCIENCE REVIEW

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