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Effects of Phosphorus-Enriched Biochar on the Growth and Phosphorus (P) Uptake of Iceberg Lettuce

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Abstract

The aim of the present study is to evaluate the effects of phosphorus-enriched biochar on growth and phosphorus uptake of iceberg lettuce (*Lactuca sativa* L.). Hazelnut husk biochar (FZB) was combined with triple superphosphate (TSP) and KH_2PO_4 as phosphorus sources and applied at four different rates of 0, 3, 6, and 12 kg P_2O_5 da^{-1} in a randomized block design with three replications. Analysis of variance revealed significant effects of phosphorus source, application rate, and their interaction on plant dry matter and phosphorus uptake, with a significance level of p<0.05. Lettuce treated with KH_2PO_4-enriched biochar showed a dose-dependent increase in dry matter, reaching 44.7 g per plant at the highest application rate of 12 kg P_2O_5 da^{-1}, corresponding to approximately 80% higher than the control. P uptake also increased substantially under KH_2PO_4 treatments, attaining a maximum of 154.7 mg plant^{-1},while TSP-enriched biochar resulted in only modest increases in dry matter and phosphorus uptake, reaching 28.2 g per plant and 82.7 mg plant^{-1}, respectively. These findings suggest that biochar acts as an effective carrier for phosphorus fertilizers, enhancing nutrient use efficiency and improving crop performance. Overall, KH_2PO_4-enriched biochar shows strong potential to increase phosphorus availability, stimulate biomass production, and support sustainable fertilization strategies in vegetable cultivation.

Keywords: biocoal, organic waste, phosphorus fertilisation, P use efficiency

Fosforla Zenginleştirilmiş Biyoçarın Iceberg Marulun Gelişimi ve Fosfor (P) Alımı Üzerine Etkileri

Öz

Bu çalışmanın amacı fosfor ile zenginleştirilmiş biyoçar'ın iceberg marulun (*Lactuca sativa* L.) gelişimi ve P alınımı üzerine etkilerini değerlendirmektir. Fındık zurufu biyoçarı (FZB), fosfor kaynağı olarak triple süper fosfat (TSP) ve KH_2PO_4 ile kombine edilerek 0, 3, 6 ve 12 kg P_2O_5 da^{-1} dozlarında, üç tekerrürlü tesadüf blokları deneme desenine göre uygulanmıştır. Varyans analizi, fosfor kaynağı, uygulama dozu ve bunların etkileşiminin bitki kuru maddesi ve fosfor alımı üzerinde istatistiksel olarak anlamlı etkileri olduğunu (p<0.05) göstermiştir. KH_2PO_4 ile zenginleştirilmiş biyoçar uygulanan marulda doz artışına bağlı olarak kuru madde miktarında belirgin bir artış gözlenmiş ve en yüksek doz olan 12 kg P_2O_5 da^{-1}'de bitki başına 44.7 g kuru maddeye ulaşılmış, bu değer kontrol grubuna kıyasla yaklaşık %80 artış göstermiştir. Toplam fosfor alımı da KH_2PO_4 uygulamalarında belirgin şekilde artmış ve maksimum 154.7 mg bitki^{-1} değerine ulaşmıştır. Buna karşın TSP ile zenginleştirilmiş biyoçar uygulamaları, kuru madde ve fosfor alımında sınırlı artış göstermiş, sırasıyla 28.2 g ve 82.7 mg bitki^{-1} değerlerine ulaşmıştır. Bu bulgular, biyoçarın fosfor gübreleri için etkili bir taşıyıcı olduğunu, besin kullanım verimliliğini artırdığını ve bitki verimliliğini desteklediğini göstermektedir. Genel olarak, KH_2PO_4 ile zenginleştirilmiş biyoçar, fosfor kullanılabilirliğini artırma, biyokütle üretimini teşvik etme ve sebze yetiştiriciliğinde sürdürülebilir gübreleme stratejilerini destekleme potansiyeli taşımaktadır.

Anahtar Kelimeler: biyokömür, organik atıklar, P'lu gübreleme, P kullanım etkinliği

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Introduction

Global projections estimate that the world population will reach 9.7 billion by 2050, and this increasing population is expected to raise industrial demands and agricultural food requirements by approximately 70% (Raghavan, 2025). In recent years, environmental pollution has accelerated due to uncontrolled population growth, intensified industrial activities, improved living standards, technological developments, and indiscriminate use of chemical substances and agricultural practices, becoming a critical global issue requiring urgent solutions. Among these environmental challenges, global warming, land degradation, and heavy metal contamination notably constrain human living standards (Korkmaz, 2007). Agriculture, while being one of the economic sectors most vulnerable to climate change, also contributes significantly to it (Tubiello et al., 2021). It is reported that greenhouse gas (GHG) emissions from food systems constitute 39% of the global anthropogenic total, and 75% of these emissions originate from agricultural activities (Mohammed et al., 2021). Considering increasing population, rising food demand, and climate change, ensuring food security represents one of the major challenges facing human societies (Fróna et al., 2019). Therefore, enhancing yield per unit area is crucial for meeting the food needs of the growing population. Fertilization is one of the primary strategies for increasing yield per unit area; however, uncontrolled fertilizer use causes serious environmental problems (Kılıç & Korkmaz, 2012).

Increasing environmental concerns have prompted research into more sustainable approaches in crop production, aiming to reduce chemical fertilizer use. In this context, replacing chemical fertilizers, which are among the most significant pollutants after detergents, with organic materials can be a crucial strategy. Globally, the quantity of organic wastes with various forms and properties continues to rise. According to the Turkish Biomass Potential Atlas (BEPA), approximately 62.5 million tons of plant-derived waste will be generated annually in Turkey by 2025 (Anonymous, 2025). Improper disposal or lack of necessary precautions for these wastes can lead to air pollution, visual pollution, proliferation of pests and pathogens, and other issues adversely affecting human and environmental health. Utilizing these wastes through environmentally friendly approaches and incorporating them into soils can improve soil physical, chemical, and biological properties depending on the type and chemical characteristics of the waste, while enhancing soil fertility. However, recent studies indicate that even when these organic wastes undergo composting or other fermentation processes, significant amounts of greenhouse gases are released into the atmosphere due to decomposition (Korkmaz, 2007). Similarly, burning agricultural residues releases large quantities of carbon, contributing substantially to global warming. Therefore, applying more stable organic materials that remain in soils for longer periods and are less prone to decomposition can provide an effective solution for reducing carbon emissions from agricultural residues. When organic materials are incorporated into soils, they rapidly decompose with the help of microorganisms, releasing CO_2 as one of the main decomposition products, which contributes to global warming. Maintaining and stabilizing existing soil organic carbon is critical both for sustaining soil fertility and preventing emissions of greenhouse gases. Biochar applications are considered among the most suitable organic materials for this purpose (Vanini et al., 2021). Biochar is inexpensive, environmentally friendly, and has been studied for various applications, including soil improvement, waste management, GHG mitigation, and energy production (Cha et al., 2016). Moreover, biochar possesses several heavy metal immobilization properties due to its microporous structure, active functional groups, high pH, and cation exchange capacity (Chen & Lin, 2001).

Biochar, also referred to as “biocoal” is produced by pyrolyzing plant residues, wood, and similar organic biomasses in oxygen-limited or anaerobic conditions (<700°C) (Akkurt et al., 2020). During pyrolysis, the carbohydrate structures of biomass convert to carbon, forming organic matter that remains in soil for an estimated 1.300–4.000 years. Its porous structure, with surface area up to 500 m^2 g^{-1}, enhances water retention and cation exchange capacity, thereby increasing nutrient availability in soils (Tan et al., 2017). Fryda and Visser (2015) describe biochar as a long-term carbon sequestration technology aimed at mitigating climate change. Technology contributes to reducing greenhouse gas emissions by retaining carbon, offering a significant strategy to mitigate climate change (Cui et al., 2011; Lehmann et al., 2006). Applying biochar to soil is crucial for improving soil health and quality, mitigating pollution, increasing water retention, and retaining carbon due to its recalcitrant properties (Mukherjee & Lal, 2013; Abbas et al., 2018). Targeted biochar applications can enhance soil physical properties (Agbede et al., 2020), reduce limitations to soil fertility (Acir & Erdem, 2020), stimulate biological processes (Wang et al., 2015), and thereby improve crop performance. Beyond environmental benefits, biochar can serve as a nutrient carrier for fertilizer matrices due to its high porosity and functional surface groups, particularly when modified or enriched (Barbosa et al., 2022; Pogorzelski et al., 2020).

Phosphorus (P) is the second most limiting nutrient after nitrogen in agricultural systems, playing a crucial role in plant development. It is a key component of DNA, RNA, ATP, and phospholipids and is essential for life globally. Plants absorb phosphorus primarily as $H_2PO_4^-$ and HPO_4^{2-} ions (Korkmaz et al., 2021). Chemically, P is highly stable; fertilizers rapidly react with soil, limiting mobility and availability (İbrikci et al., 2005; Korkmaz et al., 2009). In acidic soils, P binds with Fe and Al oxides, while in alkaline soils, it forms insoluble complexes with Ca and carbonates, rendering 80–85% unavailable to plants (Korkmaz & İbrikci, 2010). Worldwide, 30–40% of arable soils have low P content (Kirkby & Johnston, 2008). Concerns about phosphorus reserves have led to widespread, uncontrolled application of mineral fertilizers, including P fertilizers, since the Green Revolution of the 1950s-1960s. According to the United States Geological Survey (USGS) (2021), economically recoverable phosphate rock reserves globally are 71 billion tons, which would be depleted in approximately 260 years at current consumption rates (Walan et al., 2014). P scarcity or price increases can result in inorganic fertilizer shortages, impacting global food production and causing yield losses (Amundson et al., 2015; Heckenmüller et al., 2014). These challenges necessitate developing novel approaches to sustainably manage P by utilizing organic wastes that can enhance P availability, supplement conventional fertilizers, or reduce P losses (Dai et al., 2016). Reducing synthetic P fertilizer use offers both environmental and economic benefits. Recent research suggests that biochar, a carbon-rich solid produced through thermochemical conversion of biomass under minimal or no oxygen, can serve as a slow-release P fertilizer (Glaser & Lehr, 2019; Gwenzi et al., 2018; Li et al., 2020; Pogorzelski et al., 2020). Biochar application provides clear advantages over conventional disposal practices, as it not only reduces waste volume but also mitigates risks from pathogens, organic contaminants, and heavy metals, while enhancing carbon stability and thereby contributing to lower greenhouse gas emissions (Lehmann et al., 2006). Although the nutrient composition and availability of biochar depend on feedstock and pyrolysis conditions (Elkhlifi et al., 2023), its slow-release properties can enhance P availability in soils and act as a controlled-release fertilizer (Cui et al., 2011). Slow-release fertilizers provide nutrients throughout the growing season, reducing labor and fertilizer costs. Several studies indicate that P uptake by plants increases in the presence of biochar (DeLuca et al., 2009; Novak et al., 2009). Biochar may enhance P availability directly via anion exchange or indirectly by affecting cation interactions (DeLuca et al., 2009). The P content of biochar varies, with typical P_2O_5 values between 2.6% and 13.5%, while most biochars have low inherent P content (<1%) (Ducey et al., 2017). However, due to its porous structure, biochar can adsorb P and improve soil P availability. Various studies report that biochars derived from sugarcane, Miscanthus, pine, and maize straw can adsorb significant amounts of P (Trazzi et al., 2016; Yao et al., 2013; Zhao et al., 2017). Biochar application can also alter soil pH, which affects P adsorption and solubility, particularly in acidic soils (Curaqueo et al., 2014; Nelson et al., 2011; Yuan & Xu, 2011). Additionally, biochar can improve soil physical structure, root growth, nutrient uptake, and mycorrhizal activity (Hossain et al., 2020). The proportion of inorganic and mineral-bound P in biochar contributes to enhanced P bioavailability when applied to soils (Zhai et al., 2015). The P content and properties of biochar depend on feedstock and production conditions (Sepúlveda-Cadavid et al., 2021; Wang et al., 2012). Therefore, selecting suitable conditions and evaluating different organic materials is critical for producing biochar with desired characteristics (Weber & Quicker, 2018). In this study, hazelnut husk-derived biochar was chosen due to its availability in the

Black Sea region of Turkey, where hazelnuts are a major crop. Post-harvest residues, including hazelnut husks, accumulate in orchards, posing environmental problems. Annually, approximately 350,000 tons of such residues are left in orchards, facilitating disease spread and reducing subsequent crop yield and quality. Although these residues are sometimes burned, this practice contributes to carbon emissions and environmental pollution. Therefore, converting these wastes into environmentally friendly, value-added products is essential. The aim of this study was to produce biochar from hazelnut husks, develop an organic-based phosphate fertilizer, and investigate its effects on the growth of iceberg lettuce.

Materials and Methods

Production of Biochar and Biochar-Based Slow-Release Phosphorus Fertilizers

Hazelnut husks were used as the raw material for biochar production. The biomass was air-dried at room temperature (30 ± 2 °C) for 48 h, ground, and sieved through a 2 mm mesh before undergoing slow pyrolysis under limited oxygen conditions. The pyrolysis temperature was gradually increased at a rate of 10 °C per minute until reaching 400 °C and then cooled to room temperature within the furnace (Korkmaz et al., 2023). The resulting hazelnut husk biochar (FZB) was aerated for 24 h, sieved again (<2 mm), and stored in airtight containers. For the preparation of biochar-based slow-release phosphorus fertilizers (BBSR-P), FZB was immersed in a saturated KH_2PO_4 solution at a solid-to-solution ratio of 1:40 for 48 h, following a P adsorption isotherm approach (López et al., 2020), and continuously agitated at 100 rpm to facilitate phosphorus loading. A similar procedure was carried out using ground and dissolved Triple Superphosphate (TSP) to produce two distinct biochar-based P fertilizers. The materials were then dried at 65 °C to remove the liquid phase while retaining phosphorus within the biochar. In the pot trial, TSP and KH_2PO_4 were used as phosphate sources and combined with FZB to produce the fertilizer treatments.

Greenhouse Experiment

A pot experiment was conducted at the greenhouse of the Department of Soil Science, Faculty of Agriculture, Ordu University, to evaluate the effects of biochar-based slow-release organo-mineral P fertilizers on plant growth. Two kilograms of soil (air-dry weight basis) were placed in each pot. Iceberg lettuce (Bombala variety), obtained from certified seeds (AG Seed Company), was used as the test plant. The experiment included four P application rates (0, 3, 6, and 12 kg P_2O_5 da^{-1}) applied as FZB-based fertilizers prepared with KH_2PO_4 or TSP. One lettuce plant was transplanted per pot, and the experiment was arranged in a randomized complete block design with three replicates. Following transplantation, basal fertilization was applied based on soil analysis (Table 1), including 200 mg N kg^{-1} as NH_4NO_3, 125 mg K kg^{-1} as K_2SO_4 (adjusted for K supplied by KH_2PO_4), and 2.5 mg Zn kg^{-1} as $ZnSO_4 \cdot 7H_2O$. Plants were watered daily with deionized water. After 120 days, plants were harvested, washed with deionized water, oven-dried at 65 °C for 48 h, ground, and prepared for analysis.

Soil, Biochar and Plant Analyses

Soil analyses included the determination of texture (Bouyoucos, 1951), pH, and electrical conductivity (EC) (Richards, 1954), organic matter (Walkley & Black, 1934), and total nitrogen (Bremner, 1965). Available phosphorus and potassium were quantified according to Bray and Kurtz (1945) and Pratt (1965), respectively. Micronutrients (Fe, Cu, Mn, and Zn) were extracted using DTPA–$CaCl_2$–TEA solution and measured by atomic absorption spectrophotometry (Lindsay & Norvell, 1978).

Prior to analysis, biochar samples were ground and sieved to <2 mm. The pH and EC were measured in a 1:5 (w/v) biochar-to-distilled water suspension. Total N was analyzed by the Kjeldahl method, P colorimetrically, and K using flame photometry. Organic matter was determined by dry combustion, while Fe, Cu, Mn, and Zn were quantified by atomic absorption spectrophotometry following acid digestion, as described by Sg et al. (2021). The main physicochemical characteristics of the soil and biochar are presented in Table 1.

Plant samples were oven-dried to a constant weight for biomass determination, ground, and analyzed for nutrient content. Total N was determined using the Kjeldahl method (Bremner, 1965), P colorimetrically, K by flame photometry, and Fe, Cu, Zn, and Mn by atomic absorption spectrophotometry following the procedures of Kacar and İnal (2008). All experimental data were subjected to analysis of variance (ANOVA) using the SAS statistical package, and significant differences between treatments were determined using Duncan's multiple range test at $p < 0.05$.

Table 1. Some Physical and Chemical Properties of the Biochar and Soil used in the Experiment

	Texture	pH	EC	OM	N	P	K	Fe	Cu	Mn	Zn
			(µS m^{-1})	%				mg kg^{-1}			
Biochar		7.24	168.1	86.7	0.057	161.0	8101.7	271.0	11.2	45.2	41.5
Soil	SL	6.41	245.0	0.9	0.011	7.1	101.0	44.0	1.7	20.0	0.4

Results

Effect of Biochar-Based Phosphorus Fertilizers on Dry Weight of Iceberg Lettuce

Analysis of variance indicated that both the phosphorus source and application rate, as well as their interaction, significantly affected ($p < 0.05$) the dry weight of iceberg lettuce (Table 2). In the control treatment (0 kg P_2O_5 da^{-1}), the lowest dry weight was recorded at 24.7 g $plant^{-1}$. Increasing P rates, particularly in the FZB-KH_2PO_4 treatment, resulted in a marked increase in dry weight. Specifically, 3 and 6 kg P_2O_5 da^{-1} doses produced 32.0 g and 33.7 g $plant^{-1}$, respectively, while the highest dose of 12 kg P_2O_5 da^{-1} resulted in 44.7 g $plant^{-1}$. In contrast, FZB-TSP showed minimal increases across doses, remaining between 28.1 and 28.2 g $plant^{-1}$. The average dry weight across P sources was significantly higher in FZB-KH_2PO_4 (33.9 g) compared to FZB-TSP (27.3 g). The dose × source interaction was significant ($p<0.001$), with the FZB-KH_2PO_4 × 12 kg P_2O_5 da^{-1} combination achieving approximately 80 % higher dry weight than the FZB-TSP × 0 kg P_2O_5 da^{-1} control. FZB-TSP showed only a 14 % increase at the highest dose, highlighting the superior effect of FZB-KH_2PO_4 on plant biomass.

Table 2. Effect of Biochar-Based P Fertilizers on Dry Weight of Iceberg Lettuce (g $plant^{-1}$)

	P Rates (P_2O_5 da^{-1})				
Fertilizer	0	3	6	12	Mean
FZB-TSP	24.7 d	28.1 cd	28.1 cd	28.2 c	27.3 B
FZB-KH_2PO_4	25.2 cd	32.0 b	33.7 b	44.7 a	33.9 A
Mean	25.0 C	30.0 B	30.9 B	36.5 A	

Different letters indicate significant differences according to Duncan's multiple range test at p<0.05.

Effect of Biochar-Based Phosphorus Fertilizers on P Concentration of Iceberg Lettuce

The P concentration in lettuce was significantly influenced ($p<0.05$) by P source, dose, and their interaction (Table 3). Control treatments (0 kg P_2O_5 da^{-1}) exhibited the lowest P concentrations, 0.259 % for FZB-TSP and 0.263 % for FZB-KH_2PO_4. Increasing P doses led to a pronounced rise in P concentration, particularly under FZB-KH_2PO_4. At 3, 6, and 12 kg P_2O_5 da^{-1}, P concentrations reached 0.326 %, 0.380 %, and 0.346 %, respectively, corresponding to an approximate 45 % increase compared to the control.

Table 3. Effect of Biochar-Based P Fertilizers on P Concentration (%) of Iceberg Lettuce

	P rates (P_2O_5 da^{-1})				
Fertilizers	0	3	6	12	Mean
FZB-TSP	0.259 d	0.268 d	0.272 d	0.293 cd	0.273 B
FZB-KH_2PO_4	0.263 d	0.326 bc	0.380 a	0.346 ab	0.329 A
Mean	0.261 B	0.297 A	0.326 A	0.320 A	

Different letters indicate significant differences according to Duncan's multiple range test at $p < 0.05$.

FZB-TSP applications showed only minor increases (0.268–0.293 %), with a maximum of 13 % relative to the control. Average values confirmed that FZB-KH_2PO_4 (0.329 %) was significantly higher than FZB-TSP (0.273 %). Across P doses, the lowest and highest P concentrations were 0.261 % (control) and 0.326–0.320 % (6–12 kg P_2O_5 da^{-1}), respectively. These results indicate that the form of biochar-based P fertilizer affects lettuce P accumulation, with FZB-KH_2PO_4 being more effective at higher doses.

Effect of Biochar-Based Phosphorus Fertilizers on P Uptake of Iceberg Lettuce

The amount of P removed by lettuce was significantly affected ($p < 0.05$) by P source, dose, and their interaction (Table 4). In the control (0 kg P_2O_5 da^{-1}), P uptake was 63.9 mg $plant^{-1}$ for FZB-TSP and 66.4 mg $plant^{-1}$ for FZB-KH_2PO_4. Increasing P doses enhanced P uptake for both sources, but the effect was more pronounced in FZB-KH_2PO_4. For instance, P uptake under FZB-KH_2PO_4 was 103.9 mg $plant^{-1}$ at 3 kg, 128.3 mg at 6 kg, and 154.7 mg $plant^{-1}$ at 12 kg P_2O_5 da^{-1}, corresponding to 57–133 % increases over the control. In contrast, FZB-TSP showed more limited gains, with P uptake ranging from 75.1 to 82.7 mg $plant^{-1}$ and a maximum increase of ~30 % compared to the control. The average P uptake was significantly higher in FZB-KH_2PO_4 (113.3 mg $plant^{-1}$) than in FZB-TSP (74.6 mg $plant^{-1}$). The interaction between P source and dose was particularly notable. P uptake increased linearly with increasing doses under FZB-KH_2PO_4, reaching the highest value of 154.7 mg $plant^{-1}$ at 12 kg P_2O_5 da^{-1}. Conversely, FZB-TSP showed limited response to increasing doses, with a maximum uptake of 82.7 mg $plant^{-1}$. These results indicate that biochar enriched with KH_2PO_4 is more effective in enhancing P uptake by lettuce. Overall, the findings highlight the critical role of the source × dose interaction in determining plant nutrient acquisition when different P sources are applied via biochar.

Table 4. Effect of Biochar-Based Phosphorus Fertilizers on P Uptake of Iceberg Lettuce (mg $plant^{-1}$)

	P rates (P_2O_5 da^{-1})				
Fertilizers	0	3	6	12	Mean
FZB-TSP	63.9 e	75.1 de	76.5 de	82.7 d	74.6 B
FZB-KH_2PO_4	66.4 e	103.9 c	128.3 b	154.7 a	113.3 A
Mean	65.2 B	89.6 C	102.4 B	118.7 A	

Different letters indicate significant differences according to Duncan's multiple range test at $p<0.05$.

Discussion

The effects of hazelnut husk-derived P-enriched biochar fertilizers on iceberg lettuce growth, dry matter accumulation, tissue P concentration, and total P uptake were statistically significant with respect to P dose, fertilizer source, and their interactions ($p<0.05$). Across all P doses, FZB-KH_2PO_4 treatments consistently outperformed FZB-TSP applications in terms of dry matter accumulation. Particularly, the 12 kg P_2O_5 da^{-1} dose (equivalent to 1 t biochar da^{-1}) under FZB-KH_2PO_4 resulted in an approximate 80% increase in dry matter compared to the control, representing the highest observed yield. This enhanced growth can be attributed not only to the readily available PO_4^{3-} ions in the KH_2PO_4-enriched biochar but also to the synergistic contribution of K^+ ions, which are known to enhance metabolic processes and osmotic regulation in plants (Li et al., 2020). In contrast, FZB-TSP applications induced a more moderate increase in biomass, with a maximum enhancement of approximately 30% at the same P dose, indicating the superior efficacy of biochar-based P fertilizers over conventional mineral sources in promoting lettuce growth. A similar trend was observed for both tissue P concentration and total P uptake. Under FZB-KH_2PO_4 treatments, increasing P doses led to a linear rise in P removed by lettuce, reaching a peak of 154.7 mg plant^{-1} at 12 kg P_2O_5 da^{-1}. Conversely, FZB-TSP treatments showed limited P removal, with the maximum uptake not exceeding 82.7 mg plant^{-1}, even at the highest dose. These findings indicate that $KH_2PO_4^-$ enriched biochar is more effective than TSP-based applications in enhancing P acquisition, which aligns with previous reports using wheat straw (Xu et al., 2014), acacia species (Rashmi et al., 2020), and maize residues (Li et al., 2020).

The observed differences in P efficiency cannot be solely explained by the P content of biochar. The high surface area and abundance of functional groups on biochar surfaces facilitate the masking of active sites of Fe^{3+} and Al^{3+} in soil, reducing P fixation and maintaining longer-term availability for plant uptake (Song et al., 2007). Organic functional groups, including phenolic and amino moieties, can be protonated under acidic conditions, creating positively charged sites that bind orthophosphate ions via ionic interactions and van der Waals forces. Consequently, P adsorbed on biochar is gradually released, providing a slow-release mechanism that maintains plant-available P throughout the growing season. In contrast, conventional mineral fertilizers rapidly dissolve, and their P can be quickly immobilized in soil fractions, reducing bioavailability (Hosseini et al., 2019; Mukherjee et al., 2020). Furthermore, the superior performance of FZB-KH_2PO_4 can be attributed to the dual effect of direct PO_4^{3-} availability and the synergistic role of K^+ ions in enhancing plant metabolic efficiency. This effect was particularly pronounced at medium and high doses, contributing significantly to lettuce productivity. These findings highlight the potential of hazelnut husk-derived biochar-based P fertilizers as a slow-release alternative that enhances nutrient use efficiency while reducing the environmental risks associated with conventional fertilizers. The combination of controlled P release and reduced soil fixation suggests that biochar amendments can be particularly effective in acidic soils, where P availability is often limited. Moreover, the utilization of agricultural residues such as hazelnut husks not only mitigates waste-related environmental issues but also adds value by converting organic by-products into agronomically beneficial fertilizers (Li et al., 2020; Rashmi et al., 2020; Xu et al., 2014). Overall, these findings support the integration of P-enriched biochar into sustainable nutrient management strategies, highlighting its role in enhancing crop productivity, improving P use efficiency, and promoting environmentally responsible agriculture.

Conclusions

Phosphorus-enriched biochar derived from hazelnut husks significantly enhanced dry matter production, P concentration, and P uptake in iceberg lettuce. In particular, biochar-based FZB-KH_2PO_4 application at 12 kg P_2O_5 da^{-1} resulted in the highest P uptake and dry matter accumulation, achieving approximately an 80% increase in yield compared to the control. FZB-TSP applications also had a positive effect, but the increases were more limited. These findings support the use of biochar as a carrier for P fertilizers, offering a valuable alternative for both environmental sustainability and agricultural productivity. Overall, this study demonstrates the effectiveness of hazelnut husk-derived biochar in P delivery and highlights the potential of $KH_2PO_4^-$ based biochar applications at optimal doses to provide long-term plant-available P and enhance crop yield.

Author Contribution

The authors declare that they contributed equally to the manuscript. All authors have read and approved the final version of the manuscript for publication.

Ethics Statement

There are no ethical issues with the publication of this article.

Conflict of Interest

The authors declare that there is no conflict of interest.

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