PHOSPHORUS RECOVERY AND REUSE AS SOIL AMENDMENT FROM DIVERS SORBENT MATERIALS

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Abstract
Phosphorus (P) is an essential macronutrient for plant growth, yet its inefficient use and finite supply present major challenges to agricultural sustainability and environmental protection. Excessive P losses from agricultural runoff contribute to eutrophication, while the depletion of phosphate rock raises concerns about long-term food security. Sustainable P management strategies, including recovery and reuse, have gained attention as viable solutions. Sorbent materials, including mineral-based, waste-derived, and modified materials, offer promising approaches for P capture, removal from wastewater, and potential reuse in agriculture. This review evaluates the efficiency of different sorbent materials in P recovery and their application as soil amendments to enhance P availability. Mineral-based sorbents, such as calcium silicates and iron oxides, provide cost-effective solutions but have limited regeneration potential. Waste-derived sorbents, including biochar and industrial by-products, contribute to a circular economy by repurposing waste materials but require further assessment due to potential heavy metal contamination. Modified sorbents, such as lanthanum- and magnesium-modified materials, exhibit superior P adsorption and slow-release properties but face challenges in scalability and cost. Additionally, microbial interactions play a crucial role in P bioavailability, with phosphate-solubilizing bacteria enhancing nutrient release. Despite advancements in P recovery technologies, challenges remain regarding economic feasibility, regulatory frameworks, and long-term field performance. Standardized testing protocols, risk assessments, and policy support are necessary to facilitate the adoption of sorbent-based P management strategies. The integration of these materials into agricultural systems offers a sustainable pathway to improving P efficiency, reducing environmental impact, and promoting circular nutrient use.
Keywords: phosphorus recovery, phosphorus capture, soil amendment, sorbent materials, circular economy.

Introduction

Phosphorus (P) is an essential macronutrient for plant growth, playing a crucial role in energy transfer, photosynthesis, and root development. It is indispensable for global agricultural productivity and food security, with phosphate fertilizers being a primary input for enhancing crop yields (Roberts & Johnston, 2015). However, P is a finite and non-renewable resource, predominantly sourced from phosphate rock, which is being depleted at an alarming rate. Estimates suggest that global phosphate rock production may peak by 2035, raising concerns about long-term agricultural sustainability (Cordell et al., 2011). Despite its critical role, P use in agriculture remains inefficient, with a significant proportion lost through soil fixation, runoff, and erosion (Roberts & Johnston, 2015).

The loss of P from agricultural fields contributes to severe environmental issues, particularly eutrophication. Excess P leaching into water bodies accelerates the growth of harmful algal bloom, leading to oxygen depletion, fish mortality, and disruption of aquatic ecosystems (Alewell et al., 2020; Yang et al., 2021).

Agricultural runoff, soil erosion, and the overuse of P-based fertilizers are primary contributors to this issue, making it a global concern (Zou et al., 2020). Studies indicate that over 50% of total P losses in some agricultural systems occur due to soil erosion, particularly in regions with intensive farming and inadequate nutrient management (Alewell et al., 2020).

Due to P scarcity and environmental degradation, sustainable P management strategies are urgently needed. Efficient P recovery and reuse from waste streams, including manure, wastewater, and crop residues, have been proposed as viable solutions (Sarvajayakesavalu et al., 2018). Innovations in P recycling technologies, including biochar-based amendments, targeted fertilization, and microbial-assisted P mobilization, can improve P use efficiency while reducing environmental risks (Yang et al., 2021). Integrated nutrient management practices, focusing on optimizing P application and minimizing losses, are crucial for achieving a more circular P economy (Schneider et al., 2019).

To mitigate P loss and its associated environmental impacts, various technologies have been developed for P removal from wastewater and agricultural runoff. Among these, sorbent materials have emerged as an effective and sustainable solution for P sequestration (Altamira-Algarra et al., 2022). Sorbent materials are substances capable of adsorbing or precipitating P, thereby preventing its release into water bodies. These materials can be classified into natural sorbents (e.g., biochar, clay minerals), industrial by-products (e.g., red mud, steel slag), and modified materials (e.g., metal oxides, modified biochar) (Gubernat et al., 2020; Nobaharan et al., 2021).

One of the applications of sorbent materials is in wastewater treatment systems, where they enhance P removal mainly through adsorption, ion exchange and chemical precipitation mechanisms (Zhou et al., 2021). Phosphorus-binding materials, such as calcium- and iron-rich sorbents, bind P ions, forming insoluble compounds that can be easily separated from wastewater (Stávková & Maroušek, 2021). Constructed wetlands and modified P filter systems often integrate these sorbents to improve P capture efficiency (Kasprzyk et al., 2021). Additionally, waste-based adsorbents, such as modified biochar and industrial residues, are gaining attraction as cost-effective alternatives for P removal (Pap et al., 2020).

Additionally, these sorbent materials hold potential for reuse in agriculture as soil amendments. When saturated with P, sorbent materials can serve, for example, as slow-release fertilizers, replenishing soil P reserves while minimizing environmental losses (Altamira-Algarra et al., 2022). Studies have demonstrated that biochar-based sorbents, lanthanum-modified clays, and calcium-rich industrial by-products enhance P availability in soils while improving soil structure and water retention (Gubernat et al., 2020; Nobaharan et al., 2021). The integration of P sorbents into agricultural systems aligns with the principles of a circular economy, promoting nutrient recovery and sustainable soil management (Zhou et al., 2021).

By bridging wastewater treatment and agricultural nutrient management, sorbent technologies offer a promising pathway to reduce P dependency while mitigating environmental impacts. Their integration into systems such as treatment plants, constructed wetlands, and filtration units can significantly enhance P recovery efficiency, supporting the transition toward a more circular and sustainable P economy (Stávková & Maroušek, 2021; Altamira-Algarra et al., 2022).

As P recovery technologies evolve, optimizing the application of sorbent materials will play a critical role in balancing economic feasibility, environmental impact, and long-term resource security. This methodological approach ensures a comprehensive evaluation of different sorbent materials, highlighting their effectiveness in P capture and reuse while assessing their potential impact on soil fertility, microbial activity, and overall environmental sustainability.

This review aims to evaluate various sorbent materials, including natural sorbents, industrial by-products, and modified materials, for their effectiveness in P recovery and their potential as soil amendments to enhance P availability and improve overall soil health.

Materials and Methods

This review follows a structured approach to systematically analyze and synthesize existing research on P recovery and reuse using various sorbent materials. The methodology includes defining selection criteria, identifying relevant literature, and categorizing sorbent materials based on their composition and potential for P recovery and reuse as soil amendments.

The literature search was conducted using academic databases such as Scopus, Web of Science and ScienceDirect. Studies were selected based in their relevance to P recovery, their evaluation of sorbent reuse in soil, and their contribution to sustainable nutrient management. The review focused on publications from the past decade to ensure coverage of recent advancements in P recovery technologies.

Results and Discussion

Traditional P recovery methods from wastewater and sludge, such as chemical precipitation, enhanced biological P removal (EBPR), adsorption, and thermal treatment, have been widely implemented, but each comes with significant limitations. Chemical precipitation using calcium, magnesium, iron, or aluminum salts is highly effective but requires substantial chemical input and can lead to unwanted co-precipitation, making it less cost-effective, particularly for low P concentrations. EBPR, which relies on phosphate-accumulating organisms (PAOs), offers a biological alternative but is sensitive to wastewater composition and produces excess sludge requiring further treatment (Di Capua et al., 2022). Adsorption and ion exchange technologies, employing materials like modified clays, biochar, or ion-exchange resins, provide selective P removal but are constrained by high operational costs and limited regeneration cycles (Zhang et al., 2022). Meanwhile, thermal treatment of sewage sludge, including incineration and acid leaching, demands significant energy inputs and poses challenges related to heavy metal contamination and complex post-treatment requirements (Vu et al., 2023).

P adsorption efficiency varies significantly depending on the type of sorbent material, its surface chemistry, and the environmental conditions in which it operates. The mechanisms of P adsorption primarily include ligand exchange, electrostatic attraction, surface precipitation, and ion exchange, which are influenced by the mineral composition and functional groups present in the sorbent material (Du et al., 2022).

To overcome the challenges associated with P loss and limitations in conventional recovery methods, it is essential to develop sustainable and cost-effective solutions with high selectivity, reusability, and reduced chemical dependency (Di Capua et al., 2022). In this review, the proposed categories - mineral-based, waste-derived, and modified sorbents - each demonstrates distinct strengths and limitations in P capture.

Mineral-based sorbents, including zeolite, bentonite, iron oxides, and calcium silicates, exhibit effective phosphate binding due to their high surface area and natural ion-exchange capabilities (Zhao et al., 2024). Iron and aluminum oxides demonstrate a strong affinity for phosphate through ligand exchange reactions, forming stable inner-sphere complexes that prevent leaching in soil applications (Dai et al., 2014). Similarly, iron oxides and hydroxides, commonly used in wastewater treatment, effectively bind phosphate due to their large surface area and high ligand exchange capacity (Jin et al., 2024). However, calcium-rich sorbents, such as wollastonite and calcium silicate, facilitate P precipitation, but often exhibit limited adsorption capacity in acidic conditions, which affects their overall efficiency in wastewater treatment (Gustafsson et al., 2008). While naturally abundant and effective in ion exchange, mineral-based sorbents generally have lower adsorption capacities compared to modified alternatives, which enhance phosphate retention and release properties (Vu et al., 2023).

Waste-derived sorbents, such as biochar, sludge char, and industrial by-products like steel slag and fly ash, offer sustainable alternatives for P capture while simultaneously reducing waste accumulation (Altamira-Algarra et al., 2022; Di Capua et al., 2022). Biochar and activated carbon, produced from pyrolyzed biomass, offer high adsorption efficiency due to their porous structure and surface functionalization (Kaljunen et al., 2022). Additionally, treated biosolids and pyrolyzed sludge char have shown high P recovery potential, particularly when modified with metal ions to enhance adsorption capacity (Maroušek & Gavurová, 2022).

Modified sorbents demonstrate superior P adsorption due to their tailored surface functionalities and high selectivity (Du et al., 2022; Zhang et al., 2022). Functionalized biochar, modified with Mg, Ca, or La, has been developed to enhance P adsorption efficiency and controlled nutrient release (Zhao et al., 2024). Additionally, composite materials such as nanomaterials and polymer-coated sorbents have been studied for their enhanced selectivity and efficiency in P binding (Ding et al., 2023). Lanthanum-doped hydrocar shows P adsorption capacity >50 mg/ g across a wide pH range (2.5-10.5), making it a promising material for large-scale wastewater treatment (Dai et al., 2014). Nevertheless, the complexity and cost of producing modified sorbents remain key barriers to their widespread adoption (Zhao et al., 2024).

The ability to regenerate sorbents and reuse them in subsequent cycles is a critical factor in determining their feasibility for long-term P recovery. Mineral-based sorbents, particularly calcium silicates and iron oxides, show moderate regeneration potential but often experience decreased adsorption efficiency over multiple cycles due to structural degradation (Zhao et al., 2024). While some natural minerals, such as zeolites, can be regenerated via ion exchange, others, such as bentonite, require chemical washing or thermal treatment to restore their P adsorption capacity (Altamira-Algarra et al., 2022).

Modified sorbents offer the highest potential for reuse, with modifications designed to enhance their stability and longevity (Biswas et al., 2023). Layered double hydroxides (LDHs), for instance, have demonstrated strong regeneration potential through chemical treatments, allowing for multiple cycles of P capture and release without significant loss in efficiency (Zhao et al., 2024). Additionally, metal–organic frameworks and functionalized nanomaterials have been designed to facilitate controlled P desorption, ensuring that recovered P remains bioavailable for agricultural use (Gao et al., 2023). However, cost and environmental concerns related to the synthesis and disposal of modified sorbents continue to limit their large-scale implementation (Biswas et al., 2023).

Table 1 presents a comparative analysis of various sorbent materials based on their P adsorption capacity, removal efficiency and reuse potential.

The use of P-enriched sorbents as soil amendments is a promising strategy for improving P availability in agricultural soils while enhancing soil health. The efficiency of these sorbents in releasing P depends on various factors, including soil pH, microbial activity, and mineral interactions. Different sorbent materials release P at varying rates, influencing its bioavailability to crops and its long-term effectiveness as a fertilizer substitute.

Table 1
Efficiency of various sorbents in phosphorus removal and recover

Sorbent type	*Sorbent*	*Reuse Application*	*Adsorption capacity (mg·g^{-1}) / Removal efficiency (%)*	*Phosphorus source*	*Reference*
Mineral-based sorbents	Filtra P	Soil amendment, Fertilizer (slow-release)	98.20%	Synthetic P solution	Gustafsson et al., 2008
	Polonite	Soil amendment, Fertilizer	96.70%		Gustafsson et al., 2008
	Wollastonite	Limited soil use	51.10%		Gustafsson et al., 2008
	Zeolite	Soil amendment in high ion-exchange areas	73.62%	P rich wastewater from WWTP	Jiang et al., 2013
	Hydroxyapatite /calcium silicate hydrate	Remediation, Soil amendment for acidic soils	138.00 mg·g^{-1}	P rich wastewater from farmland	Liu et al., 2021
Waste-derived sorbents	Biochar	Soil amendment, Fertilizer (slow-release), Carbon enrichment	40.00 mg·g^{-1}	P leachate from wastewater sludge	Kaljunen et al., 2022
	Sludge Char	Soil conditioning, Fertilizer (slow-release)	50.00 mg·g^{-1}		
	Commercial Lignin	Organic amendment, Fertilizer (slow-release)	40.00 mg·g^{-1}		
	Humus Extract	Fertilizer (slow-release)	40.00 mg·g^{-1}		

Sorbent type	*Sorbent*	*Reuse Application*	*Adsorption capacity (mg·g^{-1}) / Removal efficiency (%)*	*Phosphorus source*	*Reference*
Modified sorbents	Lanthanum-doped Hydrochar	Soil amendment, Fertilizer (slow-release)	61.57 mg·g^{-1}	Synthetic P solution	Dai et al., 2014
	CaP enriched biochar	Fertilizer (80% plant-available P), Economic use	31.80 mg·g^{-1}	P from sludge water	Stávková & Maroušek, 2021
	Magnetic Biochar	Potential fertilizer	48.83 mg·g^{-1}	Synthetic P solution	Manoko et al., 2022
	MgO-biochar modified by hydroxyl and amino groups	Fertilizer, Biochar regeneration	43.27 mg·g^{-1}		Zhang et al., 2024
	Zirconium-modified red mud	Long-term P stabilization	33.14 mg·g^{-1}		Li et al., 2021
	MgO-impregnated magnetic biochar	Fertilizer	121.25 mg·g^{-1}		Li et al., 2016

Biochar-based sorbents, derived from agricultural residues, sludge char, or industrial by-products, exhibit slow-release P properties, making them particularly valuable in high P-fixing soils (Carneiro et al., 2021). Biochar enriched with P through pre- or post-pyrolysis treatments has been shown to increase soil P reserves, enhance plant uptake and sustain P availability over multiple growing seasons (Carneiro et al., 2021). Studies indicate that P-enriched biochar fertilizers can replace conventional P fertilizers without compromising crop yield, demonstrating both short-term efficiency and long-term sustainability (Carneiro et al., 2021).

Mineral-based sorbents, such as calcium silicates, iron oxides, and zeolites, exhibit varying P desorption capacities depending on soil conditions (Hemati Matin et al., 2020). Calcium silicate materials, for example, are highly effective in alkaline soils where they slowly release P in bioavailable forms. However, in acidic soils, P may become less available due to interactions with aluminium and iron oxides, requiring additional modifications or amendments (Hemati Matin et al., 2020). Studies suggest that modified sorbents can enhance P efficiency by over 90%, ensuring sustained crop nutrition (Chen et al., 2022).

P availability in soil is influenced by several factors, including soil pH, microbial activity, nutrient interactions, and long-term residual effects. Soil pH plays a critical role in P solubility and plant uptake. In acidic soils, P tends to bind with aluminium and iron oxides, forming insoluble complexes that reduce its accessibility to crops (Chen et al., 2022). Conversely, in alkaline soils, calcium-bound P dominates, which can be effectively released from calcium silicate-based sorbents, ensuring a more sustained P supply to plants (Chen et al., 2022). The interaction between soil amendments and pH highlights the importance of choosing the appropriate sorbent materials based on specific conditions to optimize P availability.

Microbial activity is another crucial factor that determines how efficiently P is released from sorbent materials and made available for plant uptake (Cho et al., 2020). Phosphate-solubilizing bacteria (PSB), such as *Pseudomonas* and *Bacillus sp.*, enhance P solubilization by producing organic acids and enzymes that break down P complexes (Kalayu, 2019). This microbial action is particularly beneficial when using biochar-based and waste-derived sorbents, as these materials provide a habitat for microbial colonization, thereby facilitating P release into the soil (Leader et al., 2008). In biologically active soils, the combined use of P-enriched sorbents and microbial inoculants can significantly improve P bioavailability for crops (Cho et al., 2020).

Nutrient interactions also play an important role in P uptake efficiency. The availability and uptake of P are closely linked to the presence of other soil nutrients, particularly nitrogen, calcium and iron. Studies indicate that nitrogen-phosphorus interactions influence root structure and P absorption, with evidence showing that combined applications of biochar-based sorbents and nitrogen fertilizers can enhance P efficiency (Leader et al., 2008). Additionally, iron and aluminium oxides present in some mineral sorbents may contribute to P retention, reducing leaching losses while ensuring slow and steady P release over time (Chen et al., 2022).

Long-term residual effects of P-enriched sorbents further influence soil P dynamics. Unlike synthetic fertilizers that release P immediately, sorbent-based P amendments contribute to the long-term P reserve in soil. Biochar-based phosphate fertilizers, for instance, increase the non-labile P fraction, maintaining nutrient availability for multiple growing seasons (Carneiro et al., 2021).

The gradual P release from these sorbents reduces the risk of nutrient runoff and enhances the sustainability of soil P management (Chen et al., 2022). Overall, the integration of P-enriched sorbents into soil amendment practices provides a long-term strategy for improving P efficiency while promoting soil fertility and sustainability.

P-enriched sorbents pose several challenges that must be addressed for widespread adoption in agricultural systems. One major concern is the potential accumulation of heavy metals or contaminants in soil. Waste-derived sorbents, such as biosolids, industrial by-products, and biochar from municipal sludge, may contain trace amounts of heavy metals like cadmium, lead and arsenic, which can accumulate in soil over time and pose risks to food safety (Chen et al., 2022). Regulatory measures must be implemented to ensure that these materials undergo rigorous testing and treatment before application to agricultural lands.

The economic feasibility of large-scale P recovery and reuse also presents a challenge. While P-enriched sorbents offer long-term benefits, the initial cost of processing, modification, and application can be significantly higher than that of conventional P fertilizer (Cho et al., 2020). The production of modified sorbents, such as lanthanum-modified biochar or nanocomposite sorbents, involves high material and synthesis costs, making them less accessible for widespread use (Chen et al., 2022). To improve economic feasibility, incentive programs, subsidies, and cost-sharing initiatives could encourage farmers to adopt these materials as part of sustainable soil management practices.

Lastly, regulatory considerations for applying recovered materials to farmland are crucial to ensure environmental safety and effectiveness. Many P sorbents, particularly waste-derived materials, must comply with agricultural and environmental regulations regarding heavy metal content, nutrient composition, and leaching potential (Nanda et al., 2020). However, existing fertilizer policies often lack clear guidelines for P-recovered materials creating regulatory uncertainty that hinders their adoption (Barquet et al., 2020). Recent updates to the EU Fertilizing Products Regulation aim to integrate waste-derived fertilizers, improving market access, yet many national policies remain fragmented, limiting large -scale implementation (Nanda et al., 2020).

Establishing standardized testing protocols, risk assessments, and certification programs for P-enriched sorbents will be essential to gaining farmer trust and ensuring safe, effective agricultural use (Nanda et al., 2020; Barquet et al., 2020).

Conclusions

1. P recovery and reuse through sorbent materials is a sustainable strategy to address global P scarcity and environmental challenges. The study highlights the potential of mineral-based, waste-derived and modified sorbents in improving P management efficiency.
2. Mineral-based sorbents, such as iron oxides, calcium silicates, and zeolites, offer cost-effective and naturally abundant solutions for P recovery. However, their limited regeneration potential and dependency on soil pH affect long-term performance.
3. Waste-derived sorbents, including biochar, treated biosolids, and industrial by-products, provide a sustainable approach to P recovery while reducing landfill waste. Their performance variability and potential heavy metal contamination require further treatment and regulatory oversight.
4. Modified sorbents, such as lanthanum- and magnesium- modified biochar, demonstrate high P adsorption efficiency and slow-release properties. However, their high production costs and scalability challenges hinder widespread agricultural application.
5. P-enriched sorbents improve soil fertility, crop productivity, and nutrient efficiency, offering a slow-release alternative to conventional fertilizers. Their ability to reduce P leaching mitigates the environmental risks of eutrophication.
6. Microbial interactions significantly influence P bioavailability from sorbents, with P-solubilizing bacteria playing a crucial role in nutrient release and uptake. Enhancing microbial compatibility in sorbent applications can improve long-term soil health.
7. Challenges in large-scale P recovery include economic feasibility, heavy metal accumulation, and regulatory compliance. Policy frameworks must support the safe and effective integration of recovered P materials into agricultural practices.
8. Future research should focus on optimizing sorbent modifications, improving P desorption mechanisms, and conducting field-scale evaluations to enhance the practical viability of these materials in sustainable farming.
9. The integration of P recovery into circular economy models is essential for long-term food security, environmental sustainability, and resource conservation, reducing dependence on finite phosphate reserves and promoting resilient agricultural systems.

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