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Transport Pathways of Biochar Enhanced Phosphorus Uptake to Root Surface: A Review

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Abstract

Phosphorus (P) deficiency is a major constraint to crop productivity, especially in tropical and subtropical regions where strong fixation by Fe and Al oxides limits its availability. Biochar has gained attention as a soil amendment capable of modifying soil properties to enhance P solubility, mobility, and uptake by plants. This review synthesizes understanding of the transport pathways through which biochar enhances P movement from soil to the root surface, focusing on diffusion, mass flow, desorption-resorption dynamics, and microbial mediation. The objectives were to 1) analyze how biochar influences soil pH, cation exchange capacity, and surface chemistry governing P availability; 2) evaluate its role in altering P transport mechanisms toward roots; and 3) assess interactions among biochar, soil microorganisms, and plant roots that support improved P acquisition. A systematic examination of peer-reviewed studies published over the past two decades was conducted. Our review revealed that biochar acts through multiple pathways, chemical (reducing fixation, contributing P), physical (enhancing diffusion and mass flow), and biological (stimulating microbes). In addition, transport processes are central, and that biochar's role is not just for soil amendment but a facilitator of ion flux toward roots. Therefore, integrating the effect of soil chemistry, water dynamics, and microbial mediation increases the flux of $H_2PO_4^-$ and HPO_4^{2-}. ions to the rhizosphere and improves root uptake efficiency, which is greater than any single mechanism studied in isolation. In conclusion, the review show that biochar's impact is context-dependent, varying with soil type, biochar feedstock, and microbial community composition among others.

Keywords

Transfer Mechanisms, Carbonized Biomass, Soil Fertility, Nutrient Mobility, Root Surface Interactions, Sustainable Agriculture

1. Introduction

Phosphorus is a vital element for the growth of plants, functioning as a structural component in nucleic acids (DNA and RNA), phospholipids, and adenosine triphosphate (ATP), which is crucial for energy transfer in cells [1]. It contributes significantly to processes such as root development, seed formation, flowering, fruiting, and the maturity of crops. A phosphorus deficiency can notably impede plant growth, delay maturation, reduce nutrient absorption efficiency, and heighten disease susceptibility [2] [3].

Despite being relatively abundant in the Earth's crust [4], the bioavailability of phosphorus in soils is often limited—over 80% - 90% is poorly mobile and unavailable to plants—due to factors such as chemical fixation, pH extremes, and slow mobility [5]. This poses a threat to global food security, necessitating repeated phosphorus supplementation in agriculture, often through synthetic fertilizers and manures, which can lead to environmental issues like eutrophicatio [6]. Eutrophication is an ecological concern that results from phosphorus runoff, causing excessive algal blooms, oxygen depletion, and harm to aquatic ecosystems, with an estimated economic impact of $2.2 billion annually in the United States [6]. To meet the United Nations Sustainable Development Goals focused on clean water, it's essential to address phosphorus use inefficiencies and their environmental consequences [7].

Research indicates that biochar can enhance phosphorus use efficiency, minimize environmental losses, and maintain crop productivity, particularly in nutrient-poor soils [8]. However, existing studies have approached biochar's mechanisms in isolation, without connecting nutrient release, sorption behavior, or microbial processes. So, this review aim to: 1) examine how biochar alters soil pH, cation exchange capacity (CEC), and surface chemistry to govern phosphorus (P) availability, 2) evaluate the impact of biochar on P transport mechanisms to plant roots and, 3) assess the interactions between biochar, soil microbiota, and roots that enhance P acquisition.

This review introduces a comprehensive framework to address these gaps by linking the fragmented understanding of biochar with phosphorus transformation pathways, emphasizing the roles of feedstock types, pyrolysis conditions, and soil properties. It differentiates outcomes from controlled laboratory studies and field validations, enabling the identification of robust agronomic results from potential experimental artifacts. The review situates these findings within broader conversations about sustainability, climate resilience, and policy, providing an integrative synthesis that is currently lacking in research on biochar and phosphorus availability.

2. Methodology

The review was conducted using a structured approach to gather, evaluate, and synthesize current scientific knowledge on phosphorus cycling in soil systems. The methodology involved the following steps:

2.1. Literature Search Strategy

A comprehensive literature search was performed using academic databases such as ScienceDirect, SpringerLink, Google Scholar, and PubMed (Figure 1). The search terms included combinations of keywords such as: "Phosphorus cycling in soil", "Phosphorus mineralization and immobilization", "Phosphorus adsorption and desorption", "Phosphorus precipitation and dissolution", "Soil phosphorus availability and uptake", "Phosphorus fixation in soil", and "Biochar and phosphorus availability."

The search was limited to peer-reviewed articles, book chapters, and authoritative extension publications published between 2000 and 2025 to ensure relevance and scientific rigor.

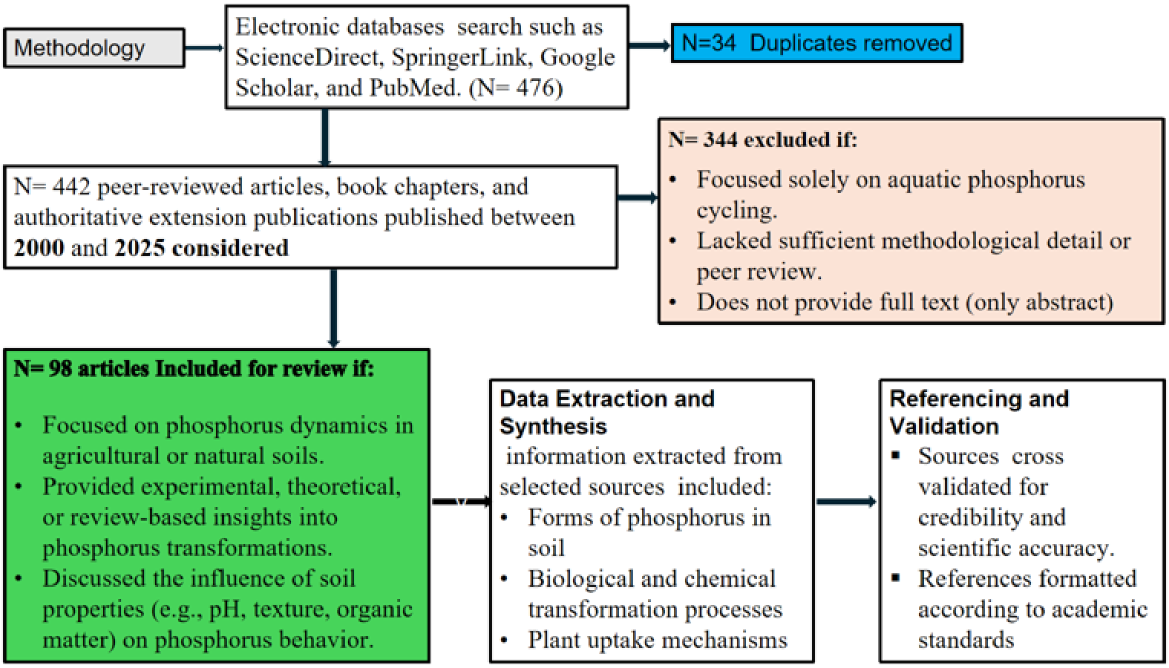

Figure 1. Literature review process flowchart.

2.2. Inclusion and Exclusion Criteria

Studies were included if they: Focused on phosphorus dynamics in agricultural or natural soils, provided experimental, theoretical, or review-based insights into phosphorus transformations, discussed the influence of soil properties (e.g., pH, texture, organic matter) on phosphorus behavior (Table 1), and studies were excluded if they: Focused solely on aquatic phosphorus cycling, lacked sufficient methodological detail or peer review, does not provide full text (only abstract).

Table 1. Key characteristics of some studies included.

Type of study	Biochar feedstocks	soil types	Reference
Field	Mixed hardwood feedstock	Leeper silty clay loam soil	[9]
Field	rice straw and rice husk.	Sandy loam Alluvial black	[10]
Field	rice straw	lateritic latosol soil	[1]
Green house	Douglas fir	Sandy loam	[2]
Laboratory	sewage sludge (SS), olive pomace (OP), (3) chicken manure (CM), and date palm residues	Sandy loam	[3]
Greenhouse	Douglas fir	Sandy loam	[5]
Laboratory	Douglas fir	Sandy loam	[11]
Laboratory	biosolids, poultry litter, mixed hardwoods, pure maple (Acer spp.), and Douglas-fir	Loamy, r soil	[12]
Laboratory	cacao shell, oil palm shell, and rice husk	Hapludults	[13]
Greenhouse	banana peels, orange peels and milk tea waste	Silty Clay Loam	[14]
Green house	Douglas fir	Sandy loam	[15]
Green house	pinewood and wheat straw	Five different soil texture	[16]
Laboratory	Bone	sandy	[17]
Field	Corn cob	sandy loam	[18]
Greenhouse	Maize straw	silt-loam	[19]
Pot/laboratory experiment	Animal based digestate solid	Sandy loam	[20]
Laboratory	rice straw and canola stalk	Ultisol	[21]
Laboratory	Rice straw	Red soil	[22]
Laboratory	Poultry litter	sandy loam	[23]
greenhouse	pomegranate wood	Sandy loam	[24]
Laboratory	Rice straw	Entisol and Inceptisol	[25]
Laboratory	wheat straw	black soil and fluvo-aquic soil	[26]
Pot experiment	Green waste, acidified green waste, corn cob and acidified corn cob	sandy-clay-loam	[27]
Laboratory	Commercial biochar	Silty clay	[28]
Pot experiment	Corn cob	Sandy loam and	[28]

Continued

Pot experiment	Poultry liter	Oxisol	[29]
Pot experiment	Sugarcane filter cake farmyard manure, and rice husk	silt loam	[30]
Field	Rice straw	Sandy clay loam	[31]
Field	Wood, agricultural residues and organic waste	Sandy loam	[32]
Field	maize cobs and stovers, coffee husks and coconut shells	Clay and sandy clay loam	[33]
Field	Paddy straw	Silt loam	[34]
Field	Pine and spruce	Sandy loam	[35]
Laboratory	Rice straw	Silt loam	[36]

2.3. Data Extraction and Synthesis

Relevant information was extracted from selected sources and categorized into thematic areas: forms of phosphorus in soil, biological and chemical transformation processes, plant uptake mechanisms, and environmental loss pathways.

The extracted data were synthesized to provide a comprehensive overview of phosphorus cycling, highlighting key mechanisms, influencing factors, and implications for soil fertility and nutrient management.

2.4. Referencing and Validation

All included sources were cross-validated for credibility and scientific accuracy. The references were formatted according to the journal's chosen style and included in the final manuscript to support transparency and reproducibility.

3. Biochar

Biochar is a carbon-rich material produced through the pyrolysis of organic biomass under limited or no oxygen conditions [11]. Although there are many organic feedstocks used in biochar production, the source of each feedstock influences the characteristics of the resultant biochar. Common feedstocks include woody biomass such as forestry residues, sawdust, and wood chips; agricultural residues like straw, husks, stover, and nutshells; and manures or biosolids derived from livestock or sewage sludge [12] [37] [38] herbaceous plants (bamboo, grasses, reeds), industrial processing wastes, and dedicated energy crops like miscanthus or switchgrass, have also been used. In most cases, the feedstock selection depended on factors such as local availability, sustainability, and the potential presence of contaminants like heavy metals or persistent organic pollutants and ash contents [37].

Originally studied for its carbon sequestration potential, biochar has gained significant attention because of its benefits in soil management. Biochar's porous structure, alkaline nature and high surface area have been reported to enhance soil's cation and anion exchange capacities, improve water and nutrient retention, buffer soil pH, and stimulate beneficial microbial activity [13] [14]. According to Singh *et al.* [39], these properties are influenced by key parameters including pyrolysis temperature, heating rate, residence time, reactor type, and feedstock characteristics. Furthermore, biochar can be engineered or enriched with nutrients to function as a slow-release fertilizer, thereby improving nutrient use efficiency and reducing leaching losses [5] [15].

3.1. Biochar Properties affecting Phosphorus (P) Dynamics

Biochar's influence on soil phosphorus dynamics is strongly governed by its physical, chemical, and surface properties, which determine how it interacts with soil minerals, organic matter, and microbial communities [40]-[42]. These characteristics ultimately shape P solubility, mobility, and plant uptake. According to Anyebe *et al.* [40], biochar properties vary with feedstock type, pyrolysis temperature, and post-production modification, all of which directly affect its performance in soil nutrient cycling. Key properties influencing P dynamics include surface area, pore volume, surface functional groups, chemical composition, feedstock origin, and biochar modification strategies [43].

3.1.1. Surface Area

The biochar surface area plays a critical role in the sorption and desorption of phosphate in soil. High specific surface area increases the density of sorption sites for phosphate and promotes a buffering (sorption-desorption) behavior that stabilizes soil solution P [44]. These sites interact with phosphate ions via hydrogen bonding and complexation. SA typically rises with higher pyrolysis temperature and activation, and it enhances P retention while providing habitats for P-solubilizing microbes in the char matrix [45]. High surface area biochars, particularly those derived from manure or modified with metals (Ca, Mg, Fe), have high negative surface charge density [43]. While negatively charged surfaces normally repel phosphate (anion), these biochars often contain metal oxides that act as bridges (Ca^{2+}, Mg^{2+}, Fe^{3+}) between the biochar surface and the phosphate ion, significantly increasing retention [44]. Materials science work confirms that activation routes and pore development strongly control SA and microtexture [46], which in turn influence nutrient interactions. In strongly acid soils, high-surface-area biochar, especially if it is also alkaline, can reduce P sorption to Fe/Al oxides, thereby increasing P availability. In alkaline soils, high-surface-area biochar can increase phosphate sorption via Ca/Mg-phosphate precipitation, reducing P mobility. In clay soils, the addition of high-surface-area biochar can improve aggregate stability, reducing the loss of particulate P [47].

3.1.2. Pore Volume and Porosity

Micro- and mesopores (1 - 50 nm) enhance soil water retention, increasing mass flow of dissolved orthophosphate to roots. Porosity also creates microhabitats that favor colonization by P-solubilizing bacteria and arbuscular mycorrhizal fungi (AMF). Field and greenhouse studies show mesoporous biochar can reshape water profiles in the root zone [48], indirectly enhancing P mobility; laboratory work in red soils shows that dissolved black carbon from biochar competes for sorption sites, modulating P sorption behavior [50].

3.1.3. Surface Functional Groups

Carboxyl, phenolic, and hydroxyl groups mediate ligand exchange and electrostatic interactions with phosphate and with Fe/Al oxides. In acidic soils, negatively charged groups can compete with phosphate for Fe/Al binding sites, decreasing fixation; conversely, functionalized (positively charged or metal-doped) surfaces can immobilize excess phosphate and later desorb it, acting as slow-release sources [49]. Dissolved organic moieties released by biochar can also compete with phosphate for sorption sites, lowering sorption in some systems [22].

3.1.4. Chemical Properties: pH (Liming Capacity), Ash, and Mineral Phases

Most biochar produced at higher pyrolysis temperatures is alkaline and contains basic cations [50]. Their liming effect raises soil pH, reducing Fe^{3+}/Al^{3+} activity and, thus, P fixation. Their ash provides Ca, Mg, and K that can form sparingly soluble Ca-P or Mg-P phases with distinct solubilities [11] [51]. Reviews and meta-analyses show the strongest P-availability responses in acidic to neutral soils. In calcareous systems, however, responses are more variable and depend on phase equilibria among Ca phosphates [50] [52] [53].

3.1.5. Feedstock Type

Feedstock dictates the baseline chemistry. Animal-derived feedstocks (manures, bones, biosolids) yield biochars with higher ash, Ca/Mg, and P contents, often functioning as P-enriched fertilizers [51]. Plant-derived feedstocks (wood, straw) yield chars with lower ash and P, more suited as structural conditioners and retentive matrices [54]. Controlled comparisons show strong contrasts in P leaching/release patterns between biosolids/manure vs. woody biochars across soils with different P-retention [12] [54]. Co-pyrolysis with Mg or Ca or post-pyrolysis mineral loading tunes release. Mg-rich phases (e.g., struvite, cattiite) generally release P more readily than Ca-rich pyrophosphates/whitlockite, which are less soluble [55].

3.1.6. Biochar-Microbe-Root Interactions

Biochar creates niches and modifies pH/moisture that favor P-solubilizing microorganisms (PSM) and AMF. In a study, the combination of arbuscular mycorrhizal fungi (AMF) and biochar significantly enhanced phosphorus uptake in maize by increasing mycorrhizal colonization and promoting phosphate-solubilizing microorganism abundance [36]. This synergy improved P availability in the rhizosphere, particularly under low-phosphorus conditions, leading to better nutrient acquisition and plant growth. Biochar likely provided a favorable habitat for

AMF and beneficial microbes, amplifying their activity. Other studies indicated that AMF do not colonize all biochar types equally; instead, specific fungi, particularly within the Paraglomus genus, are found to dominate, indicating a, select, and preferential interaction [56]. This selective colonization occurs as AMF hyphae exploit the porous structure of biochar. This selective colonization suggests biochar may act as a refuge or growth substrate, promoting symbiotic relationships that improve soil fertility and crop resilience. An experiment in acidic paddy soil show biochar both repartitions P fractions (reducing occluded P) and stimulates root citrate exudation and transporter expression, further mobilizing P [51]. The Study revealed a 75% increase in shoot P accumulation and significant improvements in plant growth due to biochar's ability to mitigate soil acidity and stabilize phosphorus.

3.2. Phosphorus Dynamics in Soil

The integration of biochar into phosphorus management strategies represents a promising pathway toward a more sustainable and resilient agricultural system. In soil, biochar application can influence both phosphorus availability and mobility [16]. While biochar can directly increase available phosphorus through desorption or mineralization processes (**Figure 2**), it can indirectly affect phosphorus retention by altering soil chemistry, such as pH and microbial interactions [53]. The extent of these effects depends on several factors, including the type of feedstock used (e.g., agricultural residues, animal bones, eggshells), pyrolysis temperature and duration, and the physicochemical properties of the target soil [17] [57].

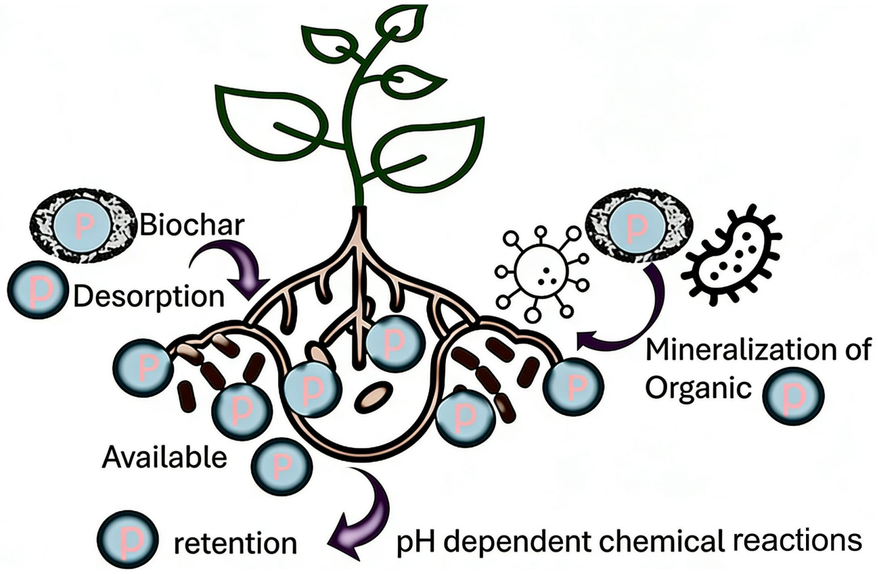

Figure 2. Phosphorus dynamics in soil.

A global meta-analysis by Zhichao Xu, Run Zhou, and Guoren Xu *et al.*, [58] found that biochar application increased available phosphorus by an average of

18% across 1200 field trials, with the greatest effects observed in acidic and phosphorus-deficient soils. Acidic soils are known to bind phosphorus tightly to iron and aluminum oxides, making it unavailable to plants [59]. Biochar, being alkaline and rich in functional groups, can raise soil pH and reduce phosphorus fixation, thus improving its availability [51]. Recent research highlights that the co-application of plant growth-promoting rhizobacteria (PGPR) and biochar significantly enhances phosphorus availability in soil [60] [61]. PGPR, particularly phosphate-solubilizing bacteria, secrete organic acids and enzymes that convert insoluble phosphorus into plant-available forms [62]. When combined with biochar, which improves soil structure and nutrient retention, this synergy boosts phosphorus uptake and utilization in crops like zea mays [61]. Biochar increases microbial habitat stability, promoting PGPR activity and improving drought resilience through better nutrient absorption. In phosphorus-deficient soils, this effect is even more pronounced, making biochar a strategic amendment for degraded or low-fertility lands [62].

Md Zahangir Hossain, Md Mezbaul Bahar, Binoy Sarkar, *et al.*, [63] reported improved nutrient retention and microbial activity (Pseudomonadaceae and Sphingomonadaceae bacteria after applying biochar, contributing to better phosphorus use efficiency. Biochar's porous structure provides microhabitats where microbes can colonize and thrive. These pores protect microbes from predators and environmental stress. Moreover, biochar absorbs nutrients like nitrogen and phosphorus, creating a nutrient-rich zone that supports microbial growth. Many other studies have shown that biochar can increase microbial biomass and enzymatic activity [18] [19], especially those involved in nutrient cycling (e.g., phosphorus mineralization, nitrogen fixation).

A field experiment conducted in a tropical ecosystem revealed that applying biochar particularly at a rate of 30 tons per hectare, significantly enhanced microbial biomass carbon and nitrogen, as well as carbon mineralization [18]. The amendment also reduced respiration rates (qCO_2), suggesting improved microbial efficiency. In addition, activities of key enzymes such as dehydrogenase and urease were elevated, while the abundance of beneficial microbial groups, including arbuscular mycorrhizal fungi (AMF), general fungi, and both Gram-positive and Gram-negative bacteria, increased. Overall, the findings indicated that biochar, especially when derived from corn cobs, can promote carbon sequestration and strengthen ecosystem stability in tropical soils. This was attributed to the ability of biochar to act as a physical refuge, chemical buffer, and nutrient reservoir, all of which enhance microbial abundance and functionality.

3.2.1. Biochar and Phosphorus: Mechanisms of Interaction

Biochar amendments influence phosphorus (P) dynamics in soils through several physical, chemical, and biological mechanisms (**Figure 3**). These mechanisms can either increase or reduce phosphorus availability subject to the biochar properties, soil characteristics, and environmental conditions (**Table 2**).

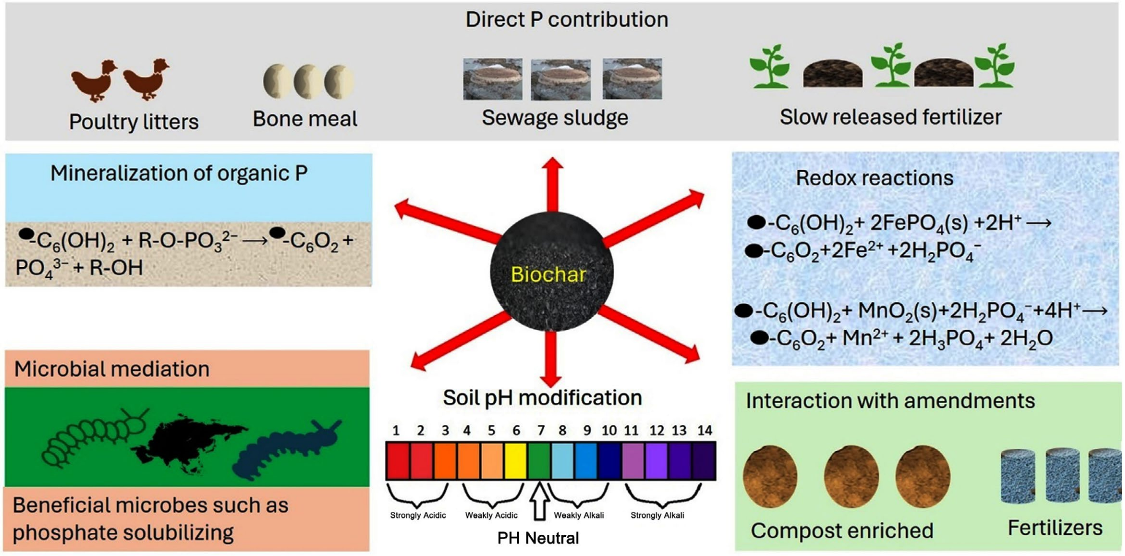

Figure 3. Mechanism of interaction between biochar and phosphorus in soil systems.

Table 2. Biochar influences phosphorus availability in soil.

Mechanism	Effect on P Availability	Notes	References
Direct P contribution	↑	Depending on feedstock	[53] [23]
pH modification	↑ (in acidic and neutral soils).	Reduces Fe/Al fixation.	[54]
	Inconsistent in alkaline soil	Calcium phosphate Precipitation may occur	[54] [64]
Sorption/desorption	↑ or ↓	Acts as slow-release or immobilizer	[54] [64] [55]
Soil mineral interactions	↑ or ↓	Alters P precipitation	[8] [54]
Microbial stimulation	↑	Enhance P solubilization. Increased biomass and affects enzymatic activities	[8] [18] [19] [54]
Interaction with Other Soil Amendments E.g. Organic matter	↑ or ↓	Affects mineralization and immobilization	[8] [27] [28] [65]
Redox reaction	↑ or ↓	Redox buffering, Electron Shuttling, surface interactions	[8] [24] [66] [67]

3.2.2. Direct Phosphorus Contribution

The availability of phosphorus (P) from biochar is influenced by several factors. Biochar with a higher initial P concentration, such as those derived from poultry litter biochar (PLB), tend to release more P [53]. Additionally, reducing the particle size of biochar, particularly when produced from manure-based digestate solids, can improve the immediate availability of P [20]. Organic biochar feedstocks are naturally rich in phosphorus. During pyrolysis, the organic phosphorus compounds are often converted into inorganic forms, such as calcium phosphates, which are more stable and less prone to leaching. These forms can act as slow-release fertilizers, providing a sustained supply of phosphorus to crops over time [63] [68] [69].

Research consistently shows that increasing pyrolysis temperature significantly reduces the ability of biochar to enhance phosphorus (P) availability in soils. Multiple studies reported decline in extractable P as biochar production shifts from low to high temperatures [21] [53]. This trend is attributed to chemical transformations during pyrolysis. Organic P species diminish at elevated temperatures, giving way to inorganic forms, and P volatilization occurs above 700˚C. Consequently, high-temperature biochar's (>700˚C) retain minimal P, whereas low- and mid-temperature biochar (<600˚C) preserve P content and improve plant availability.

Furthermore, the effect of biochar on P availability is highly soil dependent [22]. A meta-analysis by Bruno Glaser and Verena Isabell Lehr, [53] indicated that In acidic or neutral soils, biochar often enhances P availability, especially at lower pyrolysis temperatures (<600˚C) and application rates (>10 Mg ha^{-1}). Larissa Ghodszad, Adel Reyhanitabar, Shahin Oustan *et al.*, [64] found that wheat straw biochar produced at 300˚C and 600˚C had different effects on soil phosphorus availability. Alkaline biochar, specifically at 300˚C, significantly boosted P availability in acidic soils (pH 4.6). However, the 600˚C biochar showed no significant impact on saline-alkali soils (pH 8.3), while the 300˚C biochar showed potential for improving P availability in these alkaline conditions. For saline soil, modifications to biochar or other amendments are needed to enhance phosphorus availability. Also, a study by Jeffrey M. Novak, Warren J. Busscher, David L. Laird *et al.* [70] demonstrated that poultry litter biochar increased Mehlich-1 extractable P in sandy soils by up to 300%. Similarly, Julia. W. Gaskin, Christoph Steiner, K. Harris, *et al.*, [71] reported that biochar from peanut hulls and poultry litter significantly improved P availability in acidic soils. Conversely, in alkaline or calcareous soils (pH > 7.5), these positive effects are not observed; soil tests often show no significant increase in plant-available P [16]. In acidic soils, P is often bound to Al/Fe oxides. The liming effect of biochar causes pH rise resulting in increased P availability. On the contrary, in alkaline soils, higher pH favors calcium phosphate precipitation, reducing P availability [55]. Therefore, Biochar can either compete with the soil for P binding sites or act as a source of P that can be bound by soil sorption sites, influencing the overall P dynamics in the soil.

The interplay between soil type and biochar characteristics determines whether P availability improves or declines, highlighting the need for site-specific biochar management strategies. Thus, for optimal P management, it's essential to match biochar type (feedstock, pyrolysis temperature, particle size) with soil characteristics (pH, Ca/Mg content).

3.2.3. pH Modification

One of the most consistent effects of biochar application is the increase in soil pH, particularly in acidic soils. This pH shift can reduce phosphorus fixation by iron (Fe) and aluminum (Al) oxides, thereby increasing the availability of phosphorus to plants. For example, [26] reported that wheat biochar application increased P availability in alkaline soils, but their effect on acidic soils differed with the quantity of P loading. In a study by [8], the application of rice straw biochar in both lateritic red and paddy soils affected phosphorus dynamics. While the straw biochar amendments raised soil pH and significantly enhanced available P in the red soils, which are typically acidic and rich in Fe and Al oxides, the increase in paddy soil was less than that of red soil by 20%, suggesting that biochar amendments could be more effective in soils susceptible to phosphorus leaching. A meta-analysis by Bruno Glaser and Verena Isabell Lehr [53] found that while biochar significantly increased P availability in acidic and neutral soils, it had no significant effect in alkaline soils with pH > 7.5 [53]. This is primarily due to the precipitation of phosphorus with calcium (Ca), forming insoluble calcium phosphate compounds that are unavailable to plants. Additionally, biochar may absorb phosphate ions directly onto its surface, especially if it has a high surface area and contains functional groups that bind P. This sorption can reduce the pool of plant-available phosphorus, particularly in biochar produced at high pyrolysis temperatures (>600˚C), which tend to have higher pH and ash content [54].

3.2.4. Adsorption and Desorption

Biochar's high surface area and porous structure allow it to adsorb phosphate ions, which can help retain phosphorus in the root zone and reduce leaching [72]. This is particularly beneficial in sandy or degraded soils with low nutrient retention. However, excessive sorption can immobilize phosphorus, making it less available. [73] in their study using wood chips derived biochar, they observed improved P retention in acidic soils, but decreased P retention in alkaline soils. They ascribed this to biochar ability electro statistically sored P through bridge bond formation using the residual charge in acidic soils. However, in alkaline soils P retention is likely to occur at low energy sites that can easily be desorbed. Biochar surfaces are known to carry residual negative charges and functional groups that can form cation bridges (e.g., Ca^{2+}, Mg^{2+}, Fe^{3+}) between biochar and phosphate ions. This electrostatic attraction at high-energy sites leads to stronger P retention. Conversely, in alkaline soils, the dominant mechanism shifts to low-energy sorption sites (e.g., weak van der Waals forces or outer-sphere complexes). These are easily reversible, so P is more prone to desorption, reducing retention. This difference is tied to pH-dependent surface charge and availability of bridging cations. In acidic conditions, protonation and metal ions favor inner-sphere complexation; in alkaline conditions, deprotonation reduces binding strength.

3.2.5. Microbial Mediation

Biochar can stimulate microbial activity by providing habitat and energy sources for soil microorganisms. This includes phosphate-solubilizing bacteria (PSB) and mycorrhizal fungi, which play a crucial role in converting insoluble phosphorus into plant-available forms. Biochar may also enhance the activity of phosphatase enzymes, which mineralize organic phosphorus compounds. For instance, Afeng

Zhang, Rongjun Bian, Genxing Pan *et al.* [74] observed increased phosphatase activity and microbial biomass P in soils amended with straw-derived biochar. Another study by Max Kolton, Yael Meller Harel, Zohar Pasternak, *et al.* [75] showed that biochar altered microbial community composition, favoring P-cycling organisms. However, Wei He, Jun Zhang, Weichun Gao *et al.*, [8] found that application of rice straw biochar in lateritic red soil had no not significant on microbial biomass phosphorus but there was increased microbial biomass phosphorus following biochar addition in paddy soil. This was attributed to the increased soil Ph which favored positive phosphatase activity.

3.2.6. Interaction with Other Soil Amendments

Biochar can be used in combination with other soil amendments, such as compost, mineral fertilizers, or phosphate rock, to enhance phosphorus availability [28] [65]. These combinations can create synergistic effects, improving nutrient use efficiency and crop performance. For example, Millicent Wanjiku; Min, Hyungi; Kim, Min-Suk; Kim, Jeong-Gyu; Kahura *et al.*, [28] reported that combining biochar with compost increased P availability and maize yield in acidic soils. In a greenhouse experiment, De Amaral Aline Leite, Arnon Afonso De Souza Cardoso, Rafael De Almeida Leite *et al.*, [29] investigated the use of biochar-based fertilizers (BBFs) made from poultry litter and Bayóvar rock phosphate, combined with phosphate-solubilizing bacterial strains, to improve phosphorus availability and maize growth. The study demonstrated that combining biochar with rock phosphate and microbial inoculants is a cost-effective and sustainable strategy to enhance P uptake and crop productivity, especially in tropical soils with high P fixation. Such integrated approaches are particularly valuable in low-input farming systems. A separate study by Tayyba Kanwal Choudhary, Khalid Saifullah Khan, Qaiser Hussain *et al.*, [30] investigated the influence of biochar derived from farmyard manure, sugarcane filter cake, and rice husk on nutrient availability in tropical alkaline soils. Results indicated that farmyard manure biochar significantly enhanced macronutrient availability (N, P, K), whereas sugarcane filter cake biochar improved micronutrient availability (Fe, Zn, Mn). Rice husk biochar exhibited moderate effects on both macro- and micronutrients, suggesting its potential as a balanced amendment.

3.2.7. Redox Reactions

Biochar significantly influences soil redox environments. Its effectiveness stems from redox-active functional groups, electron-accepting/donating capacities, electrical conductivity, and sorptive properties [24]. These characteristics allow biochar to mediate nutrient cycling, organic matter decomposition, and contaminant transformation [67]. For instance, under reducing conditions, iron (Fe) and manganese (Mn) oxides which are major sorbents for phosphorus (P) undergo dissolution as Fe (III) and Mn (IV) are reduced to Fe (II) and to Mn (II), respectively. This transformation releases previously adsorbed phosphate into the soil solution, increasing P availability for plants.

3.3. Mechanisms of Biochar-Induced Phosphorus Mobility: Shifting P Transport from Soil Matrix to Root Surface

Phosphorus reaches root and hyphal surfaces predominantly by diffusion, with a smaller contribution from mass flow under high transpiration [59]. Because phosphate ions sorb strongly and move slowly in unsaturated soils, any amendment that increases solution P concentration (C_P), improves the effective diffusion coefficient (D_e), stabilizes water films, or expands the biological uptake surface area can meaningfully increase P delivery to plants [76]. Biochar does all four through pH mediation, pore-network effects, sorption-desorption buffering, and microbial facilitation (**Table 3**), but outcomes depend on soil type, application method, and environmental drivers [77].

At the root surface, the steady-state P supply can be represented as the sum of diffusive and convective (mass-flow) fluxes:

$$J_{\text{total}} = J_{\text{diff}} + J_{\text{flow}} = -D_e \nabla C_P + q C_P ,$$

where D_e is the effective diffusion coefficient, ∇C_P is the solution concentration gradient, and q is the volumetric water flux toward the root.

Biochar increases D_e by improving pore connectivity and water retention, elevates C_P via lower fixation and slow-release desorption, and can increase q by improving structure and hydraulic properties [77] [78]. Uptake also occurs across AMF hyphae, effectively widening the capture zone and shortening the average path length for P to reach plant sinks [79].

3.3.1. pH as a Master Regulator of Biochar-Enhanced P Mobility

At low pH (<5.5), Fe^{3+}/Al^{3+} activity and positive charges on Fe/Al (hydr)oxides drive specific adsorption and precipitation of strengite/variscite, sharply lowering solution C_P and flattening diffusion gradients [76] [80]. Biochar typically raises pH and contributes DOC, thereby reducing Fe/Al fixation and increasing labile P [73].

At pH 6 - 7, Fe/Al sorption is minimized and Ca activity is insufficient for Ca–P precipitation; solution P is dominated by $H_2PO_4^-$, a relatively mobile species [76]. Biochar's structural and moisture benefits most effectively translate into higher D_e and stronger ∇C_P in this range [77] [78].

As pH increases (pH > 7.5), phosphate speciation shifts toward HPO_4^{2-} and Ca-P precipitation (OCP, hydroxyapatite), which becomes dominant, reducing solution P [59]. High-ash or Ca-rich biochars can exacerbate this, whereas low-ash woody biochars and biologically active co-amendments may help mobilize Ca-bound P [54]. Thus, steering pH toward ~6.0 - 7.0 is pivotal for unlocking biochar's transport benefits across all pathways [77].

3.3.2. Impact of Biochar Physicochemical Properties on Phosphorus Mobility Pathways

Biochar's hierarchical micro-meso-macro pores increase water-film continuity and lower tortuosity, enabling soluble phosphate to traverse the soil matrix more efficiently [77]. Particles function as conduits, reservoirs, and bridging zones that reduce the physical gaps between aggregates and root hairs, thereby increasing D_e and the persistence of diffusion fronts [76] [78].

Weak, reversible sorption and organic coating formation on biochar surfaces create P-rich micro-environments that maintain elevated local C_P and shorten the diffusion distance to root uptake sites, especially in Fe/Al-fixing soils [50]. These hotspots also raise the mass-flow payload qC_P during transpiration pulses.

3.3.3. Enhanced AMF Colonization and Direct P Transfer

Biochar pores provide refugia that stabilize AMF hyphae, increasing hyphal biomass and exploration volume [79]. Hyphae extend beyond the root depletion zone and deliver P directly to cortical cells, effectively bypassing diffusion bottlenecks [59] [77].

3.3.4. Slow-Release Desorption: Buffered P Delivery Near Roots

Following fertilizer dissolution or mineral P mobilization, biochar adsorbs phosphate; as roots deplete solution P, desorption slowly replenishes C_P in the rhizosphere [81]. This buffering prevents rapid fixation and extends residence time in plant-available forms.

Table 3. Soil types and expected P transport dynamics in biochar-amended systems.

Soil type	Key soil characteristics affecting P transport	Dominant P limitation mechanisms	Biochar-enhanced transport pathways are most affected	Expected outcome for P mobility & uptake
Highly Weathered Acidic Soils (Ferralsols, Acrisols)	High Fe/Al oxides; low pH; strong fixation	Fe/Al adsorption/precipitation; low C_P	pH ↑ reduces fixation; DOC competition; micro-hotspots; porous diffusion; AMF	Very high improvement (diffusion, biology)
Sandy/Coarse-Textured Soils	Low water retention; poor connectivity	Water-limited diffusion; weak buffering	Water retention ↑ → D_e ↑; pore conduction; local retention/desorption; microbial habitat	High improvement; reduced leaching
Loam/Silt-Loam Soils	Balanced texture; moderate sorption	Moderate fixation; aggregate barriers	Connectivity ↑; micro-hotspots; AMF colonization; modest pH shifts	Moderate-high (context dependent)
Clay-Rich Soils (Vertisols)	High CEC; shrink-swell; tortuous paths	Strong sorption; slow diffusion	Hotspots shorten path length; AMF bypass; pH adjustment	Moderate; biology helps
Calcareous/Alkaline Soils	High Ca^{2+}/carbonate; pH > 7.5	Ca-P precipitation; low $H_2PO_4^-$	Low-ash biochar; microbial/organic acid dissolution; AMF	Variable (low-moderate); careful feedstock selection
Saline/Sodic Soils	High EC/ESP; poor structure	Ca-P precipitation; dispersive clays	Structure ↑ via porosity; AMF restoration; buffered release	Moderate; depends on biological recovery
Organic/Peat Soils	High OM; low mineral surfaces	P mainly organic-bound	Phosphatase activity ↑; AMF habitats; limited mineral interactions	Moderate; biology-driven
Andisols	Allophane/imogolite; high fixation	Strong ligand exchange	DOC blocks allophane sites; hotspots; partial pH relief	Potentially high, requires high-C functional biochar

3.4. Environmental and Agronomic Implications of Biochar Use

Over the past two decades, research on biochar has expanded rapidly, with thousands of studies exploring its effects on soil properties, crop yields, and environmental outcomes [5] [8] [9] [68] [82]. Meta-analyses and systematic reviews have generally confirmed the positive effects of biochar on soil fertility and crop productivity (**Figure 4**), although the magnitude and consistency of these effects vary widely depending on context [39] [58] [83] [84].

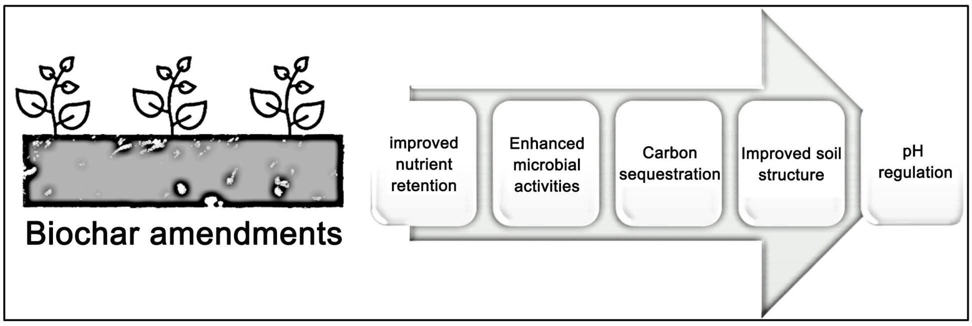

Figure 4. The benefits of biochar use in soil.

In the specific case of phosphorus (P), recent studies have shown that biochar can significantly increase available phosphorus in a variety of soil types and cropping systems [30]. For example, a global meta-analysis by Xu *et al.* [58] found that biochar application increased available phosphorus by an average of 18% across 1,200 field trials, with the greatest effects observed in acidic and phosphorus-deficient soils. These findings underscore biochar's potential as a sustainable amendment for improving phosphorus use efficiency (PUE) and reducing reliance on synthetic fertilizers.

Field experiments in China, India, Africa, and South America have demonstrated that biochar can improve phosphorus uptake and yield in crops such as maize, rice, wheat, soybean, and vegetables. In a study conducted in the Indo-Gangetic plains of India, Singh *et al.* [31] applied rice husk biochar to wheat fields and observed a 22% increase in available phosphorus and a 15% increase in grain yield compared to control plots. The biochar also improved soil aggregation and microbial biomass, contributing to long-term soil health.

In sub-Saharan Africa, where phosphorus deficiency is a major constraint to crop production, biochar has shown promise in enhancing nutrient availability and crop resilience. In a study conducted by Kätterer *et al.* [33] on the effects of locally produced biochar derived from maize cobs and other biomass on maize crops in Kenya focusing on acidic and degraded soils, which are prevalent in the region. Their findings demonstrated significant increases in maize grain yield across all sites and seasons. Additionally, the application of biochar led to consistent improvements in soil fertility, notably enhancing phosphorus availability. These results highlight the potential of biochar as a sustainable soil amendment for improving crop productivity in smallholder farming systems in sub-Saharan Africa.

In China's Yangtze River basin, a long-term field trial evaluated the combined application of biochar and phosphate rock in rice paddies [34]. The study found that the combination significantly increased phosphorus uptake and grain yield while reducing the need for chemical fertilizers. The researchers noted that biochar enhanced the solubility of phosphate rock and stimulated microbial activity, including phosphate-solubilizing bacteria.

In Europe, biochar has been tested in temperate cropping systems with mixed results. A study in Germany applied wood-derived biochar to barley fields and observed modest increases in phosphorus availability and yield [39]. However, the effects were more pronounced when biochar was combined with compost or mineral fertilizers, suggesting that biochar's benefits may be context-dependent and synergistic with other amendments.

In North America, biochar research has focused on its integration into organic and regenerative farming systems. A study in the Bayfield, Ontario, Canada applied a mixture of pine and spruce biochar to corn and soybean fields and found that it increased phosphorus availability, improved soil moisture retention, and enhanced microbial diversity [35]. The study concluded that biochar could be a valuable tool for improving nutrient cycling and resilience in organic systems.

In Australia, where phosphorus efficiency is a key concern due to limited natural reserves, researchers have explored the use of biochar in pasture systems. A study in Queensland applied sugarcane bagasse biochar to pasture soils and observed increased phosphorus availability, improved forage quality, and higher livestock productivity [85]. The biochar also reduced runoff and phosphorus loss during heavy rainfall events. These case studies illustrate the diverse applications and benefits of biochar across different regions, soil types, and cropping systems. They also highlight the importance of tailoring biochar use to local conditions and integrating it with broader nutrient management strategies.

In addition to field trials, greenhouse and laboratory studies have provided insights into the mechanisms by which biochar influences phosphorus dynamics. For example, spectroscopic analyses have shown that biochar can adsorb phosphate ions through ligand exchange and electrostatic interactions [72]. Microbial assays have demonstrated that biochar stimulates the activity of phosphatase enzymes and supports the growth of phosphate-solubilizing microorganisms [54].

Recent innovations in biochar technology have further expanded its potential. Researchers are developing engineered biochar doped with minerals such as magnesium, calcium, or iron to enhance phosphorus retention and release. For instance, a study by Muhammed Mustapha Ibrahim, Huiying Lin, Zhaofeng Chang *et al.* [86] created magnesium-doped biochar and applied it to maize fields in Egypt. The results showed a 26.5% increase in available phosphorus and a significant improvement in crop yield and nutrient use efficiency.

Another promising approach is the use of biochar-based fertilizers, which combine biochar with organic or inorganic nutrient sources. These formulations offer controlled nutrient release, improved nutrient retention, and reduced environmental losses. A study in Gajuri-1, Dhading, Nepal, tested a biochar-compost blend on okra crops and found that it increased phosphorus availability, reduced fertilizer requirements, and improved crop quality [32].

Overall, the rise of biochar in agricultural research and practice reflects a growing recognition of its multifunctional benefits. While challenges remain, including variability in biochar properties and economic feasibility, the evidence suggests that biochar can play a key role in sustainable phosphorus management and soil fertility enhancement. Continued research, innovation, and collaboration among stakeholders will be essential to realize its full potential.

4. Toward a Sustainable Phosphorus Future

Phosphorus is a non-renewable resource, primarily mined from phosphate rock deposits concentrated in a few countries [87]. The uneven global distribution of these reserves raises concerns about geopolitical vulnerability and long-term availability [88]. Moreover, the inefficiency of conventional phosphorus fertilizers, where often less than 20% of applied P is taken up by crops, leads to significant losses through leaching, runoff, and fixation in unavailable forms [5]. These losses not only represent economic inefficiency but also contribute to environmental problems such as eutrophication of water bodies and greenhouse gas emissions from fertilizer production. In this context, sustainable phosphorus management is not merely a technical challenge but a strategic imperative. It requires a shift from linear nutrient flows where phosphorus is mined, applied, and lost to circular systems that recycle and retain phosphorus within agricultural landscapes.

Biochar, with its multifunctional properties, offers a compelling solution to many of these challenges, particularly in the context of phosphorus use efficiency and soil health (**Figure 5**).

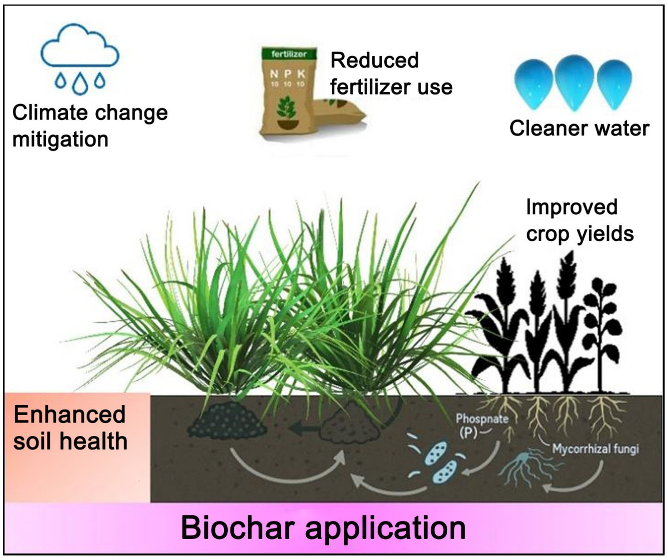

Figure 5. Biochar for sustainable phosphorus management.

Many studies demonstrated biochar's role in phosphorus management and soil fertility. Kumari *et al.* [89] reviewed the use of both unmodified and modified biochar for phosphorus adsorption and recovery from waste streams, highlighting their potential as slow-release P fertilizers and their dual function in wastewater treatment and agricultural reuse. Mingying Dong, Mengyuan Jiang, Lizhi He, *et al.* [90] examined environmental risks and unintended consequences of biochar application, emphasizing how feedstock type and pyrolysis conditions influence nutrient interactions, particularly phosphorus, which is critical for sustainable use. Furthermore, Qiumeng Zhong and Sai. Liang [91] focused on phosphorus balancing for optimal crop yields and identified biochar as a promising strategy to enhance P use efficiency in nutrient-limited cropping systems. Collectively, these studies position biochar as a key tool for sustainable phosphorus management, while stressing the need to consider its properties and environmental implications.

4.1. Biochar as a Circular Economy Tool

Biochar production demonstrates circular economy principles by converting organic and agricultural waste into useful soil amendment instead of discarding or burning them. Through pyrolysis, crop residues, animal manure, and forestry byproducts can be transformed into biochar, which not only sequesters carbon but also retains essential nutrients such as phosphorus [72]. When applied to soil, biochar functions as a slow-release fertilizer, provides habitat for beneficial microbes, and mitigates nutrient losses, thereby reducing reliance on external inputs and lowering waste disposal costs [5]. This closed-loop approach enhances farming system sustainability. For instance, in phosphorus-deficient regions such as sub-Saharan Africa and parts of Asia, locally produced biochar from nutrient-rich feedstocks like poultry litter or bone meal have been shown to offer an affordable and accessible source of plant nutrients [92] [93].

4.2. Enhancing Soil-Plant-Microbe Interactions

One of the most promising aspects of biochar is its ability to influence the soil microbiome. Research have shown that Phosphorus availability in soil is not solely a chemical process but also biologically mediated [53]. Microorganisms such as phosphate-solubilizing bacteria (PSB) and arbuscular mycorrhizal fungi (AMF) play a pivotal role in mobilizing phosphorus from both organic and mineral sources, thereby improving its bioavailability to plants [54]. PSB enhances phosphorus cycling by secreting organic acids and enzymes that solubilize insoluble phosphate compounds, while AMF form symbiotic associations with plant roots, extending the root surface area and facilitating phosphorus uptake from soil microsites [36] [54] [94]. When integrated with biochar amendments, these microbial communities can further optimize nutrient dynamics by colonizing biochar pores, which provide a favorable habitat and help retain moisture and nutrients [69]. Moreover, this microbial stimulation not only improves phosphorus availability but also contributes to broader soil health benefits, including disease suppression, nutrient cycling, and organic matter stabilization. Consequently, the synergistic interaction between biochar and soil microbes is increasingly recognized as a sustainable strategy to address phosphorus limitations in agroecosystems.

4.3. A Vision for the Future

As the global community seeks to transition to more sustainable food systems, biochar offers a valuable tool for closing the phosphorus loop, reducing dependence on finite resources, and building healthier soils for future generations. Its integration into phosphorus management strategies represents not just a technical innovation but a paradigm shifts toward regenerative agriculture.

In this vision, farms are not just sites of production but ecosystems that recycle nutrients, sequester carbon, and support biodiversity. Biochar, when used wisely and in conjunction with other sustainable practices, can help realize this vision, transforming waste into wealth, restoring degraded lands, and ensuring that the essential nutrient phosphorus remains available for generations to come.

5. Challenges and Knowledge Gaps

Despite the growing body of evidence supporting the benefits of biochar in phosphorus (P) management, several critical challenges and knowledge gaps remain. These limitations must be addressed to ensure the effective, safe, and scalable use of biochar in diverse agricultural systems. This section explores five major areas of concern: variability in biochar properties, soil-specific responses, long-term effects, economic and logistical barriers, and regulatory and policy frameworks (**Figure 6**). Additional case studies and examples are included to illustrate these challenges in real-world contexts.

5.1. Variability in Biochar Properties

Biochar is not a uniform product; its properties vary significantly depending on the feedstock and pyrolysis conditions. For instance, biochar made from manure or bone meals typically contain higher phosphorus levels than those made from woody biomass [95], but it may also carry risks of heavy metal contamination [39]. Pyrolysis temperature also plays a crucial role: higher temperatures increase surface area and porosity, enhancing adsorption capacity, but may reduce phosphorus solubility. This variability complicates the development of standardized application guidelines and makes it difficult for farmers and agronomists to predict outcomes.

The interaction between biochar and phosphorus is highly dependent on soil characteristics. In acidic soils, biochar can raise pH and reduce phosphorus fixation by aluminum and iron oxides, increasing availability [96]. However, in calcareous soils, it may exacerbate phosphorus precipitation with calcium, reducing availability [96]. Soil texture also influences outcomes. Biochar has shown greater benefits in sandy and clay soils compared to loamy soils, particularly in terms of phosphorus retention and crop yield [52]. In a field trial in Kenya, biochar application in sandy soils significantly improved maize yield and phosphorus uptake, while in loamy soils, the effect was negligible [33]. The researchers attributed this to the higher leaching potential in sandy soils, where biochar helped retain nutrients in the root zone. These findings underscore the need for site-specific recommendations and tailored biochar formulations.

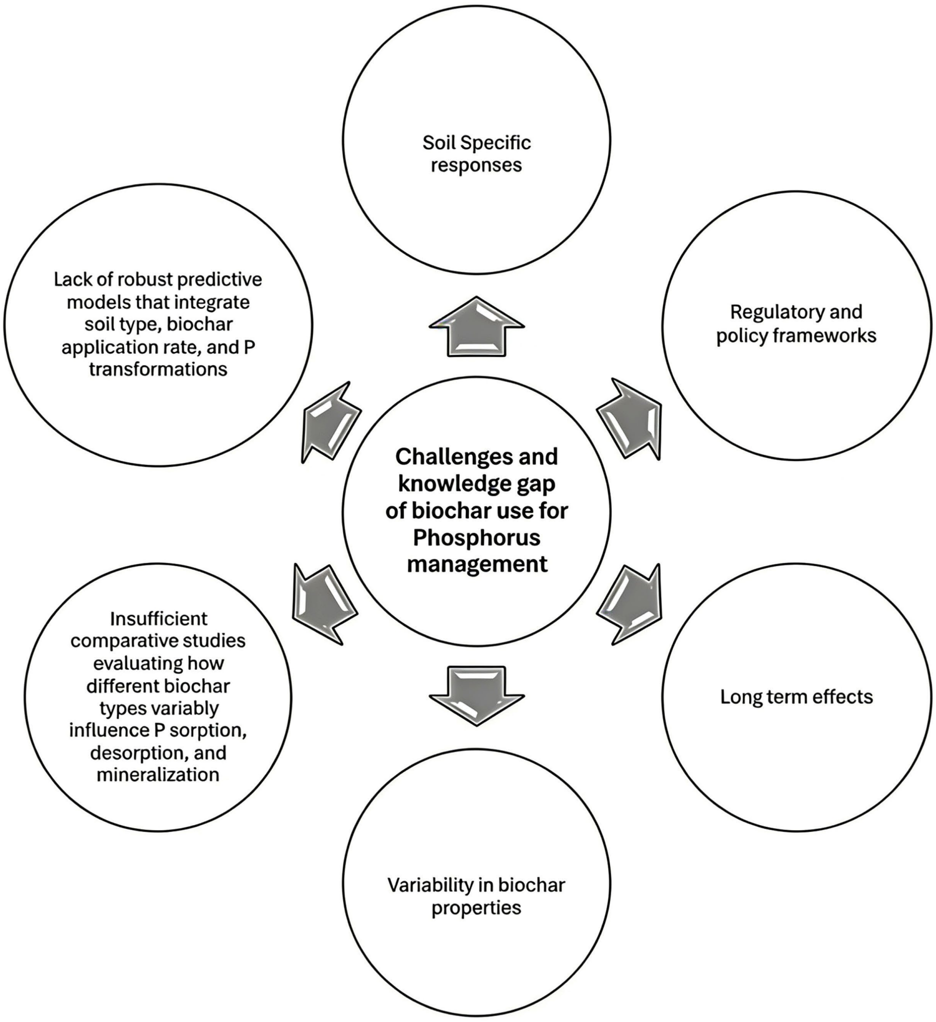

Figure 6. Challenges and knowledge gaps hindering biochar use for soil amendment.

5.2. Long-Term Effects

Most studies on biochar and phosphorus dynamics are short-term, often limited to one or two growing seasons. However, biochar undergoes aging and weathering in soil, which can alter its structure, surface chemistry, and nutrient interactions over time. Long-term field trials are essential to evaluate the persistence of biochar's benefits and potential trade-offs, such as nutrient lock-up or shifts in microbial communities. Hardeep Singh, Brian K. Northup, Charles W. Rice, [39] highlighted the importance of long-term studies to understand how biochar's properties evolve and how these changes affect soil fertility and phosphorus availability.

A comprehensive 10-year field study conducted in China investigated the long-term impacts of continuous biochar application on rice paddy ecosystems [97]. In the initial years, biochar amendments significantly enhanced soil fertility, particularly by increasing the availability of phosphorus (P), a critical nutrient for plant growth. This improvement translated into notable gains in rice yield, affirming biochar's potential as a sustainable soil amendment. However, the study revealed a nuanced trajectory of biochar's effectiveness over time. After approximately five years, the positive effects on phosphorus availability and crop yield began to plateau. This shift suggested that biochar's benefits are not linear or indefinitely sustained, but rather dynamic and influenced by evolving soil conditions and biological interactions. One of the key findings was the alteration in soil microbial communities. Biochar initially stimulated microbial activity, due to its porous structure and nutrient content, which created favorable microhabitats. Over time, however, the microbial composition shifted, potentially leading to changes in nutrient cycling processes, particularly those involving phosphorus. The researchers observed transformations in phosphorus fractions specifically, a decline in labile P forms and an increase in more stable, less bioavailable forms. This shift may have contributed to the reduced effectiveness of biochar in enhancing P availability in the latter half of the study.

These findings emphasize the importance of periodic reassessment of biochar application strategies. Rather than relying on continuous, uniform application, adaptive management approaches may be necessary such as adjusting application rates, combining biochar with other amendments, or implementing crop rotation and microbial inoculation strategies to sustain soil health and productivity. In addition, the study highlights the complexity of biochar-soil-plant-microbe interactions and the need for long-term monitoring to fully understand the ecological consequences of biochar use. It also raises important questions about the sustainability of biochar as a one-size-fits-all solution and encourages further research into optimizing its use across different agroecosystems.

5.3. Economic and Logistical Barriers

The production, transportation, and application of biochar can be cost-prohibitive, especially for smallholder farmers. Pyrolysis equipment requires capital investment, and the biochar's low bulk density makes it expensive to transport. Additionally, there is limited infrastructure for biochar distribution and few established markets in many regions. To address these barriers, decentralized production models, such as community-based pyrolysis units, and integration with existing waste management systems are being explored. However, more research is needed on cost-effective production methods and scalable application strategies. For instance, Pawan Kumar and Dheeraj Bisht reported a field trial on paddy, pearl millet, and onion. Results revealed that biochar applications improve seedling emergence by ~15% and enhance crop growth. When combined with compost or fertilizers, biochar increases yields, reduces chemical fertilizer use by 20% - 40%, and contributes to carbon sequestration. They argued that Large-scale conversion of crop residues into biochar could generate carbon credits and boost rural incomes, positioning biochar as a tool for climate-resilient agriculture [10]. Despite its potential, biochar adoption remains slow due to limited stakeholder awareness, weak market incentives, technological dependence, policy uncertainty, lack of standardized quality frameworks, inadequate infrastructure, and absence of certification systems. Experts argue that strengthening domestic production capacity, harmonizing standards, and integrating biochar into agricultural policies are critical steps toward promoting sustainable soil health and carbon management.

5.4. Regulatory and Policy Frameworks

The regulatory landscape for biochar is still underdeveloped in many countries. There are few standardized guidelines for biochar quality, safety, or application rates. This lack of regulation can hinder adoption and create uncertainty for producers and users. Policy support is also limited. Biochar is often excluded from agricultural subsidy programs and climate mitigation strategies, despite its potential to sequester carbon and improve nutrient use efficiency. Developing harmonized regulations, certification systems, and incentive structures is essential to promote wider adoption.

The European Biochar Certificate (EBC) provides a model for quality assurance and traceability [98]. Countries that have adopted EBC standards have seen increased investment and farmer confidence in biochar products. In contrast, regions without such frameworks face challenges in scaling up production and use. Therefore, addressing the policy challenges and knowledge gaps associated with biochar use is essential for unlocking its full potential. This requires a multidisciplinary approach that integrates agronomy, soil science, engineering, economics, and policy.

5.5. Knowledge Gap

Despite growing evidence on the role of biochar in modifying soil phosphorus (P) dynamics, several critical knowledge gaps remain. First, comparative studies evaluating how different biochar types variably influence P sorption, desorption, and mineralization processes are limited. Most existing research focuses on single biochar sources, making it difficult to generalize findings across diverse feedstocks and production conditions. Second, there is a lack of robust predictive models that integrate soil type, biochar application rate, and P transformations, hindering the ability to forecast P availability under different soil-biochar systems. Lastly, field-scale validation remains insufficient, as many studies rely heavily on short-term laboratory or greenhouse experiments, which do not fully capture the complexities of real-world soil environments.

6. Conclusions

Biochar has emerged as a promising and multifaceted solution to the challenges of phosphorus management in agricultural systems. Its ability to enhance phosphorus availability through chemical, physical, and biological mechanisms positions it as a valuable tool for improving soil fertility, crop productivity, and environmental sustainability. The review highlights that biochar can directly contribute to phosphorus, modify soil pH to reduce fixation, adsorb and gradually release phosphate ions, and stimulate microbial communities that facilitate phosphorus cycling.

Case studies from diverse agroecosystems demonstrate that biochar application can significantly improve phosphorus use efficiency, particularly in acidic and nutrient-depleted soils. These benefits are often accompanied by improvements in soil structure, water retention, and microbial activity, contributing to more resilient and productive farming systems. Despite its potential, several challenges remain. The effectiveness of biochar is highly context-dependent, influenced by factors such as feedstock type, pyrolysis conditions, soil characteristics, and crop species. In addition, variability in biochar properties, the need for long-term field validation, economic feasibility for smallholder farmers, and the lack of standardized guidelines for application remain a challenge. Addressing these challenges will require interdisciplinary research, farmer education, and supportive policy frameworks that promote sustainable practices. Therefore, biochar represents a strategic innovation in sustainable agriculture. When integrated thoughtfully into phosphorus management strategies, it can help close nutrient loops, reduce environmental impacts, and support global food security. Continued research, innovation, and collaboration among stakeholders will be essential to fully realize the benefits of biochar in modern farming systems.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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