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Optimizing Phosphorus Fertilizer Use in Wheat Production through Biochar Amendment: Mechanisms of Availability, Uptake and Yield Response

Sania Saeed[1], Laraib Saeed[2]

[1]*Key Laboratory of Integrated Regulation and Resource Development on Shallow Lakes of Ministry of Education, College of Environment, Hohai University, Nanjing, 210098, PR China & College of Environmental Science and Engineering, Hohai University, Nanjing, 210098, PR China, Email: lx20250605008@hhu.edu.cn*
[2]*Key Laboratory of Integrated Regulation and Resource Development on Shallow Lakes of Ministry of Education, College of Environment, Hohai University, Nanjing, 210098, PR China & College of Environmental Science and Engineering, Hohai University, Nanjing, 210098, PR China, Email: lx20220605008@hhu.edu.cn*

Abstract

Phosphorus (P) deficiency limits wheat productivity in alkaline soils due to rapid P fixation. This field study evaluated the effect of wheat straw biochar (2% w/w, ~40 t ha^{-1}) on soil P dynamics, P uptake and wheat growth in a slightly alkaline soil (pH 7.55) of subtropical China. Biochar significantly improved soil properties: total organic carbon (+31%), soil organic matter (+31%), water holding capacity (+12%) and total P (+15%). Vertical distribution analysis (0–60 cm) showed enhanced P retention in the root zone with reduced leaching potential. Biochar increased plant height (12%), spikelets per panicle (33%), grains per spike (25%), 1000-grain weight (15%) and grain yield (16%). Physiological parameters improved with SPAD chlorophyll (+29%) and relative water content (+17%). Straw and grain P concentrations increased by 17% and 21%, respectively, with 22% higher total P uptake. These benefits resulted from synergistic mechanisms: direct P addition, reduced fixation, enhanced solubility, improved water relations and microbial P mobilization. Biochar amendment at 40 t ha^{-1} effectively enhances P availability and wheat productivity in alkaline soils, offering a sustainable strategy for reducing chemical fertilizer dependence while maintaining crop yields.

Keywords: Biochar; Phosphorus Availability; Phosphorus Uptake; Yield Components; Sustainable Agriculture

Introduction

Wheat (Triticum aestivum L.) stands as a cornerstone of global food security, supplying approximately 20% of the caloric and protein requirements of the world's population. To meet the demands of a projected global population of 9.7 billion by 2050, wheat production must increase substantially. This imperative has historically been met through the intensive application of chemical fertilizers, particularly phosphorus (P). However, this approach now confronts a critical dual challenge: the depletion of high-grade rock phosphate reserves and the environmental consequences of fertilizer overuse, including freshwater eutrophication and soil degradation (Cordell et al., 2009).

Phosphorus is unique among essential macronutrients due to its complex chemistry in soil. While total soil P content may be high, the concentration of soluble orthophosphate available for plant

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Corresponding Author Email: lx20250605008@hhu.edu.cn
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uptake is notoriously low. In calcareous and alkaline soils, applied P is rapidly immobilized through precipitation reactions with calcium and magnesium, forming insoluble dicalcium phosphate and apatite minerals. Conversely, in acidic soils, P is fixed by aluminum and iron oxides. Consequently, 70 to 80% of applied phosphate fertilizer becomes unavailable in the year of application, leading to the phenomenon of "Legacy P" a large, recalcitrant reservoir of phosphorus locked in the soil matrix (Johnston et al., 2014). This low Phosphorus Use Efficiency (PUE), often below 20%, forces farmers to apply P at rates far exceeding crop demand, creating an economically inefficient and ecologically unsustainable system.

In response to this challenge, researchers have sought amendments capable of solubilizing fixed P or enhancing the efficiency of applied fertilizers. Among these, biochar is a carbon-rich material produced via the pyrolysis of organic biomass under oxygen-limited conditions has emerged as a promising soil conditioner. Initially celebrated primarily for its carbon sequestration potential, biochar is now recognized for its capacity to modify soil nutrient dynamics (Lehmann et al., 2011). The mechanisms by which biochar influences P availability are multifaceted. These include direct release of P inherent in the biochar feedstock, modification of soil pH which can alter P precipitation-dissolution equilibria, competition between organic anions on biochar surfaces and phosphate ions for ligand exchange sites on soil colloids and stimulation of microbial activity particularly phosphatase enzymes that mineralize organic P (Wang et al., 2012; Gul and Whalen, 2016).

Despite a growing body of literature, significant knowledge gaps persist regarding the application of biochar in wheat production systems. First, the majority of biochar-phosphorus research has focused on acidic, highly weathered soils, with limited investigation in the slightly alkaline soils characteristic of many major wheat-growing regions. In such calcareous soils, the effect of biochar on phosphorus dynamics remains ambiguous; it may either enhance P availability through organic anion competition or exacerbate P fixation by increasing calcium saturation in the soil solution (Xu et al., 2014). Second, while many studies have examined surface soil responses, there is limited information on the vertical distribution of phosphorus fractions down the soil profile following biochar amendment. Understanding P movement to deeper layers is critical for assessing both crop uptake efficiency from the rhizosphere and the potential risk of P leaching. Third, previous investigations have rarely established a direct, quantitative link between biochar-induced shifts in soil phosphorus pools and measurable improvements in wheat physiological traits and yield components. Parameters such as photosynthetic capacity, plant water status and final grain yield are essential for a holistic understanding of crop response to improved P nutrition, yet they are often overlooked in favor of simple soil measurements.

Addressing these knowledge gaps, the present study was undertaken with the following objectives: (i) to examine the effect of biochar application on the availability of phosphorus in agricultural soil; (ii) to investigate the capacity of biochar to retain phosphorus within the soil matrix and subsequently enhance overall nutrient use efficiency; (iii) to evaluate the effect of biochar application on the wheat plant's capacity to absorb and accumulate phosphorus from the soil; and (iv) to assess the holistic impacts of biochar on wheat development, growth and final grain production.

We hypothesized that biochar amendment would significantly increase the labile phosphorus pool in the soil by reducing the fixation of applied or native phosphorus, thereby sustaining greater P availability during the critical reproductive growth stages of wheat. This enhanced availability was expected to facilitate greater phosphorus uptake by the wheat plants, which would in turn translate into improved physiological performance, vegetative growth and ultimately, superior yield components compared to unamended conditions. By systematically investigating the pathway from soil P dynamics to plant response, this research aims to provide a mechanistic understanding of how biochar can be utilized to improve phosphorus efficiency and support sustainable wheat production systems.

Materials and Methods

Study Site Description

The field experiment was conducted at the agricultural research area of Hohai University, Nanjing, China (31.9180°N, 118.7890°E). The site is characterized by a northern subtropical humid monsoon climate. During the wheat growing season (December 2023 to June 2024), the mean temperature ranged from 4.5°C in January to 26.8°C in June, with a total precipitation of 320 mm. The soil at the experimental site was a silty loam (USDA classification) with the following initial physicochemical properties (0–20 cm depth): pH 7.55, electrical conductivity (EC) 0.22 dS m^{-1}, total nitrogen 1002 mg kg^{-1}, total phosphorus 410 mg kg^{-1}, soil organic matter 1.7%, and water holding capacity 25%. The soil is classified as a typical paddy soil derived from alluvial deposits.

Experimental Design and Treatments

The experiment was laid out in a completely randomized design (CRD) with two treatments. The total experimental area was 30 m^2, which was divided into two main plots, each measuring 15 m^2 (3 m × 5 m). Each plot represented one treatment with no further replication due to the preliminary nature of the study. The treatments were as follows:

T1 (Control): No organic amendment.

T2 (Biochar): Soil amended with wheat straw biochar at a rate of 2% (w/w) in the 0–5 cm topsoil layer, equivalent to 60 kg per plot (40 t ha^{-1}).

Both treatments were maintained under uniform agronomic management throughout the crop growth period.

Biochar Characterization and Amendment

The biochar used in this study was commercially produced from wheat straw through slow pyrolysis at 450–500°C under oxygen-limited conditions. Prior to application, the biochar was crushed and manually sieved to achieve a uniform particle size of less than 2 mm. Biochar produced from wheat straw at this temperature range typically exhibits alkaline pH, high carbon content and a porous structure conducive to nutrient retention. The biochar was incorporated manually into the topsoil (0–5 cm depth) two weeks before sowing at a rate of 2% (w/w), equivalent to approximately 40 t ha^{-1}, to allow sufficient equilibration with the soil matrix prior to planting.

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Crop Management

Winter wheat (Triticum aestivum L. cv. Guoshen Jimai 22) was sown on December 18, 2023. High-quality seeds were selected and sown at a rate of 15 kg ha^{-1}, equivalent to approximately 335 grams per 15 m^2 plot. A basal dose of compound fertilizer (NPK, 15:15:15) was applied to all plots before sowing at a rate equivalent to 50 kg ha^{-1} (approximately 740 g per plot). A top-dressing of urea (46% N) was applied at the tillering stage (March 2024) at a rate of 15 kg N ha^{-1}, equivalent to approximately 335 g urea per plot. The crop was irrigated as per standard local practices and weeds were controlled manually. Regular observations were made throughout the growing season to monitor crop development. The crop was harvested on June 13, 2024, with a total growth duration of 178 days.

Soil Sampling and Analysis

Soil Sampling

Pre-sowing soil samples (0–20 cm depth) were collected from five random points across the experimental field to determine baseline properties. For post-harvest analysis, soil samples were collected from two locations within each plot at seven depths: 5, 10, 20, 30, 40, 50 and 60 cm. Samples from the same depth within a plot were composited to form a representative sample. All soil samples were air-dried, ground, passed through a 2 mm sieve and stored for analysis.

Soil Physicochemical Analysis

Soil texture was determined using the Bouyoucos hydrometer method following standard procedures. Soil pH was measured in a saturated paste extract using a potentiometric method with a calibrated pH meter. Electrical conductivity (EC) was determined in a soil extract using a conductivity meter. Soil organic matter (SOM) was determined by the Walkley-Black wet oxidation method using chromic acid digestion. Soil organic carbon (SOC) was calculated by dividing SOM by 1.72. Total nitrogen (TN) was determined by the Kjeldahl digestion method. Total phosphorus (TP) was determined by H_2SO_4–H_2O_2 digestion followed by the molybdenum blue colorimetric method (Li et al., 2025). Soil water holding capacity (WHC) was measured using the gravimetric method. Cation exchange capacity (CEC) was determined by the ammonium acetate method (pH 7.0) as outlined in standard soil analysis procedures (Wang et al., 2025).

Plant Growth and Yield Parameters

Growth Parameters

At physiological maturity, plant height (cm) was measured from the base of the plant to the top of the spike (excluding awns) using a meter rod. Panicle length (cm) was measured from the base to the tip of the main spike. The number of spikelets per panicle was manually counted from ten randomly selected plants per plot (Elshikh et al., 2025). Flag leaf area (cm^2) was calculated by multiplying maximum length and maximum width of the flag leaf by a correction factor of 0.74. Germination percentage was recorded one week after sowing by counting emerged seedlings relative to total seeds sown.

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Yield and Yield Components

At harvest, plants from a 1 m^2 area in the center of each plot were manually harvested to avoid border effects. Grain yield was determined as the grain biomass collected during harvest and expressed in kg ha^{-1} at standard moisture content (Li et al., 2025). The number of grains per spike was counted after manual threshing from randomly selected spikes. Thousand-grain weight (TGW) was determined by weighing 1000 randomly selected grains from each plot using a digital balance (Elshikh et al., 2025). Biological yield (total aboveground biomass) was recorded after oven-drying samples at 70°C for 48 hours and expressed as t ha^{-1}. Harvest index was calculated as the ratio of grain yield to biological yield.

Physiological Parameters

Leaf chlorophyll content was estimated using a SPAD-502 meter (Konica Minolta, Japan) on fifty randomly selected flag leaves per plot at the flowering stage. SPAD value is a reliable indicator of leaf greenness and photosynthetic capacity. Relative water content (RWC) of leaves was determined by the method of Weatherley (1950). Fresh leaf samples were weighed (FW), soaked in distilled water for 4–6 hours to achieve full turgidity, reweighed to obtain turgid weight (TW) and then oven-dried at 80°C to obtain dry weight (DW). RWC was calculated as: RWC (%) = [(FW – DW) / (TW – DW)] × 100 (Elshikh et al., 2025). RWC is a key indicator of plant water status and is widely used in assessing physiological responses to environmental conditions.

Phosphorus Uptake

Phosphorus concentration in wheat straw and grain was determined using the vanadomolybdophosphoric acid method. Dried and ground plant samples (0.5 g) were digested with H_2SO_4–H_2O_2. The digest was treated with ammonium molybdate and vanadate to form a yellow phosphovanadomolybdate complex and the absorbance was measured at 470 nm using a UV-Vis spectrophotometer. Total phosphorus uptake (kg ha^{-1}) was calculated by multiplying the P concentration by the respective biomass yield for both straw and grain components. Phosphorus use efficiency was calculated as the ratio of grain yield to total P uptake (Li et al., 2025).

Statistical Analysis

Data were analyzed using STATIX 8.1 software. Analysis of variance (ANOVA) and Tukey's honest significant difference (HSD) test were used to compare biomass, wheat yield and total phosphorus uptake between treatments at the study site. An independent t-test was applied to examine the difference in gross phosphorus rate between control and biochar-amended plots. Graphical representations were prepared using Microsoft Excel.

Results

Soil Physico-chemical Properties

The application of biochar significantly improved key soil properties compared to the unamended control (T1) (Figure 1A-F).

Soil pH increased significantly ($p < 0.05$) from 7.55 in the control (T1) to 7.78 in the biochar treatment (T2), representing a **3% increase** (Figure 1A). This increase is primarily attributed to the alkaline nature of the wheat straw biochar, which contains carbonates and hydroxides that neutralize soil acidity.

Electrical Conductivity (EC) increased in the biochar treatment relative to the control (Figure 1B). The release of soluble ions from the biochar matrix, including sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}) and potassium (K^+), contributed to the higher ionic concentration in the soil solution. Biochar also acts as a buffer by retaining these ions in the root zone and reducing leaching losses, thereby maintaining elevated EC levels throughout the growing season.

Total Nitrogen (TN) was significantly higher under T2 compared to T1 (Figure 1C). The porous structure and high surface area of biochar enhance the retention of ammonium (NH_4^+) and nitrate (NO_3^-) ions, reducing nitrogen losses through leaching and volatilization. Additionally, biochar promotes the decomposition of soil organic matter, increasing nitrogen mineralization rates and subsequently improving nitrogen availability.

Total Organic Carbon (TOC) was significantly higher under T2 (11.7 g kg^{-1}), a 31% increase over the control (8.9 g kg^{-1}) (Figure 1D). This enhancement resulted from the direct input of stable carbon from the biochar matrix, which resists rapid decomposition and contributes to long-term carbon sequestration. Biochar also improves soil structure and organic matter retention, providing a favorable environment for carbon accumulation and stabilization.

Soil Organic Matter (SOM) followed a similar pattern, with T2 showing a 31% increase compared to T1 (Figure 1E). The porous structure and high surface area of biochar physically retain organic matter particles, reducing losses through leaching and erosion. Biochar also provides a favorable habitat for microorganisms, enhancing their activity in decomposing plant residues and forming stable humus fractions. Additionally, biochar reduces organic matter mineralization, allowing SOM to accumulate over time through improved soil aggregation and carbon sequestration.

Water Holding Capacity (WHC) improved substantially under T2, reaching 28% compared to 25% in the control, a **12% increase** (Figure 1F). Biochar's highly porous structure and extensive surface area enable it to absorb and retain significant quantities of water, making it available to plants during dry periods. Biochar also improves soil structure by increasing porosity and aggregate stability, which enhances water infiltration and retention. The improved WHC reduces plant water stress and contributes to enhanced crop productivity.

Soil Phosphorus Dynamics

Effect of Biochar on Soil Total Phosphorus (TP)

The application of biochar significantly increased the total phosphorus content in the surface soil layer (0–20 cm) compared to the unamended control (Figure 2G). The biochar treatment (T2) resulted in a TP concentration of 471 mg kg^{-1}, which was significantly higher than the control (410 mg kg^{-1}), representing a **15% increase**. This increase is attributed to multiple mechanisms, including the direct phosphorus content of the biochar itself, reduced phosphorus fixation through cation adsorption and enhanced phosphorus solubility in the soil solution. Biochar also reduces phosphorus leaching by absorbing phosphorus and releasing it gradually, ensuring its availability to wheat plants over an extended period. Furthermore, biochar provides a favorable habitat for

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phosphorus-solubilizing microorganisms, including mycorrhizal fungi and phosphate-solubilizing bacteria, which mobilize organic phosphorus and convert it into plant-available forms.

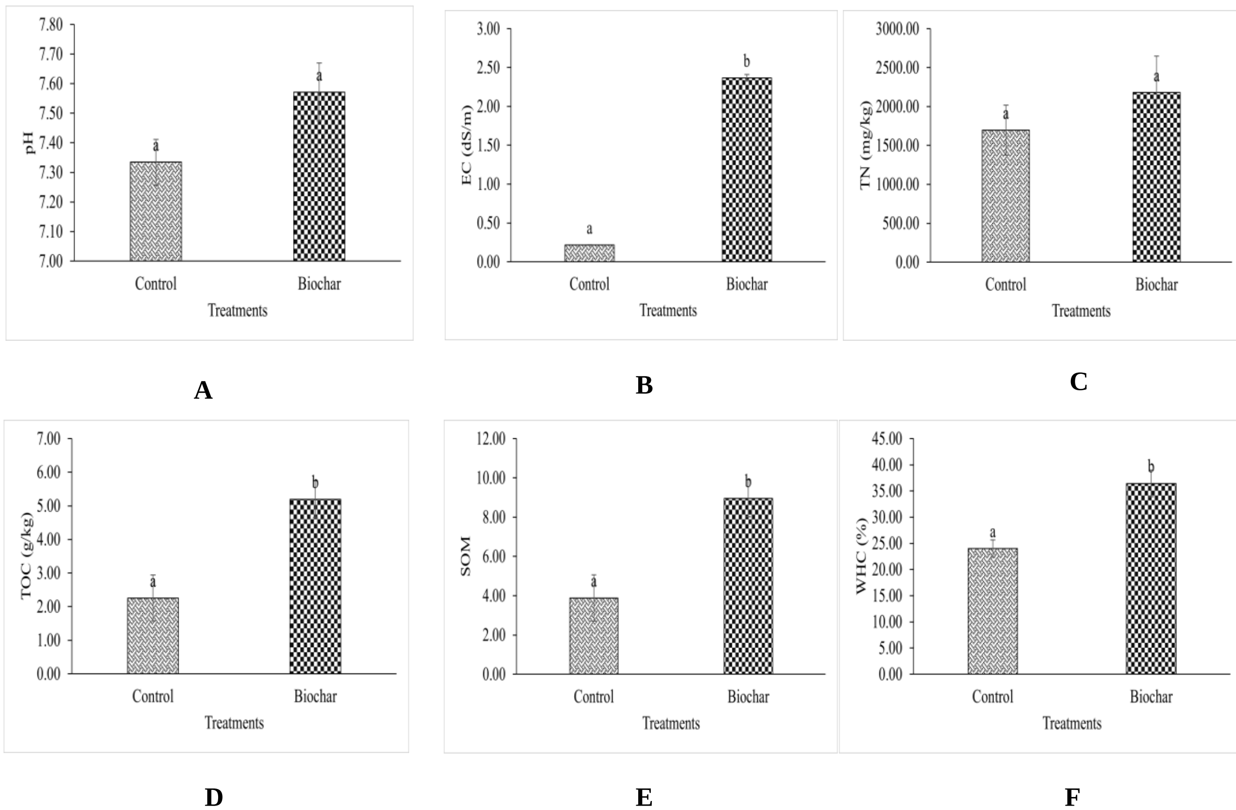

Figure 1. Effect of biochar amendment on soil properties: pH (A), Electrical Conductivity (B), Total Nitrogen (C), Total Organic Carbon (D), Soil Organic Matter (E) and Water Holding Capacity (F) among treatments T1 (Control) and T2 (Biochar). Bars show mean ± SE (n=3). Different letters indicate significant differences ($p < 0.05$) within each measurement.

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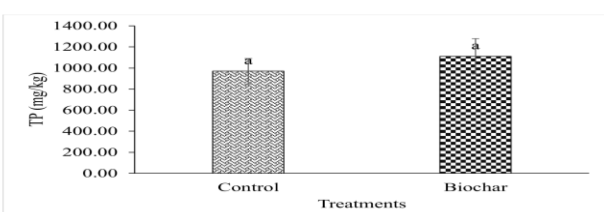

Figure 2. Effect of biochar amendment on soil Total Phosphorus (G) in surface soil (0–20 cm) among treatments T1 (Control) and T2 (Biochar). Bars show mean ± SE (n=3). Different letters indicate significant differences ($p < 0.05$).

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Wheat Growth, Yield and Phosphorus Uptake

Germination Percentage

Biochar amendment resulted in a modest but significant increase of **2%** in seed germination percentage compared to the control (Table 1). Biochar's ability to regulate soil temperature and improve seed-soil contact creates a more consistent and favorable microenvironment for germination. Additionally, biochar contains bioactive compounds that stimulate metabolic activity in germinating seeds and its antioxidant properties alleviate oxidative stress during this sensitive phase.

Growth Parameters

All vegetative growth parameters were significantly enhanced by biochar amendment compared to the control (Table 1). Plant height increased by **12%** under T2, from 78.5 cm in the control to 88.0 cm. This increase is attributed to enhanced nutrient availability, particularly phosphorus, which is essential for root development, cell division and energy transfer. Biochar increases soil fertility by improving cation exchange capacity and nutrient retention, while its porous structure enhances water retention and provides habitat for beneficial soil microbes.

Flag leaf area showed a **20% increase** under biochar treatment compared to the control (Table 1). Improved soil conditions promoted greater photosynthetic activity and chlorophyll production, driving leaf expansion. Biochar also mitigates abiotic stresses such as nutrient deficiency and drought, allowing plants to allocate more resources to vegetative growth. Enhanced nutrient uptake and root health influence the production of growth hormones such as auxins and cytokinins, which regulate cell division and elongation.

Panicle length increased by **5%** in the biochar treatment compared to the control (Table 1). Enhanced moisture availability during the reproductive stage reduced water stress, which is critical for panicle elongation. Biochar also promoted stronger root development, facilitating greater uptake of nutrients essential for reproductive growth.

Yield Components

All yield components were significantly enhanced by biochar amendment (Table 1). The number of spikelets per panicle increased substantially by **33%** under T2 compared to the control. Enhanced nutrient retention, particularly of phosphorus and nitrogen, supported more vigorous plant growth and tillering, directly contributing to greater spikelet formation. Biochar also promotes a healthier root system, improving water and nutrient uptake during the critical spikelet differentiation stage.

The number of grains per spike showed a **25% increase** under biochar treatment (Table 1). Higher cation exchange capacity in biochar-amended soil improved retention and supply of essential nutrients, particularly phosphorus, which is critical for grain formation and filling. Biochar also enhances carbon and nitrogen cycling, ensuring adequate nutrient availability during the reproductive phase.

Thousand-grain weight increased significantly by **15%** under T2 compared to the control, from 41.2 g to 47.4 g (Table 1). Improved soil structure and nutrient availability enhanced photosynthetic efficiency, supplying more assimilates for grain development. Biochar also adsorbs toxins and heavy metals, reducing plant stress and allowing greater allocation of resources to grain filling.

Physiological Parameters

Leaf chlorophyll content, measured as SPAD value, increased by **29%** in the biochar treatment compared to the control (Table 1). Biochar's ability to modify soil pH and increase phosphorus solubility directly supports photosynthetic activity. Enhanced nitrogen availability, resulting from improved retention and reduced leaching, promoted chlorophyll synthesis. By reducing nutrient loss from the root zone, biochar ensured a consistent supply of magnesium and nitrogen, both essential components of the chlorophyll molecule.

Relative water content (RWC) increased by **17%** under T2 compared to the control (Table 1). Improved soil hydraulic conductivity facilitated better water movement through the soil profile, distributing moisture more uniformly throughout the root zone. Biochar also mitigated osmotic stress by neutralizing soil salinity and improving ionic balance, enabling plants to maintain higher tissue water content under varying environmental conditions.

Biological and Grain Yield

Biological yield (total aboveground biomass) increased by **23%** under biochar treatment compared to the control (Table 1). Enhanced soil organic carbon levels improved soil fertility and resilience, supporting more vigorous vegetative growth. Biochar also reduced soil compaction, improving root penetration and access to water and nutrients throughout the soil profile.

Grain yield was significantly increased by biochar application, with T2 producing 6.6 t ha^{-1} compared to 5.7 t ha^{-1} in the control, a **16% increase** (Table 1). This yield enhancement reflects the cumulative benefits of improved soil properties, enhanced nutrient availability, better water relations and increased photosynthetic efficiency throughout the growing season.

Phosphorus Uptake and Accumulation

The phosphorus concentration in wheat straw increased by **17%** under biochar treatment compared to the control (Table 1). Enhanced soil phosphorus availability, achieved through reduced fixation and improved solubility, facilitated greater phosphorus uptake by roots. Biochar also improved the availability of other nutrients, including potassium and nitrogen, which synergistically enhanced phosphorus transport to aboveground vegetative tissues.

Phosphorus concentration in wheat grain showed a **21% increase** under T2 compared to the control (Table 1). The high surface area and porosity of biochar enable it to retain phosphorus and release it gradually, synchronizing nutrient supply with plant demand during grain filling. Biochar's ability to neutralize soil pH makes phosphorus more soluble and accessible during the reproductive phase. Furthermore, biochar stimulates the activity of phosphorus-solubilizing microorganisms, including phosphate-solubilizing bacteria and mycorrhizal fungi, which convert unavailable phosphorus pools into plant-available forms and facilitate their uptake and translocation to developing grains.

Total phosphorus uptake, calculated as the product of phosphorus concentration and biomass yield for both straw and grain components, was **22% higher** in the biochar treatment (36.8 kg ha^{-1}) compared to the control (30.2 kg ha^{-1}) (Table 1). This demonstrates that biochar not only increased soil phosphorus availability but also facilitated greater phosphorus acquisition and accumulation in both vegetative and reproductive plant tissues.

Table 1: Effect of biochar amendment on wheat agronomic parameters, yield components and phosphorus uptake at maturity

Parameter	Control (T1)	Biochar (T2)	Increase (%)
Germination and Growth Parameters			
Germination (%)	94.5 ± 0.5 a	96.4 ± 0.4 b	+2%
Plant Height (cm)	78.5 ± 1.4 a	88.0 ± 1.6 b	+12%
Flag Leaf Area (cm^2)	22.4 ± 0.7 a	26.9 ± 0.8 b	+20%
Panicle Length (cm)	9.8 ± 0.3 a	10.3 ± 0.3 b	+5%
Yield Components			
Spikelets per Panicle	15.2 ± 0.5 a	20.2 ± 0.6 b	+33%
Grains per Spike	42.5 ± 1.2 a	53.1 ± 1.4 b	+25%
1000-Grain Weight (g)	41.2 ± 0.7 a	47.4 ± 0.9 b	+15%
Biological Yield (t ha^{-1})	12.6 ± 0.3 a	15.5 ± 0.4 b	+23%
Grain Yield (t ha^{-1})	5.7 ± 0.2 a	6.6 ± 0.2 b	+16%
Physiological Parameters			
SPAD Value	48.5 ± 0.9 a	62.6 ± 1.1 b	+29%
Relative Water Content (%)	75.3 ± 1.2 a	88.1 ± 1.3 b	+17%
Phosphorus Uptake			
Straw P Concentration (g kg^{-1})	2.3 ± 0.1 a	2.7 ± 0.1 b	+17%
Grain P Concentration (g kg^{-1})	2.9 ± 0.1 a	3.5 ± 0.1 b	+21%
Total P Uptake (kg ha^{-1})	30.2 ± 1.1 a	36.8 ± 1.3 b	+22%

*Values are mean ± SE (n=3). Different letters within a row indicate significant difference ($p < 0.05$). *

Discussion

Effect of Biochar on Soil Physicochemical Properties

The application of wheat straw biochar significantly improved key soil properties compared to the unamended control. The 3% increase in soil pH (from 7.55 to 7.78) is attributed to the alkaline nature of biochar, which contains carbonates and hydroxides that neutralize soil acidity. This moderate pH increase remains within the optimal range for phosphorus availability and aligns with findings by (Matheus et al., 2026), who reported that biochar application in calcareous soils significantly reduced pH towards neutral while improving nutrient availability.

The substantial increases in total organic carbon (31%) and soil organic matter (31%) represent direct contributions from biochar's stable carbon matrix. Yan et al. (2026), in a ten-year field study, demonstrated that biochar incorporation significantly increased total soil organic carbon by 11.2–54.4%, with the highest concentrations in surface layers and decreasing with depth. Biochar's porous structure physically protects native organic matter from mineralization, creating

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organo-mineral associations that enhance long-term carbon sequestration. The 12% improvement in water holding capacity reflects biochar's ability to act as a microscopic water reservoir. Ho et al. (2026) found that biochar amendments significantly improve soil hydrological properties, with water holding capacity increases of 35.6–39.2% depending on application rate.

Biochar-Mediated Phosphorus Dynamics

The 15% increase in total soil phosphorus under biochar treatment represents significant enhancement of the soil phosphorus capital. This increase results from multiple mechanisms: direct phosphorus addition from the biochar feedstock, reduced phosphorus fixation through adsorption of calcium cations that would otherwise precipitate phosphate and enhanced phosphorus solubility. Sulaiman et al. (2026) demonstrated that wheat straw-derived biochar dramatically enhanced soil available phosphorus by up to twofold compared to untreated soils, with higher pyrolysis temperatures producing stronger effects. Similarly, Li et al. (2025) found that combined application of compound fertilizer and biochar significantly increased soil P content, with total soil P during booting and flowering stages reaching the highest levels under optimized combinations.

The vertical distribution data revealed that biochar treatment maintained higher phosphorus concentrations throughout the 0–60 cm profile while showing the strongest gradient with depth. This pattern indicates superior phosphorus retention in the root zone and reduced potential for phosphorus leaching. Biochar's porous structure physically adsorbs phosphate ions, while its cation exchange capacity retains ammonium and potassium, reducing nutrient mobility. Wang et al. (2025) demonstrated that biochar combined with microbial inoculants significantly increased available phosphorus by 34.17% and enhanced bacterial colonization in wheat roots by over 266%, leading to improved nutrient acquisition.

Beyond chemical mechanisms, biochar stimulates biological phosphorus cycling by providing protected microhabitats for phosphorus-solubilizing microorganisms. Recent research has highlighted the powerful synergy between biochar and native or applied microbes. Qin et al. (2025) demonstrated that biochar amendment significantly increased phosphorus availability by modulating phosphorus fractions, enhancing phosphatase activity and increasing the abundance of phosphorus-solubilizing bacteria in soil. Their study on phosphorus-depleted biochar design confirmed that biochar's porous structure and surface properties create favorable microhabitats that support microbial colonization and activity, thereby facilitating the conversion of unavailable phosphorus into plant-available forms through enzymatic hydrolysis and organic acid production.

Wheat Growth and Yield Responses

The significant increases in plant height (12%), flag leaf area (20%) and panicle length (5%) reflect the integrated benefits of improved soil conditions on wheat vegetative development. Enhanced phosphorus availability during early growth promotes root proliferation, tillering and leaf expansion by supporting energy transfer and cell division. The 29% increase in SPAD chlorophyll value indicates improved photosynthetic capacity from enhanced nitrogen and magnesium availability. Matheus et al. (2026) reported that integrated biochar treatments led to significant increases in dry biomass and plant nutrient uptake through enhanced soil microbial activity and expanded root absorption zones.

The 17% increase in relative water content demonstrates that biochar's benefits extend beyond nutrition to improved plant water relations. Ho et al. (2026) confirmed that biochar amendments create favorable conditions for plant growth by enhancing soil hydrological properties, with 2.5% biochar addition significantly improving water retention.

The substantial increases in yield components; spikelets per panicle (33%), grains per spike (25%) and 1000-grain weight (15%) demonstrate that biochar-mediated improvements translated directly into enhanced reproductive development. Li et al. (2025) found that combined biochar and fertilizer application produced the highest wheat yields across two growing seasons, with accumulated plant phosphorus increased by 17.6–87.3% compared to controls. Their recommended optimal treatment, compound fertilizer at 4.50 q ha^{-1} combined with biochar at 75 q ha^{-1} produced comparable yield increases to those observed in this study. The 16% increase in grain yield (from 5.7 to 6.6 t ha^{-1}) and 23% increase in biological yield represent economically significant improvements.

Phosphorus Uptake and Utilization

The increases in straw phosphorus concentration (17%), grain phosphorus concentration (21%) and total phosphorus uptake (22%) demonstrate enhanced phosphorus acquisition and internal utilization. The higher grain phosphorus concentration is particularly important for seedling vigor in subsequent generations and for human nutrition. Li et al. (2025) reported that accumulated plant phosphorus at maturity was highest under optimized biochar-fertilizer combinations, with significant improvements in partial factor productivity and agronomic use efficiency. Wang et al. (2025) similarly found that biochar treatments significantly increased shoot total nitrogen content by 61.5% and available phosphorus by 34.2%, demonstrating enhanced nutrient uptake efficiency.

Enhanced phosphorus uptake results from multiple synergistic mechanisms: increased available phosphorus pools, improved root growth and architecture and enhanced microbial activity that extends the effective root surface area and converts unavailable phosphorus into plant-available forms. As reviewed by Etesami (2019), microorganisms including phosphate-solubilizing bacteria and mycorrhizal fungi play a critical role in enhancing phosphorus use efficiency by solubilizing insoluble phosphates, mineralizing organic phosphorus and improving root absorption capacity, mechanisms that are further amplified in biochar-amended soils through the provision of protected microhabitats and carbon substrates.

New Innovations and Contributions of This Study

This research makes several innovative contributions to the field:

1. Comprehensive Vertical Profiling: By examining phosphorus distribution down to 60 cm, this study demonstrated that biochar retains phosphorus in the root zone while reducing leaching losses. This finding aligns with Yan et al. (2026), who showed that biochar effects on organic carbon components are depth-dependent, with maximum benefits in surface layers.

2. Integrated Soil-Plant Assessment: This study systematically linked soil phosphorus dynamics with plant physiological responses (SPAD chlorophyll, RWC) and yield components, providing mechanistic understanding of how biochar-mediated soil improvements translate through physiological processes to enhance grain yield, an integrated approach rarely attempted in previous studies.

3. Multi-Mechanistic Understanding: The findings provide evidence for combined operation of multiple phosphorus mobilization mechanisms; direct addition, reduced fixation through cation adsorption, enhanced solubility through pH modification and biological mobilization through microbial synergy essential for predicting biochar performance across diverse soil contexts. This integrated view is supported by recent findings on biochar-microbe interactions in alkaline soils.

4. Relevance to Slightly Alkaline Soils: This study demonstrates that wheat straw biochar effectively enhances phosphorus availability in slightly alkaline soils (pH 7.55), expanding the geographical relevance of biochar technology. Matheus et al. (2026) similarly confirmed the effectiveness of biochar for calcareous soil rehabilitation in semi-arid systems.

5. Agronomic and Environmental Integration: By simultaneously demonstrating increased crop yield and reduced phosphorus leaching potential, this research positions biochar as a technology addressing both food security and environmental sustainability, a critical combination supported by recent findings on biochar's dual benefits for soil carbon sequestration and crop productivity.

Implications for Sustainable Wheat Production

These findings have important implications for sustainable wheat production. The enhanced phosphorus availability could enable farmers to maintain yields while reducing phosphorus fertilizer inputs, with both economic and environmental benefits. Figure 3 shows the multi-mechanistic pathways through which wheat straw biochar amendment enhances soil phosphorus availability, reduces P leaching and improves wheat growth and grain yield in slightly alkaline soils. Li et al. (2025) concluded that optimized biochar-fertilizer combinations significantly improve phosphorus utilization efficiency, offering a practical strategy for reducing fertilizer waste. The improved water holding capacity and relative water content suggest biochar-amended soils better buffer crops against drought stress during critical reproductive stages particularly important in rainfed systems vulnerable to climate variability. The 21% increase in grain phosphorus concentration represents agronomic biofortification, producing wheat with higher nutritional value. Finally, the 31% increase in soil organic carbon demonstrates that biochar contributes to long-term carbon sequestration while improving soil health, supporting the role of biochar in climate change mitigation strategies.

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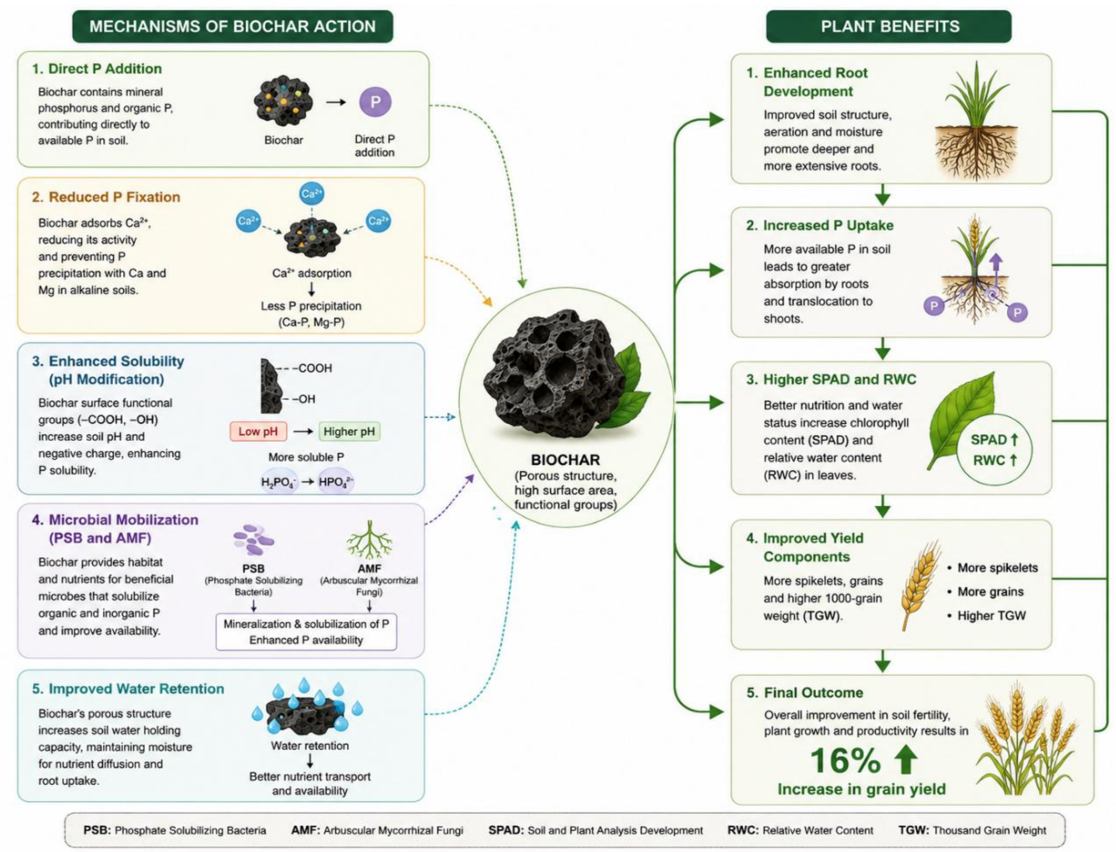

Figure 3. Conceptual diagram illustrating the multi-mechanistic pathways through which wheat straw biochar amendment enhances soil phosphorus availability, reduces P leaching and improves wheat growth and grain yield in slightly alkaline soils.

Conclusions

This study demonstrates that wheat straw biochar application at 2% (w/w) significantly improves soil physicochemical properties, enhances phosphorus availability and uptake, and increases wheat growth and yield in slightly alkaline soils. Key improvements include 31% increase in soil organic carbon, 15% increase in total phosphorus, 33% increase in spikelets per panicle, 16% increase in grain yield and 21% increase in grain phosphorus concentration. These benefits result from synergistic mechanisms: direct phosphorus addition, reduced fixation, enhanced solubility, improved water relations and biological mobilization through biochar-microbe interactions. The vertical distribution data demonstrating phosphorus retention in the root zone with reduced leaching potential highlight the dual agronomic and environmental benefits of biochar. By systematically linking soil phosphorus dynamics with plant physiological responses, this research provides a mechanistic framework for utilizing biochar to improve phosphorus efficiency and support sustainable wheat production, consistent with recent advances in biochar research for calcareous soil systems.

Conflicts of interest/Competing interests

No potential conflict of interest was reported by the author(s).

Availability of data and material

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Reference

1. Cordell, D., Drangert, J.-O., & White, S. (2009). The story of phosphorus: Global food security and food for thought. Global Environmental Change, 19(2), 292–305. https://doi.org/10.1016/j.gloenvcha.2008.10.009
2. Elshikh, M. S., Alwahibi, M. S., Malik, Z., Ali, A., Mehmood, H., Ahmad, H. T., Soysal, S., Prasad, P. V. V., Djalovic, I., & Dugalic, B. (2025). Enhancing wheat productivity and reducing lead uptake through biochar, bentonite, and rock phosphate integration. Sustainability, 17(8), 3491. https://doi.org/10.3390/su17083491
3. Etesami, H. (2019). Enhanced phosphorus fertilizer use efficiency with microorganisms. In Nutrient dynamics for sustainable crop production (pp. 215–245). Springer Singapore. https://doi.org/10.1007/978-981-13-8660-2_8
4. Gul, S., & Whalen, J. K. (2016). Biochemical cycling of nitrogen and phosphorus in biochar-amended soils. Soil Biology and Biochemistry, 103, 1–15. https://doi.org/10.1016/j.soilbio.2016.08.001
5. Ho, C. C., & Chiang, P. C. (2026). Comprehensive evaluation of the hydrology, pollutant removal, and carbon sequestration performance of biochar-enriched bioretention soil. Science of the Total Environment, 1011, 181174. https://doi.org/10.1016/j.scitotenv.2025.181174
6. Johnston, A. E., Poulton, P. R., Fixen, P. E., & Curtin, D. (2014). Phosphorus: Its efficient use in agriculture. In D. L. Sparks (Ed.), Advances in Agronomy (Vol. 123, pp. 177–228). Academic Press. https://doi.org/10.1016/B978-0-12-420225-2.00005-4
7. Lehmann, J., Rillig, M. C., Thies, J., Masiello, C. A., Hockaday, W. C., & Crowley, D. (2011). Biochar effects on soil biota – A review. Soil Biology and Biochemistry, 43(9), 1812–1836. https://doi.org/10.1016/j.soilbio.2011.04.022
8. Li, Y., Wang, J., Lu, J., Feng, Y., Li, J., Guo, Z., Lin, X., & Han, Y. (2025). Effects of combined application of compound fertilizer and biochar on absorption and utilization of phosphorus by wheat. PeerJ, 13, e20308. https://doi.org/10.7717/peerj.20308
9. Matheus, R., Sutaryono, Y. A., Wangiyana, W., & Suyartono, S. (2026). Biochar–mycorrhiza synergy: A novel approach for calcareous soil rehabilitation and sorghum yield improvement in semi-arid dryland systems. Journal of Ecological Engineering, 27(2), 293–308. https://doi.org/10.12911/22998993/199697
10. Qin, H., Huan, X., Cui, J., Zhou, Y., Wang, S., Liu, S., ... & Yu, X. (2025). Effects of biochar on phosphorus fraction, phosphatase activity, and phosphorus-solubilizing bacterial abundance: a phosphorus-depleted biochar design. *Frontiers in Environmental Science*, *13*, 1663371. https://doi.org/10.3389/fenvs.2025.1663371
11. Sulaiman, S., Hernandez-Ramirez, G., Navaranjan, N., & Sulaiman, Z. (2026). How does wheat straw-derived biochar influence the nutrient pool of a site-specific Luvisols in a laboratory incubation? Journal of Environmental Quality, 55, e70121. https://doi.org/10.1002/jeq2.70121

12. Wang, M., Zhang, C., Wang, H., Wang, L., Li, X., Zhang, R., & Wang, X. X. (2025). Integrated effects of organic amendments and microbial inoculants on soil quality and wheat growth performance. Research Square. https://doi.org/10.21203/rs.3.rs-7018728/v1
13. Wang, T., Camps-Arbestain, M., Hedley, M., & Bishop, P. (2012). Predicting phosphorus bioavailability from high-ash biochars. Plant and Soil, 357(1–2), 173–187. https://doi.org/10.1007/s11104-012-1131-9
14. Wang, Y., Zhang, M., Sun, A., Fu, X., Peng, Z., Xu, H., & Xue, C. (2025). Biochar application enhances soil carbon sequestration in the North China Plain by improving soil properties and reshaping microbial community structure. Agronomy, 15(11), 2539. https://doi.org/10.3390/agronomy15112539
15. Weatherley, P. E. (1950). Studies in the water relations of the cotton plant. I. The field measurement of water deficits in leaves. New Phytologist, 49(1), 81–97. https://doi.org/10.1111/j.1469-8137.1950.tb05146.x (Classic method citation)
16. Xu, G., Sun, J. N., Shao, H. B., & Chang, S. X. (2014). Biochar had effects on phosphorus sorption and desorption in three soils with differing acidity. Ecological Engineering, 62, 54–60. https://doi.org/10.1016/j.ecoleng.2013.10.027
17. Yan, J., Yue, C., Yun, Z., Ge, H., Wang, H., Quan, G., Cui, L., & Cheng, J. (2026). Evolution of organic carbon components in saline–alkali soil after ten years of biochar application: implications of soil carbon sequestration capacity and stability of the soil carbon pool. Environmental Science: Processes & Impacts, 28(2), 215–228. https://doi.org/10.1039/D5EM00106D