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# Microbial and biotechnological approaches to harness agricultural wastes for sustainable phosphorus management in crop production

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Global phosphorus (P) management faces critical challenges driven by rising demand, inefficient fertilizer use, and environmental degradation. The depletion of finite phosphate rock reserves, coupled with low crop uptake efficiencies and substantial soil fixation, underscores the unsustainability of the current linear phosphorus economy. These inefficiencies contribute to eutrophication, biodiversity loss, and escalating economic burdens on farmers and governments. In response, this review explores a systems based approach centered on circular strategies for P recovery from agricultural wastes such as manure, crop residues, and food industry byproducts, which offer renewable alternatives while enhancing soil health and carbon sequestration. Biological treatments, including composting, vermicomposting, and anaerobic digestion, demonstrate promising recovery efficiencies but remain limited by scalability, nutrient imbalances, and pollutant risks. Microbial and biotechnological processes, such as phosphate solubilizing bacteria, may play crucial roles in enhancing P availability through enzymatic and acidification mechanisms. Integrating these tools into crop production, particularly via precision application and microbial consortia design, can significantly reduce reliance on mined P, mitigate environmental harm, and bolster agricultural sustainability. Future directions must prioritize omics driven inoculant development, regulatory frameworks for biofertilizer deployment, and climate resilient microbial strategies to ensure resilient phosphorus cycling in agroecosystems.

## KEYWORDS

phosphorus recovery, fertilizer inefficiency, circular economy, phosphate solubilizing bacteria, agricultural waste, sustainability

## 1 Introduction

Phosphorus (P) is essential for all living organisms, playing a vital role in many biological processes. It constitutes a fundamental component of essential biomolecules like DNA and RNA, supports the integrity of cellular membranes, and plays a pivotal role in energy transfer via adenosine triphosphate (ATP). These functions make phosphorus a crucial element for plant development, cellular differentiation, and overall growth (Alewell et al., 2020; Kolodiazhyi, 2021; Khan et al., 2023a). Despite its importance, phosphorus availability in agricultural soils is often limited. This limitation is primarily due to its low solubility and restricted mobility in soil, which leads to inefficient uptake by plants, even when fertilizers are applied. As a result, phosphorus deficiency can severely restrict crop yield and reduce the effectiveness of other nutrients (Alewell et al., 2020; Tiecher et al., 2023). In both natural and cultivated soils, inorganic phosphate (Pi) serves as the primary form of phosphorus absorbed by plants. However, the solubility of Pi is strongly influenced by soil pH. In acidic conditions, phosphate tends to react with iron and aluminum, forming compounds like  $\text{FePO}_4$  and  $\text{AlPO}_4$ , which are largely unavailable to plants. In contrast, in alkaline environments, phosphate binds with calcium to form similarly insoluble minerals such as  $\text{Ca}_3(\text{PO}_4)_2$ . These chemical reactions greatly reduce the amount of phosphorus that remains accessible for plant uptake (Bechtaoui et al., 2021; Hu et al., 2023; Jahan et al., 2025; Johan et al., 2021).

The world's dependence on phosphorus to sustain food production is considerable. This essential nutrient is mainly derived from phosphate rock; a finite resource found in only a few regions globally. Driven by population growth and more intensive agriculture, the use of phosphorus fertilizers has risen sharply; from about 5 Tg in 1961 to nearly 25 Tg by 2020. It's expected to reach 27 Tg by 2050 (Cordell et al., 2009; Cordell and White, 2013). Rising demand for phosphorus is not without its challenges. One major concern is the uneven distribution of global phosphate reserves, which makes the supply network highly sensitive to geopolitical instability and economic shifts (Luo et al., 2024). A major complication is that much of the phosphorus added to farmlands doesn't actually benefit crops. In fact, less than 15% is usually taken up by plants. The rest tends to stay locked in the soil or washes away with rainwater, contributing to water pollution and harming freshwater ecosystems (Akinawo, 2023; Ge et al., 2023). This inefficiency is especially troubling for farmers in developing countries, who often struggle to increase crop yields while keeping input costs down. The issue also ties directly into global goals like Sustainable Development Goal 2, which aims to end hunger through more sustainable farming methods (Pérez-Escamilla, 2017; Hiywotu, 2025). When more phosphorus is removed through harvests than is returned via fertilizers or organic materials, soils gradually become depleted. This imbalance lowers soil fertility and reduces the land's ability to support future food production (Grzebisz et al., 2024). Given that phosphate rock is a limited and non-renewable resource, rethinking how we manage this nutrient is essential. The solution will require more than just applying more fertilizer. Steps like boosting phosphorus use

efficiency, recycling it from farm and city waste, and enhancing plant uptake through natural means must be prioritized.

In this context, there is growing interest in microbial and biotechnological strategies, especially those aimed at making phosphorus from agricultural residues easier for absorption by plants. Developing a clearer understanding of how phosphorus behaves in soil systems will be vital for creating smarter, more sustainable ways to protect this critical resource and reduce its environmental footprint.

## 2 Challenges in phosphorus management

### 2.1 Global phosphorus demand and resource depletion

#### 2.1.1 Phosphate rock and phosphorus: global supply, use, and outlook (2025–2029)

Phosphate rock continues to serve as the primary source of phosphorus, a mineral element essential not only for global agriculture but also for several industrial applications (El Bamiki et al., 2021). The main use of rock phosphate is in producing phosphoric acid, which plays a central role in the manufacture of fertilizers, animal feed supplements, and various chemical products. In 2024, phosphate rock production in the United States (US) totaled about 22 million metric tons. Mining was carried out at seven locations across Florida, Idaho, North Carolina, and Utah, overseen by four leading producers. The vast majority was directed toward fertilizer manufacturing, highlighting just how critical this material is for food production and agricultural output. To supplement domestic needs, the U.S. imported nearly 1.9 million metric tons of phosphate rock. These imports were valued at around \$390 million, with Morocco accounting for almost the entire supply. Looking at the global picture, phosphate rock reserves are estimated to total roughly 68 billion metric tons (USGS, 2025).

Morocco holds the world's largest phosphate reserves, with nearly 50 billion metric tons; accounting for over 70% of the known global total. Other countries with notable deposits include China, Egypt, Algeria, Syria, Jordan, and South Africa. In recent years, Morocco has moved far beyond raw phosphate extraction. The country has emerged as a global leader in producing value added phosphate derivatives, thanks in large part to the expansion of the state owned OCP Group. Once focused mainly on mining, the company now manufactures advanced products such as phosphoric acid, diammonium phosphate (DAP), and monoammonium phosphate (MAP). These fertilizers are critical for preserving soil fertility and ensuring reliable food production worldwide (De Ridder et al., 2012; Taib, 2025; Bourazza et al., 2025). Moroccan phosphate is becoming important in industrial sectors, particularly in the production of lithium iron phosphate batteries, a key component in the growing electric vehicle market. To enhance its international standing, Morocco has made major investments in industrial facilities, particularly in coastal areas such as Jorf Lasfar. These sites are equipped to process phosphate rock into customized

fertilizer formulations suited to diverse crops and soil types. Such efforts have boosted the country's export capacity, particularly to African and Asian markets. Environmental stewardship is also part of Morocco's strategy. OCP has implemented strategies to enhance energy efficiency, minimize freshwater use by utilizing seawater desalination, and reclaim phosphorus from waste materials. These efforts contribute to wider objectives focused on sustainability and advancing a circular economy (Table 1) (USGS, 2025).

The phosphoric acid industry experienced notable growth in 2024, with global production increasing by 5% to reach a record 89.6 million metric tons, largely driven by enhanced operational efficiencies. Production of monoammonium phosphate (MAP) and diammonium phosphate (DAP) also raised by 5%, totalling 67.2 million metric tons, one of the highest levels seen in recent years. While production declined in regions such as South Asia, North America, and Central Europe, these losses were offset by gains in East Asia and Africa, especially from China (11% increase) and Morocco (4% increase). Global trade in phosphoric acid edged up 1% to 8.3 million metric tons, marking five year peak, while MAP and DAP trade reached 29.1 million metric tons despite export restrictions imposed by China earlier in the year. To compensate for China's reduced shipments, countries including Saudi Arabia, Russia, and Morocco expanded their exports (USGS, 2024; 2025).

Looking ahead, the worldwide capacity for phosphoric acid production is expected to grow by around 14% from 2024 to 2029, reaching close to 71.7 million metric tons of  $P_2O_5$ . Much of this expansion is projected to come from regions like Africa, West Asia, and East Asia, with key contributions from major producers such as Morocco. Additional capacity gains are also planned in countries including Jordan, Egypt, and Tunisia (IFA, 2025; Statista, 2025). In China, recent investments are targeting domestic demand for purified phosphoric acid (PPA), particularly due to its use in industries like electric vehicle battery manufacturing. Beyond China, Canada is preparing for a significant increase in PPA

capacity, with a new large scale plant expected to start operations by 2028. Overall, global phosphoric acid production capacity is forecasted to rise from 63.9 million metric tons of  $P_2O_5$  in 2024 to 71.7 million metric tons by 2029, reflecting roughly a 12% increase over five years. While this growth might temporarily exceed demand, the market is expected to stabilize later on, supported by an estimated annual 5% growth in PPA demand (IEA, 2025; USGS, 2025).

Global use of phosphate fertilizers has experienced steady but moderate increases. In the Fertilizer Year 2024, phosphate fertilizer consumption (measured as  $P_2O_5$ ) reached an estimated 47 million metric tons, still about 4% shy of the record 49 million metric tons recorded in 2020. While total fertilizer application has recovered following declines in 2021 and 2022, phosphate fertilizers have not bounced back as strongly as nitrogen and potash. High prices for phosphate fertilizers compared to crop values have limited affordability, particularly impacting demand in major consuming regions such as East and South Asia, as well as in Eastern Europe and Central Asia (EECA) (IFA, 2025).

Facing rising costs, farmers have adjusted their practices by applying fertilizers more sparingly, targeting only the most nutrient poor areas, or opting for more affordable alternatives. Consequently, phosphate fertilizers' proportion of total global nutrient use dropped from 25% in FY 2021 to 23% in FY 2022 and has yet to fully rebound. Forecasts suggest phosphate fertilizer demand will increase moderately by about 1–2% annually from FY 2025 through FY 2029. Despite this slow growth, phosphate remains essential for maintaining food production worldwide. The strongest demand growth is expected in South Asia and Latin America, with more tempered increases anticipated in East Asia and Eastern Europe and Central Asia (EECA). In China, usage is predicted to rise in the short term due in part to expanded non fertilizer applications, though growth may stabilize later in the period (Cordell et al., 2009).

TABLE 1 Global phosphate rock production and reserves by country (2024–2025).

| Country       | Production 2024 (million metric tons) | Reserves (billion metric tons) | Notes                                                                        |
|---------------|---------------------------------------|--------------------------------|------------------------------------------------------------------------------|
| Morocco       | 30.0                                  | 50.0                           | Largest global reserves (>70% of world total). Major exporter and processor. |
| China         | 85.0                                  | 3.2                            | Largest producer. Domestic consumption high.                                 |
| United States | 22.0                                  | 1.0                            | Significant producer, mainly for domestic fertilizers.                       |
| Russia        | 13.0                                  | 0.6                            | Major exporter.                                                              |
| Jordan        | 11.0                                  | 1.3                            | Key producer and exporter.                                                   |
| Egypt         | 6.5                                   | 2.8                            | Growing producer.                                                            |
| Saudi Arabia  | 6.5                                   | 1.4                            | Investing heavily in new capacity.                                           |
| Brazil        | 5.5                                   | 1.2                            | Domestic supply crucial for agriculture.                                     |
| Tunisia       | 3.5                                   | 1.0                            | Moderate production.                                                         |
| Algeria       | 2.2                                   | 2.2                            | Significant reserves, moderate production.                                   |
| Syria         | 2.1                                   | 1.8                            | Production limited by regional instability.                                  |

Source: USGS Mineral Commodity Summaries 2025.

Sustainability challenges continue to loom large for the phosphate sector. Excessive phosphorus runoff contributes to eutrophication in lakes and rivers, causing algal blooms and harming aquatic life. Therefore, enhancing phosphorus efficiency and recovering phosphorus from waste streams have become critical strategies to manage this limited yet vital resource responsibly (IFASTAT, [https://www.ifastat.org/databases/graph/1\\_1](https://www.ifastat.org/databases/graph/1_1)).

### 2.1.2 Phosphorus, food security, and the dual challenge of soil fixation and fertilizer efficiency

Phosphorus, primarily delivered through phosphate fertilizers, is essential for maintaining global food supplies. It supports critical plant functions that promote healthy crop growth and overall agricultural yield (Khan et al., 2023a, b; Pandian et al., 2024). However, in recent years, phosphate fertilizer prices have steadily increased due to limited global availability, geopolitical conflicts, trade barriers, and interruptions in supply chains (Penuelas et al., 2023). These rising costs pose serious challenges, especially for farmers in low and middle income nations where agriculture is a key livelihood. As fertilizer expenses become prohibitive, many growers reduce application rates, restrict phosphorus use to the most deficient soils, or turn to cheaper, lower quality alternatives. While such strategies may help in reducing expenses temporarily, they risk exhausting soil nutrients and lowering future crop production, putting long term farming sustainability at risk. Unlike nitrogen, whose shortage effects are often immediate and visible, phosphorus deficiencies tend to impact crops more gradually but can be just as detrimental to productivity over time (De Ridder et al., 2012; Lun et al., 2021).

Rising costs for phosphate fertilizers are pushing up the overall expenses of food production, adding financial pressure on small scale farmers who already face tight budgets. Economic factors like inflation and unstable currency values make these challenges even harder, restricting farmers' ability to purchase necessary farming inputs (Brownlie et al., 2023; Leconte-Demarsy and Rice, 2025). If elevated phosphate prices continue long term, many farmers may permanently cut back on fertilizer use, risking soil degradation and weakening the capacity of agriculture to supply the growing global population. Tackling these issues calls for careful monitoring of fertilizer markets, efforts to secure stable supply chains, and policies focused on making fertilizers more accessible and affordable for those who need them most (Solangi et al., 2023; Penuelas et al., 2023). Guaranteeing fair and lasting availability of phosphorus fertilizers is vital for maintaining food security worldwide, especially in areas where farming relies heavily on steady nutrient supplies. Managing phosphorus responsibly and adopting new approaches to boost fertilizer effectiveness will play a central role in sustaining crop yields and meeting the nutritional needs of a growing population (<https://www.foodsecurityportal.org/>).

In addition to these economic and accessibility concerns, phosphorus limitation is further compounded by the dual challenge of soil fixation and low fertilizer efficiency. Phosphorus is an essential nutrient for plant growth, playing a key role in energy

transfer, photosynthesis, and overall crop performance. Despite its critical importance, phosphorus availability in soils is often severely limited due to two main issues: inefficient fertilizer use and soil phosphorus fixation (Mwende Muindi, 2019; Khan et al., 2023a, b). In soils, phosphorus exists in multiple chemical states, from stable minerals like apatite, strengite, and variscite to more reactive, soluble forms. The natural process of converting phosphorus from these stable minerals into forms that can be absorbed by plants is very slow, unable to meet the high nutrient demands of modern farming practices (Shen et al., 2011; Ducouso-Détrez et al., 2022; Pang et al., 2024). Even with fertilizer application, only a small proportion of phosphorus becomes available for plant uptake. This is largely because of soil fixation, chemical reactions that quickly lock phosphorus onto soil particles. In acidic conditions, phosphorus bonds tightly with iron and aluminum oxides, whereas in neutral to alkaline soils, it forms insoluble compounds with calcium, such as octacalcium phosphate and hydroxyapatite (Fink et al., 2016; Johan et al., 2021; Iqbal et al., 2023). These reactions reduce phosphorus solubility and limit plant absorption. Additionally, phosphorus availability peaks within a narrow soil pH range of about 5.5 to 6; outside this range, phosphorus uptake declines notably. Environmental factors like elevated temperatures worsen the fixation process, increasing phosphorus binding to metals and decreasing fertilizer phosphate solubility (Mwende Muindi, 2019; Penn and Camberato, 2019; Barrow et al., 2020; Johan et al., 2021; Ibrahim et al., 2022).

Phosphate fertilizers often fall short of their potential, not just because of chemical issues, but also because of how phosphorus behaves in the soil. Once it's applied, phosphorus doesn't move much; it stays concentrated in a small area around the plant roots, known as the rhizosphere. This limited reach makes it harder for plants to absorb the nutrient, especially during dry or cold conditions, which slow down its movement even more (Hinsinger et al., 2015; Johan et al., 2021). To make up for this and avoid losing yield, many farmers apply extra fertilizer as a kind of safety net. While this helps in the short term, it leads to a build-up of what's known as "legacy phosphorus", reserves of the nutrient that get stuck in the soil and aren't easily taken up by plants anymore. Over time, some of this excess phosphorus can wash away with rain or irrigation, eventually ending up in nearby rivers or lakes. That runoff contributes to serious environmental issues like eutrophication and harmful algal blooms, which damage aquatic ecosystems and reduce water quality (Sharpley et al., 2013; McDowell et al., 2020; Solangi et al., 2023; Jahan et al., 2025).

Addressing the persistent challenges of soil phosphorus fixation and fertilizer inefficiency is central to achieving sustainable nutrient management in agriculture. One key strategy involves reducing reliance on conventional inorganic fertilizers by optimizing application methods to improve uptake efficiency. Integrating alternative phosphorus sources, particularly those recovered from organic waste streams and livestock manure, can also contribute to a more circular and resilient nutrient economy. In parallel, enhancing root access to phosphorus through soil health practices can significantly improve phosphorus availability and plant acquisition in the root zone.

### 3 Harnessing agricultural wastes for phosphorus recycling

The finite nature of rock phosphate reserves and the geopolitical sensitivities surrounding their supply necessitate a paradigm shift towards a circular phosphorus (P) economy. Global phosphate resources are increasingly concentrated in a few countries, raising concerns about supply security and long term availability (Walsh et al., 2023). Agricultural systems, which are major consumers of P, paradoxically generate vast quantities of P rich organic wastes. These materials including animal manures, crop residues, and food processing by products represent a strategic and largely underutilized resource for nutrient recovery (Hollas et al., 2021).

The potential of these waste streams for P recycling has attracted significant attention in recent years. Biological treatments, such as enhanced biological phosphorus removal (EBPR) and struvite precipitation, are efficient in municipal and agricultural waste systems but are limited by microbial sensitivity and operational complexity (Witek-Krowiak et al., 2022). Thermochemical methods, including incineration and pyrolysis, can transform waste into biochar or ash with concentrated phosphorus, though they often incur high energy costs and require secondary extraction processes (Adeniyi et al., 2024). Physicochemical technologies, such as adsorption, crystallization, and ion exchange offer high selectivity and recovery potential, yet are typically costly and sensitive to competing ions (Abdoli et al., 2024). A robust transition to a circular phosphorus economy hinges on integrating these

technologies with sustainable policy frameworks and improving nutrient flow management across agricultural landscapes.

#### 3.1 Agricultural waste as a phosphorus resource

Agricultural residues are a significant reservoir of recoverable P, with concentrations typically ranging from 0.5% to 3.2% by dry weight, contingent on the specific feedstock and its preceding processing (Raza et al., 2022). Beyond their P content, these organic materials are rich in carbon, nitrogen, and essential micronutrients. Their valorisation, therefore, offers multifaceted benefits for agroecosystem health, including enhancements to soil structure, microbial biomass, and long term fertility. For instance, the application of compost derived from these wastes can contribute significantly to soil carbon sequestration, with reported rates of 0.6 to 1.8 Mg C ha<sup>-1</sup> year<sup>-1</sup>, particularly within organically managed systems (Xie et al., 2023). Consequently, recycling P from agricultural wastes is not merely a waste management strategy but a foundational component of building regional nutrient circularity and enhancing agroecological resilience.

#### 3.2 Technologies for phosphorus recovery and their efficacies

A spectrum of technologies is employed to recover and stabilise P from agricultural waste streams. These can be broadly categorised

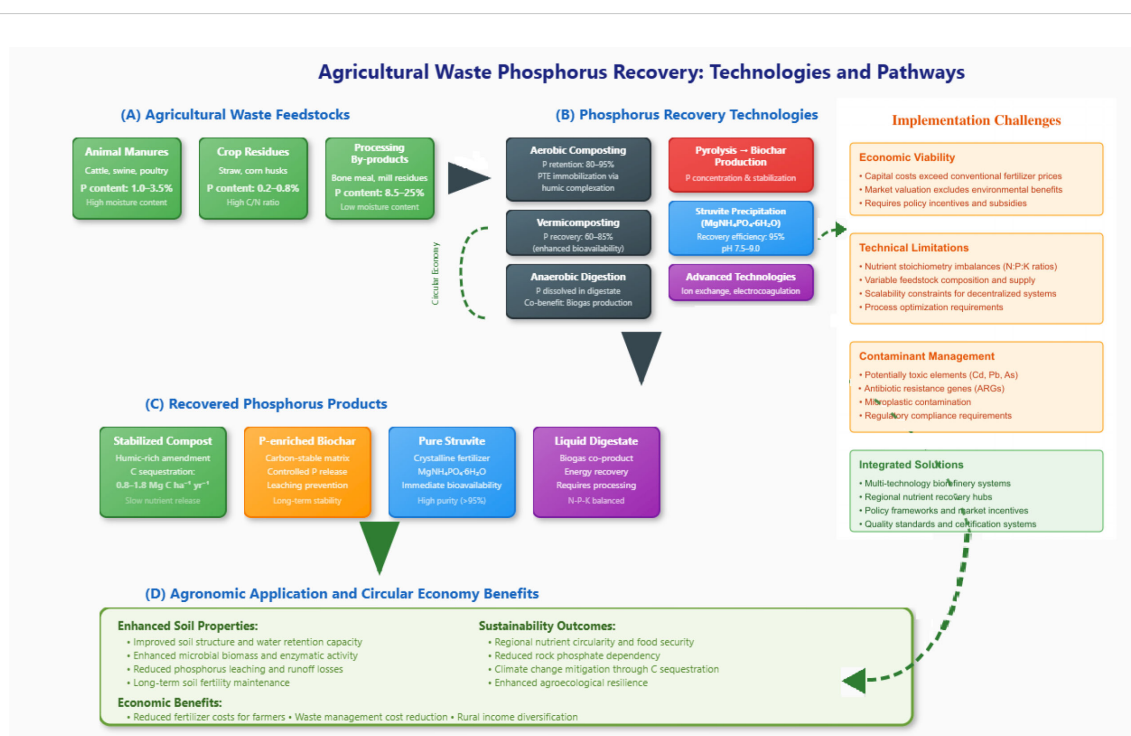


FIGURE 1

Agricultural waste phosphorus recovery: technologies and pathways. The framework illustrates the progression from (A) Agricultural Waste Feedstocks to (B) Phosphorus Recovery Technologies, resulting in (C) Recovered Phosphorus Products, which lead to (D) Agronomic Application and Circular Economy Benefits. Implementation challenges and integrated solutions are outlined on the right.

TABLE 2 Comparative summary of phosphorus recovery technologies from agricultural waste.

| Technology                            | P recovery efficiency | Key advantages                                                                                | Primary limitations                                                                                                 | Reference                       |
|---------------------------------------|-----------------------|-----------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------|---------------------------------|
| Composting                            | 80–95% (Retention)    | Low-tech, high scalability; improves soil organic matter; immobilizes PTEs                    | Slow process; incomplete degradation of ARGs and microplastics; potential nutrient loss via leaching/volatilisation | (Ahmed et al., 2019)            |
| Vermicomposting                       | 60–88%                | High P bioavailability; rapid humification; reduces pathogens and ARGs; enhances soil biology | Labour-intensive; moderate scalability; sensitive to climate and feedstock quality                                  | (Chojnacka, 2023)               |
| Anaerobic Digestion (AD)              | >90% (in digestate)   | Co-produces renewable energy (biogas); reduces pathogens and odours                           | Low P bioavailability in digestate (10–20%); requires secondary treatment; high capital cost                        | (Walling et al., 2019)          |
| Pyrolysis (Biochar)                   | High (Concentration)  | Produces stable, slow-release P fertiliser; enhances soil carbon and water retention          | P availability depends on feedstock/conditions; may immobilise P with high ash content                              | (Zielińska and Bulkowska, 2024) |
| Struvite Precipitation                | >95% (from liquid)    | Produces clean, concentrated, slow-release fertiliser; highly selective for P                 | Requires Mg and pH control; operationally expensive; suitable only for liquid streams                               | (Karunanithi et al., 2015)      |
| Advanced Systems (Ion-Exchange, etc.) | 70–90%                | Highly selective; produces high-purity P; potential for automated, precision recovery         | High capital and operational costs; technical complexity; low technology readiness level                            | (Jacob et al., 2025)            |

into biological, thermochemical, and physicochemical processes, each with distinct advantages and operational constraints that are summarised in [Figure 1](#) and [Table 2](#).

### 3.2.1 Biological treatments

Include different microbial and macro-faunal activities to mineralise organic P and stabilise nutrients.

**Composting:** Conventional aerobic composting is one of the most established and economically accessible methods for recycling organic residues. Typically, it conserves 80–95% of the initial phosphorus (P) content within the final product. A further advantage lies in its ability to immobilize potentially toxic elements (PTEs), such as cadmium and lead, through their interactions with humic substances ([Sayara et al., 2020](#)). Nevertheless, aerobic composting is not without drawbacks. Persistent contaminants, including certain antibiotic resistance genes (ARGs) and microplastics, are not fully degraded and may accumulate in soils following compost application ([Waqas et al., 2023](#)). To mitigate these shortcomings, stabilizing agents such as biochar and zeolites are often introduced, improving contaminant retention while contributing to a more balanced nutrient composition ([Dai et al., 2016](#)). Taken together, these features position composting as a practical and sustainable route for phosphorus recovery, with added benefits for soil fertility, reduced reliance on mineral fertilizers, and long term agricultural sustainability.

The transformation of phosphorus during composting is driven primarily by microbial decomposition of organic matter, which induces pronounced shifts in phosphorus speciation and availability. Unlike synthetic fertilizers that tend to precipitate rapidly in soils with calcium, iron, or aluminum into insoluble forms, phosphorus in compost exists in a broader spectrum of chemical states ([Lanno et al., 2021](#); [Ahmed et al., 2023](#); [Xie et al.,](#)

[2023](#)). It occurs both as inorganic orthophosphates ( $\text{H}_2\text{PO}_4^-$  and  $\text{HPO}_4^{2-}$ ), which are readily available to plants, and as a variety of organic compounds such as inositol phosphates, monoesters, and diesters. Through microbial enzymatic activity, these organic forms are gradually mineralized, thereby enlarging the pool of plant accessible phosphorus. The efficiency of this transformation, however, is strongly conditioned by factors such as pH, aeration, feedstock composition, and the use of amendments. Since microbial communities are unable to mineralize all organic phosphorus species, careful process management remains crucial to optimizing nutrient release ([Shen et al., 2011](#); [Johan et al., 2021](#); [Ducousso-Détrez et al., 2022](#)).

To monitor these dynamics, researchers have relied heavily on phosphorus fractionation. Early fractionation schemes, first proposed by [McAuliffe and Peech \(1949\)](#) and subsequently refined by [Hedley et al. \(1982\)](#), divide phosphorus into pools such as water soluble, exchangeable, Fe/Al-bound, Ca/Mg-bound, and organic fractions, each associated with different degrees of stability and bioavailability ([Wei et al., 2015](#); [Graça et al., 2022](#)). Evidence indicates that composting generally reduces the proportion of mobile phosphorus, which is more susceptible to leaching, while simultaneously enriching more stable fractions. For instance, when the carbon-to-nitrogen ratio was adjusted to 28, mobile phosphorus decreased by 14% ([Wang et al., 2019](#); [Aboutayeb et al., 2023](#); [Xu et al., 2025a](#)). The addition of amendments such as biochar or peat can further stabilize phosphorus, limiting environmental losses but occasionally diminishing its short term availability to crops. Conversely, co-composting nutrient rich inputs like poultry manure with carbonaceous plant residues has been shown to enhance the proportion of phosphorus that remains readily accessible to plants ([Dai et al., 2016](#); [Folina et al., 2025](#)).

More recently, advanced spectroscopic and microscopic techniques have deepened insights into phosphorus speciation in

compost. Solution state  $^{31}\text{P}$  nuclear magnetic resonance (NMR) permits direct identification of both organic and inorganic phosphorus species, revealing the persistence of recalcitrant molecules such as inositol hexakisphosphate. X-ray diffraction (XRD) enables the detection of crystalline phosphorus minerals including struvite and calcium phosphates, while X-ray absorption near edge structure (XANES) analysis provides information on bonding environments. By integrating these approaches with fractionation, a more complete picture of phosphorus forms, stability, and availability in compost can be obtained (Doolette and Smernik, 2011; Yamaguchi et al., 2021; Ran et al., 2025).

Maximizing phosphorus recovery through composting requires a balance between environmental protection and agronomic effectiveness. On one hand, stabilizing phosphorus into less mobile fractions helps mitigate eutrophication risks associated with runoff and leaching. On the other, excessive immobilization may limit short term plant uptake, making supplementary fertilization necessary. Strategies to achieve this balance involve adjusting feedstock ratios, maintaining appropriate aeration and moisture conditions, and selecting amendments that either stabilize phosphorus or promote microbial mineralization of organic forms.

Despite the challenges of time requirements, land use, and the need for careful control of carbon-to-nitrogen ratios, aeration, and moisture, composting is increasingly recognized as a cornerstone in circular agricultural systems. By converting manure and other organic wastes into a stable, nutrient rich product, composting simultaneously improves soil health, reduces dependency on finite phosphate rock reserves, and lowers the risk of phosphorus losses to water systems. Continued advances in composting technologies and analytical methodologies will be central to unlocking its full potential as a reliable and sustainable pathway for phosphorus recovery in agriculture (Folina et al., 2025).

**Vermicomposting:** Vermicomposting, which employs epigeic earthworms such as *Eisenia fetida*, is increasingly recognized for its superior performance compared to conventional composting systems. By accelerating humification and enhancing phosphorus (P) bioavailability through enzymatic mineralization, this process achieves recovery efficiencies ranging between 60% and 88% (Nieto-Cantero et al., 2025). In parallel, vermicomposting substantially lowers antibiotic resistance genes (ARGs) and pathogenic microorganisms, typically by 60–80%, owing to enzymatic degradation and microbial antagonism within the earthworm gut (Gupta et al., 2019). Despite these advantages, large scale deployment remains constrained by several factors, including high labor demand, dependence on a consistent feedstock supply, and sensitivity to environmental conditions (Liégui et al., 2021). Even so, vermicomposting stands out as a sustainable biotechnological approach that harnesses the synergy between earthworms and microorganisms to stabilize organic matter while enhancing nutrient release. In applications involving dewatered sludge, it not only improves waste treatment efficiency but also creates favorable conditions for phosphorus recovery through biological mineralization and physicochemical transformations, ultimately supporting subsequent recovery via struvite crystallization (Folina et al., 2025).

Phosphorus mobilization in vermicomposting is driven largely by the degradation of extracellular polymeric substances (EPS) and the mineralization of organic phosphorus (OP). Earthworm activity physically fragments the sludge matrix, while microbial enzymes break down EPS and associated macromolecules, liberating bound phosphorus into soluble forms (Chen et al., 2023). In parallel, microbial activity converts OP into inorganic phosphorus (IP), primarily orthophosphate ( $\text{PO}_4^{3-}\text{P}$ ), the form most accessible to plants. During the early phases, high levels of ammonium nitrogen ( $\text{NH}_4^+\text{N}$ ) are also released. The simultaneous presence of  $\text{NH}_4^+\text{N}$  and  $\text{PO}_4^{3-}\text{P}$  encourages the precipitation of magnesium ammonium phosphate (MAP, commonly referred to as struvite). Consequently, vermicomposting not only enhances nutrient availability but also primes sludge for efficient phosphorus recovery through struvite crystallization (Pathma and Sakthivel, 2012; Rehman et al., 2023; Turp et al., 2023; Sande et al., 2024).

Nevertheless, several challenges hinder seamless integration with phosphorus recovery systems. Post-vermicomposting sludge is chemically complex, containing soluble organics, humic substances, and diverse competing ions. Humic acids can bind phosphorus, thereby lowering its availability for crystallization, while cations such as  $\text{Ca}^{2+}$  and  $\text{Fe}^{3+}$  promote the formation of less soluble phosphate minerals or inhibit MAP nucleation (Ahmed et al., 2019; Rusănescu et al., 2022; Dume et al., 2022; Xia et al., 2025). Residence time is another critical factor: short treatment durations increase the availability of labile phosphorus and ammonium, whereas extended processing favors immobilization through secondary binding. Additionally, the heterogeneity of sludge; shaped by feedstock origin and wastewater treatment methods; introduces variability into recovery outcomes. Operational optimization of residence time, aeration, pH adjustment, and crystallization timing remains an active research priority (Yuan et al., 2024; Xia et al., 2025).

Looking ahead, vermicomposting is increasingly considered a promising pretreatment step to enhance phosphorus recovery from sludge. Fine tuning operational variables, particularly treatment duration and environmental parameters, will be central to maximizing phosphorus bioavailability. From a systems perspective, incorporating vermicomposting into wastewater treatment facilities could provide dual benefits: reducing sludge volumes while producing phosphorus rich outputs suitable for agriculture. Life cycle assessment studies further suggest that such integrated systems can lower greenhouse gas emissions, decrease reliance on mineral fertilizers, and advance circular economy objectives (Rusănescu et al., 2022; Gómez-Roel et al., 2024).

Beyond sludge management, vermicomposting has demonstrated promise in treating other organic residues. For instance, processing apple pomace; alone or combined with straw; reduced waste volume by up to 85% and yielded stable compost enriched with nitrogen, phosphorus, potassium, and magnesium, underscoring its potential as an organic fertilizer (Hanc and Chadimova, 2024). Complementary innovations have also emerged. In Bangladesh, a biochar blended composting system was shown to recycle nearly 50% of the carbon, nitrogen, phosphorus, and potassium from municipal waste while cutting

methane and nitrous oxide emissions and generating substantial economic returns (Mia et al., 2017). Similarly, an integrated composting system in Suzhou, China, outperformed traditional windrow composting by reducing moisture more rapidly, boosting efficiency by 40%, and producing compost with superior stability and nutrient quality. Field trials in rice cultivation revealed gains in soil organic matter (+17%) and available nitrogen (+11%), reinforcing its potential for sustainable nutrient and phosphorus recovery (Wei et al., 2021).

**Anaerobic Digestion (AD)** is widely applied for renewable energy production, as it converts organic substrates into biogas while leaving behind a nutrient rich digestate. Although most of the phosphorus (P) originally present is conserved in this residue, only a small fraction; around 10–20%; is found in soluble, plant available forms. The remainder tends to be locked within particulates or precipitated into poorly soluble mineral phases (Waqas et al., 2023). Because of this limited bioavailability, AD is often regarded more as a pre-treatment step within phosphorus management schemes rather than a final recovery pathway. The liquid fraction of digestate usually requires further processing, most commonly chemical precipitation, to secure effective P recovery (Katakula et al., 2021). While these downstream measures involve notable chemical or energy inputs, they allow targeted extraction from liquid streams and can also concentrate phosphorus in solid phases.

Within the digestion process, polyphosphates and organic P compounds are hydrolyzed, gradually releasing orthophosphate ions. These accumulate in the effluent at levels commonly ranging from 100–500 mg/L, with extreme cases exceeding 1500 mg/L (Xi et al., 2023). Under appropriate physicochemical conditions; such as favorable pH, ionic ratios, and supersaturation; orthophosphate can be precipitated as magnesium ammonium phosphate (struvite,  $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$ ) or as other phosphate salts (González-Morales et al., 2021; Xi et al., 2023). Struvite crystallization has attracted particular interest, as it combines high recovery rates with environmental safety and yields a slow release fertilizer rich in balanced nutrients. Technologies such as fluidized bed reactors have reached recoveries above 90%, producing dense pellets of adequate strength for direct agricultural application. Beyond chemical precipitation, biological processes also contribute: polyphosphate accumulating organisms release intracellular phosphorus during anaerobic metabolism, further enriching the effluent (Zhang et al., 2019; Shim et al., 2020).

Nevertheless, several obstacles still constrain the efficiency of phosphorus recovery in AD systems. Orthophosphate levels above 250 mg/L can inhibit hydrolytic and acetogenic microbial populations, thereby reducing both substrate degradation and methane output; though this inhibition is often reversible (Keating et al., 2016; Xi et al., 2023). Suspended solids present another barrier by disturbing crystal nucleation and growth, which lowers struvite purity. The presence of competing cations, especially calcium, frequently shifts precipitation pathways toward less soluble calcium phosphates, lowering yields and diminishing the agronomic value of the recovered product. Recovery performance is also highly sensitive to design and operational variables, including hydraulic retention time, mixing regimes, and reactor type

(González-Morales et al., 2021; Yan et al., 2025; Mores et al., 2025). Even when struvite is successfully formed, impurities such as organics or trace metals are often incorporated into the crystals, necessitating additional polishing to meet fertilizer quality standards.

Overcoming these hurdles requires a combination of technological refinement and system integration. Enhanced clarification methods, targeted pretreatments, and carefully designed codigestion strategies have the potential to increase the fraction of bioavailable phosphorus and improve recovery outcomes. Pairing AD with struvite crystallization not only provides a viable route for closing the phosphorus cycle but also helps reduce nutrient losses, curb dependence on finite phosphate rock reserves, and advance circular economy objectives in waste management. However, realizing the full potential of AD in this context will depend on continued innovation to resolve chemical, microbial, and operational limitations that currently constrain recovery efficiency and product quality (Li et al., 2020a; Kolb et al., 2025).

### 3.2.2 Thermochemical and physicochemical methods

Thermochemical and physicochemical processes play a significant role in phosphorus (P) recovery, with pyrolysis and struvite precipitation being among the most established techniques (Figure 1).

**Biochar production and applications:** Biochar is produced through the pyrolysis of agricultural and organic biomass. This process generates a carbon rich, chemically stable material that retains a significant portion of the phosphorus (P) present in the original feedstock. Unlike incineration, which consumes high energy and causes substantial carbon losses, pyrolysis occurs under oxygen limited conditions, concentrating phosphorus in the solid biochar fraction while requiring comparatively lower energy input (Meyer et al., 2011; Sohi, 2012). A wide variety of feedstocks can be used, including crop residues, forestry waste, animal manure, sewage sludge, and industrial or food by-products, many of which pose challenges for disposal or management (Thornley et al., 2009; Ahmad et al., 2014; Nanda et al., 2016). Initially, biochar was valued for its role in improving soil fertility and sequestering carbon. More recently, it has gained attention as a material capable of recovering nutrients from waste streams. Its large surface area, porous structure, and functional groups; such as carboxyl, hydroxyl, and aromatic moieties; enable strong interactions with inorganic nutrients and environmental contaminants (Dai et al., 2020; Shakoor et al., 2021). These features make biochar an appealing, low cost, and low waste alternative to conventional phosphorus recovery techniques, including ion exchange, chemical precipitation, and membrane filtration (Oliveira et al., 2017).

Biochar captures phosphorus through multiple mechanisms, combining physical, chemical, and biological processes. Physical adsorption involves electrostatic attraction between negatively charged phosphate ions and positively charged surface sites, particularly under acidic conditions, and also occurs through pore

filling within the biochar's microstructure. Chemical processes include ion exchange, where phosphate replaces other surface bound ions, and surface complexation with functional groups like hydroxyl and carboxyl. Precipitation of insoluble mineral phases, such as calcium or magnesium phosphates, can also take place when biochar contains these metals naturally or has been modified with them. Modifying biochar with calcium, magnesium, iron, or aluminum is commonly done to increase reactive sites and enhance mineral precipitation (Tan et al., 2015). After application to soil, biological mechanisms further contribute: phosphorus solubilizing microorganisms and mycorrhizal fungi interact with phosphorus bound to biochar, gradually making it available for plants. Together, these mechanisms allow biochar to act as both a sink for recovered phosphorus and a slow release source for agricultural use (Truong et al., 2023; Mansour et al., 2025; Laishram et al., 2025).

Experimental and field studies confirm biochar's high phosphate adsorption capacity and its ability to release nutrients over time, making it a valuable slow release fertilizer. Chen et al. (2011) highlighted its strong sorption potential, while Yao et al. (2011) demonstrated effective phosphorus recovery from wastewater using biochar derived from sugar beet tailings. When enriched with phosphorus, biochar can be applied directly to soils, reducing dependence on mineral fertilizers, minimizing nutrient losses, and supporting long term soil fertility (Glaser and Lehr, 2019; Li et al., 2020). Field scale studies further show improvements in soil structure, increased crop yields, reduced leaching, and enhanced carbon sequestration (Oni et al., 2019; Vijay et al., 2021). Beyond agriculture, phosphorus laden biochar has been tested in wastewater treatment systems such as constructed wetlands and biological filters, where it efficiently removes phosphate and other contaminants. Recent research has also explored its incorporation into construction materials, like concrete, where it improves material performance while immobilizing nutrients, highlighting biochar's multifunctional role in circular economy strategies (Kumari et al., 2025; Varkolu et al., 2025).

Despite its benefits, biochar based phosphorus recovery faces some limitations. Untreated biochar typically has low phosphate affinity due to its negative surface charge, which often necessitates chemical or physical modifications that increase production costs. In real wastewater systems, competing ions such as sulfate, carbonate, nitrate, and fluoride can occupy active sites, reducing adsorption efficiency, while dissolved organics and other pollutants may interfere with phosphorus binding. Strong phosphorus retention, although beneficial for stability, can also limit desorption and hinder controlled nutrient release in agricultural settings, creating a trade off between adsorption efficiency and bioavailability. Moreover, most studies have been conducted under controlled laboratory conditions, leaving uncertainty about large scale performance. Variability in phosphorus concentrations, wastewater chemistry, and contaminant loads presents additional challenges for practical application. Finally, scaling up is limited by the economic feasibility of biochar production, which depends on feedstock availability, pyrolysis equipment costs, and the expenses

associated with material modifications (Osman et al., 2022; Zhou et al., 2025; Kumari et al., 2025; Tian et al., 2025; Fakhar et al., 2025).

**Struvite precipitation:** It is widely recognized as one of the most reliable chemical techniques for phosphorus recovery from ammonium and phosphate rich liquid streams, such as effluents from anaerobic digesters and livestock manure slurries. The method relies on raising the pH to mildly alkaline levels (about 7.5–9.0) and ensuring sufficient magnesium availability so that phosphorus can crystallize as magnesium ammonium phosphate hexahydrate ( $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$ ), commonly referred to as struvite. Under well controlled laboratory conditions, recovery rates can surpass 95%, and the resulting crystalline product serves as a slow release fertilizer with considerable agricultural value (Witek-Krowiak et al., 2022).

The driving force for struvite formation is crystallization. Supersaturation initiates nucleation and sustains subsequent crystal growth and agglomeration. Careful regulation of supersaturation is essential: too little suppresses nucleation, whereas too much produces fine, poorly separable particles. In alkaline environments, the reaction proceeds through a sequence of nucleation, crystal growth, and particle aggregation. To improve performance, seed materials such as quartz sand or recycled struvite are frequently introduced, encouraging controlled nucleation, enhancing recovery efficiency, and producing larger, more settleable crystals (Regy et al., 2001; Zhang et al., 2017; Natividad-Marin et al., 2023).

A range of reactor designs has been proposed to stabilize the process. Fluidized bed reactors (FBRs) are commonly used because they enable continuous operation and fine tuned control over crystal growth. However, these systems demand careful management of flow velocity and agitation to avoid scaling, clogging, or excessive fines formation (Sheibat-Othman and Timothy Mckenna, 2021; Seckler, 2022). Another approach, the Crystalactor developed in the Netherlands, employs quartz sand as a seeding medium and typically achieves recovery efficiencies of around 70%. Pilot scale studies on relatively dilute wastewaters (40 mg/L phosphate) have reported efficiencies close to 62% when operated at an optimized pH (8.8) with adequate magnesium addition (Regy et al., 2001).

Despite these advances, several obstacles limit broader adoption. Chemically, maintaining the required alkaline pH (8–9.5) often entails substantial chemical dosing, usually with sodium hydroxide, which increases operating costs. High calcium-to-magnesium ratios present another challenge, as they tend to favor precipitation of less desirable calcium phosphates, reducing both yield and product quality. Moreover, at phosphate concentrations below roughly 50 mg/L, recovery efficiencies decline sharply, requiring more stringent control of supersaturation and process conditions. From a technical standpoint, continuous pH adjustment, precise magnesium dosing, and sometimes seeding are needed to maintain stability. If these conditions are not met, the process produces fine particles with poor settling characteristics, complicating recovery (González-Morales et al., 2021; Achilleos et al., 2022; Kolb et al., 2025).

Economic considerations further constrain large scale application. The costs of magnesium salts and alkali chemicals are

significant, particularly for dilute wastewaters where nutrient concentrations are too low to justify treatment expenses. Reported recovery efficiencies in full scale plants generally fall between 60% and 70%, meaning that a considerable share of phosphorus remains unrecovered. Persistent scaling in pipes and treatment equipment also remains a maintenance concern. Although struvite is well established as a slow release fertilizer, its market penetration is uneven and largely shaped by local agricultural demand, regulatory frameworks, and the practicalities of distribution (Regy et al., 2001; Achilleos et al., 2022; Santos et al., 2024).

### 3.2.3 Advanced and electrochemical recovery technologies

New approaches for phosphorus (P) recovery are drawing increasing interest as alternatives to conventional chemical precipitation. The aim is to achieve greater selectivity and efficiency while lowering chemical consumption. Among the most promising methods are ion exchange, electrochemical processes, and electrocoagulation (EC). Each shows considerable potential but also faces technical and economic obstacles that currently limit their large scale deployment.

Ion exchange, long established in desalination and deionization, has been adapted for phosphorus removal and recovery. It works through the reversible transfer of ions between water and a solid exchange medium. Because phosphorus in wastewater is usually present as phosphate anions, these can be captured by the media and later released during regeneration. Early systems often struggled with interference from competing anions such as chloride and sulfate. More recently, however, polymeric ligand exchangers functionalized with immobilized metal cations, often enhanced with ferric oxide nanoparticles, have shown far greater selectivity. Laboratory tests using ferric oxide or aluminum hydroxide pretreated media report phosphate removal efficiencies of 80-90%. Regeneration also produces phosphate rich solutions that can be reused, representing a true recovery pathway. Even so, the relatively high cost of media, reliance on regenerant chemicals, and sensitivity to pH fluctuations remain obstacles to scaling up, particularly in small or decentralized plants. While ion exchange offers clear advantages in regeneration and reuse over precipitation or adsorption, its expansion is constrained by cost and operational complexity (Martin et al., 2009; Seo et al., 2013).

Electrochemical techniques form another emerging pathway for phosphorus recovery. They are attractive because they can operate with little or no added chemicals and often integrate well with existing infrastructure, making them appealing for decentralized systems. Methods under investigation include electrodialysis, electrosorption, electrocoagulation, and electrochemically induced precipitation. One example is electrochemically mediated precipitation, in which water reduction at the cathode increases the local pH, causing phosphate minerals to form without external alkali dosing (Wang and He, 2022). Such methods have been applied to difficult wastewaters, including acidic, high salinity cheese effluents, where stable calcium phosphate precipitation has been demonstrated (Lei et al., 2021). More complex designs, such as double chamber reactors, allow phosphorus release in the anode

chamber and subsequent recovery in the cathode chamber. Despite their flexibility, challenges remain: reactor design is often complex, capital costs are high, and performance can be unstable when wastewater characteristics vary. As a result, most applications remain limited to laboratory and pilot scales (Chen et al., 2025a).

Electrocoagulation (EC) has also emerged as a promising option, particularly where space and reliable chemical supply are limited, such as in on site wastewater treatment. Unlike conventional coagulation, EC generates its own coagulant ions from sacrificial electrodes, usually aluminum or iron, when current is applied. These ions hydrolyze to form hydroxide flocs, which either adsorb phosphate or precipitate it as insoluble metal phosphate complexes. Efficiency depends on factors such as electrode material, current density, pH, and wastewater composition. Aluminum electrodes are often favored for producing strong Al-P complexes, while iron electrodes can simultaneously remove other pollutants. Key benefits of EC include reduced chemical demand, lower sludge production compared with chemical coagulation, and compact reactor design. Phosphorus captured in EC sludge may also be reused as fertilizer, adding a recovery dimension to the treatment (Omwene et al., 2018; Reza et al., 2024).

Still, EC faces barriers to widespread adoption. Energy consumption can be significant at higher current densities, and electrodes may corrode or passivate, reducing efficiency and raising maintenance requirements. Although sludge production is lower than in chemical coagulation, its composition varies, and its safety for direct agricultural reuse is not always guaranteed. So far, most successful demonstrations have been limited to laboratory or pilot projects, with real world stability under fluctuating wastewater conditions remaining a challenge. Compared with precipitation, EC cuts chemical inputs and produces less sludge, but it is less established, more energy intensive, and technically more demanding to scale up (Phu et al., 2025; Al-Qodah et al., 2025a, b; Etafo et al., 2025).

## 3.3 Overarching challenges and future perspectives

Although interest in a circular phosphorus (P) economy has expanded considerably, its practical implementation continues to encounter several intertwined barriers. One of the main constraints is economic viability, since most advanced phosphorus recovery systems demand substantial investment and high operational expenditure, often exceeding the market price of conventional phosphate fertilizers. Consequently, their large scale adoption generally depends on policy support or incentive mechanisms; such as subsidies, nutrient credit schemes, or valuation frameworks that recognize ecological and social returns (Bagheri et al., 2024). Instruments like green finance, carbon or nutrient trading, and the inclusion of ecosystem service valuation could help close this financial gap by accounting for the wider societal benefits of phosphorus recycling.

Another central challenge involves scaling and logistics, particularly within decentralized recovery systems that must

process diverse and inconsistent waste streams (Koseoglu-Imer et al., 2023). Laboratory studies frequently demonstrate promising recovery efficiencies that are difficult to replicate at pilot or industrial scales. Variations in feedstock quality, microbial community dynamics, and non ideal reactor performance often lead to lower real world outcomes. For example, while chemical precipitation; especially struvite crystallization; can achieve recovery efficiencies of 85–99% under controlled conditions, operational plants often report efficiencies below 70% because of fluctuating wastewater chemistry, reagent costs, and maintenance requirements. Similarly, biochar based adsorbents and metal modified biochars (Mg/Al types) exhibit strong laboratory performance but lose cost effectiveness upon scale up due to elevated energy demand and regeneration expenses.

Technologies such as electrocoagulation and anaerobic digestion are promising for integration within current wastewater treatment infrastructures but require additional refinement to stabilize recovery rates and control contaminants under variable feed conditions. In contrast, biological processes; including vermicomposting and advanced composting; offer co-benefits such as carbon sequestration, soil enrichment, and emission reduction. However, they remain limited by slower phosphorus release rates, longer processing durations, and dependency on local economic conditions such as feedstock supply, labor costs, and the market for secondary products (compost or digestate). Hybrid applications that combine composting with biochar have demonstrated enhanced nutrient retention and soil structure improvement, though production costs (up to €1,200 ha<sup>-1</sup> for biochar) and logistical constraints still hinder their large scale implementation (Table 3; Figure 2).

Across all approaches, scalability bottlenecks commonly arise from performance decline under heterogeneous inputs, high reagent use, and uncertainty surrounding the regulatory classification of recovered materials as fertilizers. Environmental trade offs are also evident: while chemical and electrochemical systems deliver rapid and efficient phosphorus recovery, they often produce secondary waste and require significant energy input; biological routes, on the other hand, are slower but inherently more sustainable and resource efficient. Laboratory results typically overstate field performance by 10–30% because of idealized conditions.

At present, chemical precipitation and electrochemical recovery technologies exhibit the highest technological readiness levels (TRL 7–9) and are close to commercial deployment, though their expansion is limited by investment intensity and moderate carbon emissions. Biological options such as composting, vermicomposting, and anaerobic digestion possess intermediate readiness (TRL 5–7), balancing environmental benefits with slower throughput. Biochar based and hybrid methods remain in the early development phase (TRL 3–5), constrained by scaling barriers and insufficient life cycle evidence. In the short term, chemical precipitation offers the most feasible route for practical application, whereas biological and hybrid systems align better with long term circular bioeconomy goals that prioritize ecological sustainability over immediate yield. This underlines the

importance of techno-economic analysis (TEA) and life cycle assessment (LCA) for identifying solutions that are regionally optimized and context specific (Table 3, Figure 2).

A further challenge in achieving efficient phosphorus (P) recovery relates to nutrient stoichiometry. Many recycled phosphorus products tend to be rich in P but deficient in nitrogen (N) and potassium (K), requiring additional nutrient inputs to meet crop needs (Xie et al., 2023). To overcome this imbalance, ongoing research focuses on multi nutrient recovery strategies, such as co-precipitating struvite with ammonium or potassium salts, or combining P recovery with nitrogen fixing microbial consortia to produce fertilizers that deliver a more balanced nutrient profile aligned with circular nutrient management principles.

Environmental and health considerations are equally pressing. Recovered phosphorus materials can contain contaminants including potentially toxic elements (PTEs), antibiotic resistance genes (ARGs), and microplastics. These impurities necessitate strict process control, comprehensive monitoring systems, and harmonized regulations to guarantee product safety and consistency (Almaramah et al., 2024). Establishing shared certification schemes and unified quality standards will be essential to building public and industry confidence while facilitating the broader commercialization of recycled fertilizers.

Beyond technical and economic hurdles, institutional and social dimensions critically shape the transition toward a circular phosphorus economy. Fragmented governance across agricultural, industrial, and environmental domains often leads to disjointed policy implementation and limited coordination. Public hesitation toward the use of recycled fertilizers; largely driven by low awareness and safety concerns; further constrains adoption. Expanding outreach through knowledge exchange platforms, farmer demonstration projects, and cross sector collaboration can help bridge this gap, highlight co-benefits, and strengthen acceptance among stakeholders.

Looking forward, emerging biotechnological and digital tools hold considerable promise for addressing many of these limitations. Advances in microbial genomics, metabolic engineering, and synthetic biology are enabling the development of phosphorus accumulating and solubilizing microorganisms with improved stability and recovery performance. In parallel, artificial intelligence (AI), automation, and data driven monitoring systems are being applied to optimize reactor control, predict operational inefficiencies, and enable real time adjustment in wastewater and agricultural recovery processes.

The future of phosphorus recovery is likely to be integrated and multi technology based. Systems that link anaerobic digestion (AD) for energy generation with struvite precipitation and biochar amendment of digestates can simultaneously recover nutrients and enhance soil health. Establishing regional nutrient recovery hubs following biorefinery concepts could streamline material flows, lower operating costs, and strengthen local nutrient self sufficiency. Likewise, hybrid configurations that combine microbial, chemical, and electrochemical recovery routes offer the potential for higher efficiency and reduced environmental impact.

TABLE 3 Comparative analysis of laboratory vs. field performance of phosphate recovery technologies.

| Technology | Lab/small-scale                                                                                                                                                                                                                                                                                                                                                                                           | Economic benefits/cost-benefit                                                                                                                                                                                                     | Field (Pilot/Full-scale)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Economic benefits/cost-benefit                                                                                                                                                                                                                                                                                                                                                                                               | Main limitation                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | References           |
|------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------|
| Composting | -Laboratory experiments indicate that superphosphate application markedly enhances the retention of both phosphorus (P or P <sub>2</sub> O <sub>5</sub> ) and nitrogen. Earlier bench-scale trials similarly reported higher nutrient concentrations accompanied by reduced nutrient losses.                                                                                                              | Laboratory-scale cost analyses and small experimental trials have demonstrated advantages including improved nutrient retention and reduced emissions, with overall positive tradeoffs observed in certain integrated assessments. | Industrial-scale trials showed that superphosphate supplementation increased both total nitrogen (TN) and P <sub>2</sub> O <sub>5</sub> compared with the untreated control, with the 15% treatment achieving the greatest P <sub>2</sub> O <sub>5</sub> concentration.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | In large-scale practice, superphosphate use incurred costs of roughly USD 100 per ton plus transport, whereas benefits were derived from enhanced retention of P <sub>2</sub> O <sub>5</sub> , N, and K, along with reductions in emissions. Although the financial gains from greenhouse gas abatement were insufficient to outweigh the additional costs, nutrient savings could represent a major compensating advantage. | Practical improvements are achievable, although the benefits tend to plateau or involve trade-offs, such as effects on compost maturity. In applied settings, expenses related to materials, transportation, and handling are more influential, with cost efficiency further shaped by economies of scale and prevailing fertilizer prices in local markets.                                                                                                                       | (Chen et al., 2025b) |
|            | Laboratory experiments consistently demonstrate enhanced retention or increased availability of phosphorus following amendment application, with leachate losses generally minimal. Under optimal amendment ratios, high levels of organic matter degradation and favorable humification or stability indices are achieved, and the thermophilic phase can be readily maintained with greater uniformity. | Smaller treatment volumes reduce logistical complexity, enable more precise additive dosing, minimize variability, and typically result in lower costs per unit of compost processed.                                              | In the pilot-scale trial, additive treatments increased the availability of phosphorus relative to the control, although the magnitude of this enhancement was less pronounced than in many laboratory studies. Windrows amended with biochar (BC), humic compounds (HC), or hydroxyapatite (HAP) exhibited greater organic matter loss compared with the control, and compost maturity improved, as indicated by finer texture, reduced odor, and more uniform consistency. Moisture content, pH, and C/N ratios in the treated windrows remained within recommended ranges. Thermophilic phases occurred in all treatments, with some spatial and temporal temperature variability; certain windrows reached approximately 50–55 °C, reflecting typical composting dynamics. Differences among treatments in peak temperatures were minimal. | At larger scales, the handling and mixing of substantial additive quantities (BC, HC, HAP) require additional turnings, moisture management, and monitoring. These factors increase logistical complexity and operational costs, while the procurement and uniform distribution of additives remain key constraints.                                                                                                         | Under controlled conditions with consistent feedstock quality, smaller-scale operations face fewer challenges related to homogeneity, aeration, and moisture distribution. At a 10-ton scale, however, issues such as uneven moisture, variable additive mixing, spatial heterogeneity in temperature and pH, and slower or less uniform compost maturity were observed. Additionally, attention to heavy metal content, pathogen reduction, and odor management becomes critical. | (Feng et al., 2025)  |

(Continued)

TABLE 3 Continued

| Technology                              | Lab/small-scale                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Economic benefits/cost-benefit                                                                                                                                                                                 | Field (Pilot/Full-scale)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Economic benefits/cost-benefit                                                                                                                                                                                                                                                                              | Main limitation                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | References            |
|-----------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------|
| Compost/Biochar Amends in Olive Orchard | Laboratory and short-term field studies frequently demonstrate that compost amendments significantly increase soluble or available phosphorus, while biochar can enhance P retention or reduce leaching depending on feedstock type and pyrolysis conditions. Increases relative to baseline are generally observed within 1–2 years, often accompanied by higher leaf P concentrations and improved yields during the first one to two growing seasons. Amendments typically elevate extractable P fractions and may stimulate microbial activity, thereby accelerating P mineralization and nutrient cycling. However, these effects often decline over time due to leaching or immobilization, whereas biochar tends to persist and gradually contributes structural benefits to the soil. | Amendment and production costs are frequently estimated, with compost generally less expensive and biochar more costly; blending the two has been proposed as a potential strategy to reduce overall expenses. | In a five-year field study, applications of compost alone or in combination with biochar increased soil dissolved nutrients, including phosphorus, relative to the unamended control. In adult olive trees, however, leaf P concentrations and overall nutritional status were not significantly affected across compost, biochar, or blend treatments. In contrast, a bioassay using young plantlets demonstrated that the compost + biochar blend enhanced growth and biomass phosphorus accumulation, although leaf P concentrations remained similar. Compost and compost + biochar consistently elevated soil soluble P compared with control, whereas biochar alone had a smaller effect. Microbial activity, which contributes to P cycling, was higher in soils amended with compost or the blend. Amendments were applied biennially. Both biochar and the blend exhibited long soil residence, and biochar in particular improved physical properties such as bulk density, porosity, and water retention in the topsoil. Compost treatments maintained improvements in chemical and biological fertility over time. | Cost estimates indicate that compost application amounts to approximately 150 €/ha, biochar alone about 1,200 €/ha, and a 90:10 compost–biochar blend around 255 €/ha. Given typical orchard profit margins, biochar alone is likely cost-prohibitive, whereas the blend represents a more feasible option. | Controlled experiments conducted under uniform moisture, temperature, and homogeneous feedstock conditions tend to overestimate compost and biochar stability and nutrient availability. Short-duration trials (weeks to months) may exaggerate early nutrient release while failing to capture long-term immobilization processes. Plant responses are often assessed using fast-growing annuals, which are more sensitive than mature perennial orchards, leading to overestimation of leaf and tissue phosphorus uptake. In mature olive trees, soil P increases did not translate into significant changes in leaf P. Large-scale orchard soils exhibit spatial heterogeneity in moisture, root distribution, and microbial activity, resulting in less uniform effects. Nutrient dilution by long-term soil reserves can mask short-term gains. From an economic perspective, biochar at effective agronomic doses (~€1,200/ha) is prohibitively expensive, whereas compost–biochar blends are more feasible but yield smaller benefits. Additional considerations include potential increases in soil electrical conductivity from compost applications, which may affect sensitive crops, and the requirement for biennial re-application to maintain benefits, indicating that a single amendment is insufficient for long-term impact. | (Fornes et al., 2024) |

(Continued)

TABLE 3 Continued

| Technology                      | Lab/small-scale                                                                                                                                                                                                                                                                                                                                                                              | Economic benefits/cost-benefit                                                                                                                                                                                            | Field (Pilot/Full-scale)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | Economic benefits/cost-benefit                                                                                                                                                                                                                                                                    | Main limitation                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | References             |
|---------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------|
| Composting                      | Lab studies report compost P content ~0.3–0.5% of dry matter; high apparent retention due to controlled losses. Often 60–70% mass reduction reported in lab; final compost ~30–40% of input.                                                                                                                                                                                                 | Lab not typically assessing costs.                                                                                                                                                                                        | Field compost contained approximately 0.24% phosphorus (P <sub>2</sub> O <sub>5</sub> equivalent) on a dry matter basis, with partial nutrient retention. One tonne of wet biomass yielded roughly 614 kg of compost at 37% moisture.                                                                                                                                                                                                                                                                                                                                                                      | Life cycle assessment (LCA) accounted for transport, shredding, and pile maintenance. The benefits of compost valorization are strongly influenced by the proximity of logistics operations.                                                                                                      | Life cycle assessment (LCA) accounted for transport, shredding, and pile maintenance. The benefits of compost valorization are strongly influenced by the proximity of logistics operations.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | (Brás et al., 2024)    |
| Struvite/Chemical Precipitation | Under laboratory conditions or using synthetic urine/clean wastewater, phosphorus recovery of approximately 85–99% was achieved at optimal Mg:P ratios (~1.2–1.3:1) and pH values of 8.5–9.0. Laboratory studies commonly yield struvite crystals with high purity and predictable morphology, exhibiting high solubility and good phosphorus availability when applied to controlled soils. | Laboratory studies frequently consider only reagent or chemical costs and do not account for the full economic implications. Using clean wastewater can lower costs associated with pretreatment and impurity management. | In pilot-scale studies using mobile toilet wastewater, phosphorus recovery ranged from 1.9% to 65.2%, with the highest recovery (~65.2%) observed at pH 9 and an Mg:P ratio of 1.25:1. Solid precipitates, including sludge crystals and pelletized fertilizer prepared with fillers such as ash or filter cake, contained up to 21.5% P by weight under optimal conditions. Pellet dissolution and leaching were tested over 90 days in sandy loam, silt loam, and clay loam soils, yielding dissolution efficiencies of ~97.7%, 86.9%, and 88.0%, respectively, for the best pellet–filler combinations. | Neamhom et al. conducted a cost analysis for a 300 L experiment, comparing the phosphorus product with the market price of commercial fertilizer (18–46-0). Operational costs were assessed relative to potential selling prices, with exact values varying according to experimental conditions. | Under laboratory conditions, high phosphorus recovery is typically achieved only under ideal wastewater compositions with minimal interference, while factors such as scale, mixing, and the costs of reagents or pH adjustment are often not fully considered. In the pilot study, recovery efficiencies were lower under certain conditions, with variability influenced by pH and Mg:P ratio. The complexity of the wastewater matrix reduced performance, and pelletization introduced additional steps, including filler sourcing and drying. Leaching behavior was dependent on soil type, while drying and handling times were significant. The mixed composition of the wastewater, including solids, increased sludge production and impurity content. | (Neamhom et al., 2025) |
| Vermicomposting                 | Although not directly quantified, laboratory studies generally report increased phosphorus availability resulting from mineralization and stabilization processes. These experiments are typically conducted over 2–6 weeks under controlled conditions with constant temperature and moisture.                                                                                              | Minimal lab cost; only small reactors and worms.                                                                                                                                                                          | Pilot-scale vermicomposting of OFMSW improved nutrient stabilization, with phosphorus availability higher in the final vermicompost compared to raw waste. The process required 8–12 weeks, depending on worm density, feedstock composition, and environmental conditions.                                                                                                                                                                                                                                                                                                                                | Vermicomposting requires infrastructure for bins, labor for feeding and monitoring, and ongoing management of the worm population.                                                                                                                                                                | Vermicomposting is sensitive to feedstock composition, temperature, and moisture, with the potential for heavy metal accumulation in worms. In large-scale operations, feedstock heterogeneity, risk of leachate contamination, and slower phosphorus mineralization compared to laboratory conditions can reduce overall efficiency.                                                                                                                                                                                                                                                                                                                                                                                                                           | (Licitra et al., 2024) |

(Continued)

TABLE 3 Continued

| Technology             | Lab/small-scale                                                                                                                                                                                                                                                                  | Economic benefits/cost-benefit                                                                                                            | Field (Pilot/Full-scale)                                                                                                                                                                                                                                                       | Economic benefits/cost-benefit                                                                                   | Main limitation                                                                                                                                                                                                                                                                                                                                                                   | References              |
|------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------|
| Biochar                | High phosphorus recovery efficiencies were observed under controlled conditions, with struvite precipitation achieving up to 90%. Recovery rates for struvite typically ranged from 80–90%, while electrochemical and biological methods generally exhibited lower efficiencies. | Costs were relatively low due to small-scale operations, with chemical expenses representing the primary cost for struvite precipitation. | Phosphorus recovery efficiency varied under field conditions, with struvite precipitation achieving 70–80%. Struvite generally provided 60–80% recovery, whereas other methods showed lower efficiencies.                                                                      | Costs increased at larger scales due to infrastructure requirements and operational complexities.                | Phosphorus recovery is limited by scale, potential overestimation of laboratory recovery rates, and the absence of real-world variability. Additional challenges include system stability, maintenance requirements, and adaptation to heterogeneous feedstocks, with performance influenced by feedwater composition and operational conditions.                                 | (Meier et al., 2025)    |
| Mg/Al-Modified Biochar | Column experiments demonstrated phosphorus adsorption of up to 7.0 mg P g <sup>-1</sup> biochar, with high efficiency observed under controlled conditions.                                                                                                                      | Costs were lower owing to small-scale operations and the controlled experimental environment.                                             | A 211 cm diameter, 50 cm height column treating 116 m <sup>3</sup> day <sup>-1</sup> of real wastewater is projected to recover over 0.5 kg P day <sup>-1</sup> . Recovery efficiency may vary, highlighting the need for field-scale studies to validate laboratory findings. | Costs are expected to increase at larger scales due to infrastructure requirements and operational complexities. | Potential challenges include maintaining system stability, addressing maintenance requirements, and adapting to variable feedstocks.                                                                                                                                                                                                                                              | (Jellali et al., 2024)  |
| Electrocoagulation     | High efficiency was observed under controlled experimental conditions.                                                                                                                                                                                                           | Lower costs were observed due to small-scale operations and the controlled experimental environment.                                      | Efficiency may vary, highlighting the need for field-scale studies to validate laboratory results.                                                                                                                                                                             | Higher costs are anticipated at larger scales due to infrastructure requirements and operational complexities.   | Recovery is constrained by scale, potential overestimation of laboratory efficiencies, and limited representation of real-world variability. Additional challenges include system stability, maintenance requirements, and adaptation to heterogeneous feedstocks. Scaling up from laboratory to field conditions introduces complexities not captured in controlled experiments. | (Debela et al., 2025)   |
| Anaerobic Digestion    | Agro-waste digestates (AW_D) exhibited high labile phosphorus content, suggesting strong potential for plant availability. Both AW_D and its composted form (AW_C) demonstrated superior phosphorus efficiency in soil incubation and pot experiments.                           | Not determined                                                                                                                            | Field validation is necessary, as laboratory conditions may not fully replicate field dynamics. Field-scale trials are required to confirm laboratory findings.                                                                                                                | Not determined                                                                                                   | Recovery is constrained by scale, potential overestimation of laboratory efficiencies, and the absence of real-world variability. Additional challenges include system stability, maintenance requirements, and adaptation to heterogeneous feedstocks.                                                                                                                           | (Grigatti et al., 2023) |

Achieving this vision will require enabling policy and market conditions that reduce financial risk and reward innovation. Measures such as fiscal incentives for nutrient recovery, stricter contaminant regulations, and certification schemes for recycled fertilizers can help create favorable conditions for investment. Aligning these initiatives with circular economy frameworks and the Sustainable Development Goals (SDGs) will be crucial for scaling nutrient recovery technologies sustainably. Building a resilient circular phosphorus economy depends on coordinated efforts among researchers, policymakers, industry leaders, and farmers. Integrating technological innovation with sound economics and social acceptance can transform today's linear, waste oriented phosphorus cycle into a regenerative, closed loop system that sustains agricultural productivity while safeguarding environmental integrity (Katakula et al., 2021).

## 4 Microbial and biotechnological strategies for phosphorus recovery

### 4.1 Microbial solutions for P solubilization and mobilization

The growing demand for phosphorus (P) fertilizers, along with concerns about their environmental impacts, has driven research into sustainable ways to increase phosphorus availability in agriculture. One of the most promising strategies involves phosphorus solubilizing microorganisms (PSMs), which include bacteria (PSB) and fungi (PSF). These microbes are crucial in the soil P cycle because they convert insoluble forms of phosphorus into bioavailable forms, helping plants overcome P deficiencies and improving nutrient uptake.

Researchers have isolated a wide variety of phosphate solubilizing bacteria and fungi from soils, rhizospheres, and even sewage sludge (Supplementary Table S1; Supplementary Figure S1). Among them several genera present a high potential when applied to different crops growing under field conditions (Table 4). Genera like *Pseudomonas*, *Bacillus*, *Enterobacter*, and *Burkholderia* have been most extensively studied due to their consistent ability to support plant growth and nutrition (Buch et al., 2008; Kalayu, 2019; Nacoon et al., 2020; Yu et al., 2022). Other genera with phosphate solubilizing potential include *Serratia*, *Pantoea*, *Acinetobacter*, and *Klebsiella*, although they are less commonly applied (He and Wan, 2021; Kerketta et al., 2025; Prasad et al., 2022). These bacteria release organic acids, phosphatases, and siderophores that mobilize phosphorus otherwise unavailable to plants (Pradhan et al., 2025; Figiel et al., 2025).

For instance, *Bacillus* species solubilize phosphate through acidification and enzyme production, while also functioning as multifunctional biofertilizers. They produce phytohormones, enhance root development, and stimulate systemic resistance in plants (Abuhena et al., 2024; Vitorino et al., 2024; Iqbal et al., 2024; Rakshit et al., 2024). Similarly, *Pseudomonas* strains are efficient rhizosphere colonizers that produce gluconic acid and siderophores, making them reliable components of commercial

biofertilizers (Revitaningrum et al., 2024; Qessaoui et al., 2025; Soliman et al., 2025).

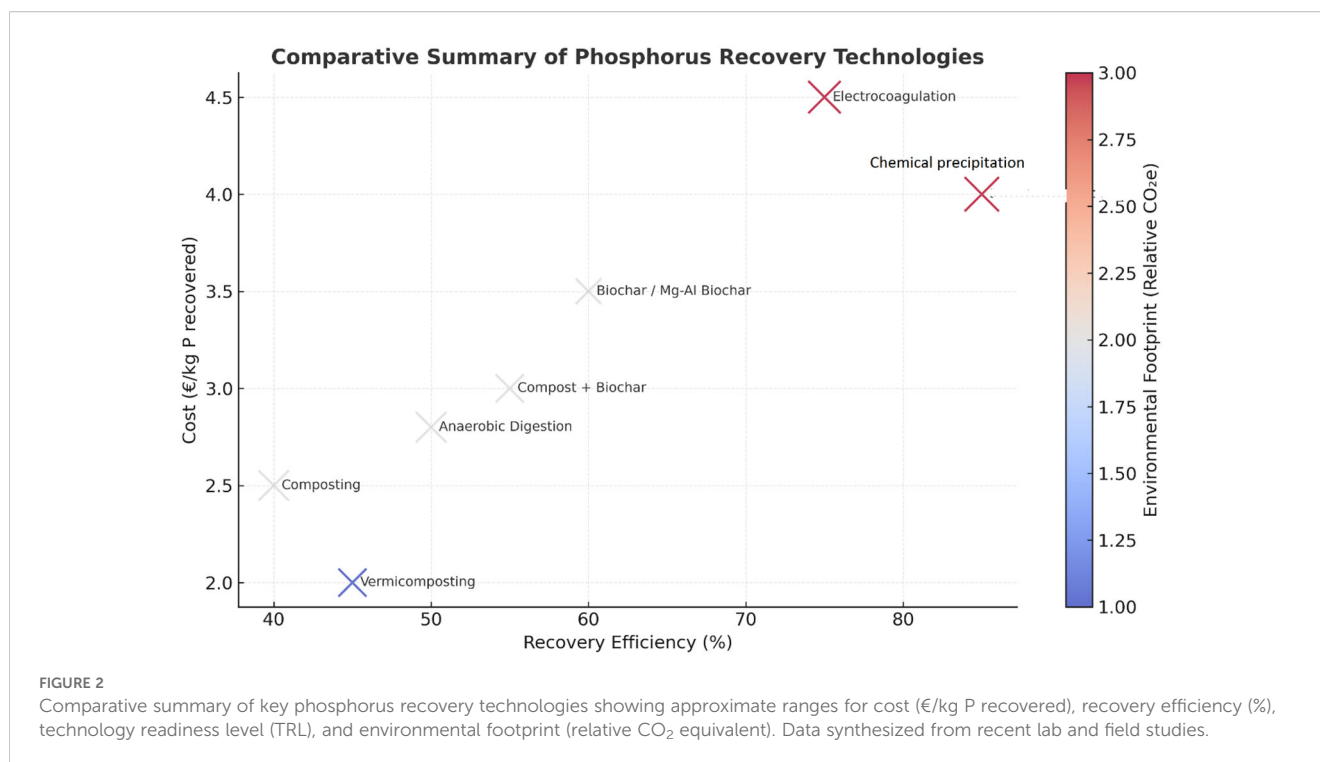
*Burkholderia* and *Paraburkholderia* play a particularly important role in highly weathered or acidic soils, where phosphorus is often bound to iron and aluminum oxides. These genera effectively solubilize Fe and Al phosphates and, aided by phytase and siderophore production, can also mobilize organic phosphorus sources such as phytate. Their prevalence in P limited environments underscores both their ecological importance and their potential for agricultural applications (Tu et al., 2023; Oh et al., 2024; Hua et al., 2024; Rojas-Rojas et al., 2025; Guo et al., 2025a).

Fungi also contribute significantly to phosphorus solubilization. Phosphate solubilizing fungi (PSF) are known for their high solubilization efficiency, adaptability, and genetic stability (Rashid et al., 2004). The genera *Aspergillus* and *Penicillium* are the most studied, producing diverse organic acids capable of dissolving mineral phosphates and penetrating soil matrices (Arrieta et al., 2015; Vassileva et al., 2022; Bareduan et al., 2025; Akpelo et al., 2025). Other effective PSF include *Trichoderma* and arbuscular mycorrhizal fungi such as *Glomus* species. *Trichoderma*, in particular, also acts as a biocontrol agent, combining soil fertility enhancement with plant protection. Although PSF are highly efficient, PSB are often preferred in agricultural practice due to their faster colonization and adaptability to variable soil conditions (Prasetya et al., 2024; Guzmán-Guzmán et al., 2025; Ouhaddou et al., 2025).

In addition to bacteria and fungi, cyanobacteria such as *Anabaena* and *Nostoc* have emerged as valuable contributors to nutrient management. These photosynthetic microorganisms not only solubilize inorganic and organic phosphates but also fix atmospheric nitrogen, offering dual benefits particularly useful in rice paddies and aquatic based cropping systems (Elshobary et al., 2025). Concentrating research on these core microbial groups offers a practical route to advance microbial biofertilizers, improve phosphorus availability, boost crop productivity, and support sustainable agricultural practices (Guo et al., 2025b; González et al., 2025).

Recent studies have highlighted that the efficiency of phosphorus (P) solubilization in soils is shaped not only by the activity of individual microorganisms but also by the composition, dynamics, and interactions within entire microbial communities (Pan and Cai, 2023a; Zhu et al., 2024; Kiprotich et al., 2025; Tariq et al., 2025). In natural ecosystems, phosphorus solubilizing bacteria (PSB) and fungi (PSF) seldom function independently; rather, they coexist with diverse microbial partners; such as arbuscular mycorrhizal fungi (AMF), nitrogen fixing bacteria, and other plant growth promoting rhizobacteria (PGPR); that together regulate nutrient turnover and soil fertility. This understanding has led to the concept of synthetic microbial consortia, deliberately composed of functionally complementary species, as a next generation strategy for improving phosphorus availability and soil health (Nanjundappa et al., 2019; Etesami et al., 2021; Khan et al., 2024a; Tharanath et al., 2024).

These engineered consortia function through synergistic interactions that extend beyond the capacity of individual isolates.



For instance, organic acids secreted by PSB lower soil pH and release bound phosphate, while mycorrhizal hyphae expand the nutrient absorption zone, increasing phosphorus uptake efficiency (Khan et al., 2024b). At the same time, nitrogen fixing bacteria enrich the rhizosphere with bioavailable nitrogen, indirectly stimulating plant growth and microbial metabolism (Igiehon and Babalola, 2018; Timofeeva et al., 2023a). These processes are coordinated by microbial communication systems; quorum sensing, metabolite exchange, and cross feeding; that synchronize population movement and enhance resilience under fluctuating environmental conditions (Douglas, 2020; Pan et al., 2023b; Deo et al., 2025).

Recent advances in microbiome engineering, metagenomics, and synthetic biology are enabling the rational design and optimization of these microbial assemblies. Using multi omics tools (metagenomics, transcriptomics, metabolomics) and computational modeling, researchers can identify critical interactions, metabolic interdependencies, and regulatory pathways that govern phosphorus solubilization (Ke et al., 2021; Thakur et al., 2023; Ramachandran et al., 2025). This knowledge supports the construction of microbial consortia that are ecologically compatible, metabolically cooperative, and adaptable to a variety of soil environments. Moreover, tailored consortia can be optimized for specific crop systems or stress conditions; such as salinity, drought, or nutrient depletion; thereby improving nutrient use efficiency and soil resilience (Niranjan et al., 2023; Timofeeva et al., 2023b; Wu et al., 2023; Patra et al., 2025).

The long term success of such bioengineered communities depends on their ecological stability and persistence once introduced into the soil. Strategies including encapsulation in biochar or alginate matrices, carrier based formulations, and co-

inoculation with organic amendments are being explored to enhance microbial survival and field performance. When effectively established, synthetic consortia can transform the rhizosphere into a self regulating, interactive micro-ecosystem that supports sustainable phosphorus management (Zegeye et al., 2019; Rebello et al., 2021; Wu et al., 2023; Khan et al., 2023b; Ibáñez et al., 2023).

In parallel, omics guided research is revolutionizing the development and deployment of microbial inoculants for sustainable phosphorus management. Integrated genomic, metagenomic, metatranscriptomic, and metabolomic analyses allow researchers to map the genetic and functional potential of key taxa involved in P solubilization and mobilization. These approaches reveal genes linked to organic acid synthesis, phosphatase activity, and phosphate transport, while transcriptomic and metabolomic profiles elucidate the active biochemical pathways that drive phosphorus turnover under real soil conditions. Comparative genomics further aids in identifying elite microbial strains with superior metabolic performance, stress tolerance, and plant associative traits, forming the basis for precision designed biofertilizers (Das and Maity, 2025; Srikanth et al., 2025; Wang et al., 2025; Chukwuneme and Babalola, 2025).

The integration of multi omics datasets; linking genetic potential, transcriptional response, and metabolite flux; provides a systems level understanding of soil microbiomes. This holistic framework enables the customization of microbial inoculants for distinct soil types, plant genotypes, and agroclimatic conditions, improving scalability and consistency in field performance. Omics guided inoculant design, which aligns microbial traits with crop and environmental demands, marks a transition in biofertilizer development from trial and error methods to data informed

TABLE 4 Relevant genera of phosphate solubilizing microbe (PSMs) in the soil.

| Genus                             | Evidence of field efficacy                                                                                                                                   | References                                                         |
|-----------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------|
| Bacillus                          | Commonly applied in field inoculants, with multiple trials demonstrating enhanced phosphorus uptake and improved yields in cereals, legumes, and vegetables. | (Ramos Cabrera et al., 2024; Ughamba et al., 2025)                 |
| Pseudomonas                       | Documented multi crop field trials reported increases in grain yield, shoot biomass, and phosphorus use efficiency.                                          | (Gouli et al., 2024; Ughamba et al., 2025; Pilotto et al., 2025)   |
| Rhizobium                         | Field studies in legumes have demonstrated its effectiveness, combining nitrogen fixation with phosphorus solubilization.                                    | (Teng et al., 2024; Ughamba et al., 2025)                          |
| Trichoderma                       | Consistently enhances root development and crop yield, while improving phosphorus uptake in field grown maize and legumes.                                   | (Teng et al., 2024; Ughamba et al., 2025)                          |
| Penicillium                       | Field application of rock phosphate resulted in increased crop phosphorus uptake and higher yields                                                           | (Teng et al., 2024; Ughamba et al., 2025)                          |
| Aspergillus                       | A. niger strains show significant P solubilization in soils, and yield increases.                                                                            | (Toribio et al., 2025)                                             |
| Enterobacter                      | Reported in field maize and wheat trials; improves P uptake and biomass.                                                                                     | (Ughamba et al., 2025; Toribio et al., 2025; Pilotto et al., 2025) |
| Burkholderia/<br>Paraburkholderia | Documented field cases in maize and rice; strong rhizosphere colonizers with multi-trait benefits.                                                           | (Li et al., 2024; Ramos Cabrera et al., 2024)                      |
| Streptomyces                      | Actinobacteria shown to mobilize organic P and improve crop yields in plots.                                                                                 | (Ughamba et al., 2025)                                             |
| Serratia                          | Emerging evidence from field level maize/wheat trials; improved P uptake and root biomass.                                                                   | (Trinh et al., 2024)                                               |

engineering (Fan et al., 2025; Díaz-Rodríguez et al., 2025; Patel and Gang, 2025; Sahoo et al., 2025).

Beyond harnessing natural diversity, biotechnological tools are being applied to enhance phosphorus solubilization through genetic and metabolic engineering. CRISPR Cas genome editing and targeted gene knock-in or knock-out techniques are being used to amplify key traits such as organic acid production, phosphatase secretion, and tolerance to abiotic stresses (Halami and Sundararaman, 2024; Chauhan et al., 2024; Ramos Cabrera et al., 2024; Thankappan et al., 2024; Kavya et al., 2024). Synthetic biology further extends these possibilities by constructing modular phosphorus solubilizing pathways and engineered biofilms with controllable metabolic activity. Engineered microbial chassis, such as *Bacillus*, *Pseudomonas*, and *Azotobacter*, can integrate nutrient solubilization, stress alleviation, and plant signaling within a single platform, forming multifunctional smart biofertilizer systems (McCarty and Ledesma-Amaro, 2019; Dundas and Dinnyen, 2022; Martínez-García and De Lorenzo, 2024; Shafi et al., 2025; Nawaz et al., 2025; Xu et al., 2025b).

To ensure environmental safety, these innovations are accompanied by robust biosafety and biocontainment measures. Strategies such as synthetic auxotrophy, genetic circuit regulation, and kill switch mechanisms provide control over microbial persistence and horizontal gene transfer, mitigating ecological risks and addressing regulatory concerns (Ke et al., 2021; Ahmed et al., 2024; Jones et al., 2024; Chemla et al., 2025).

By uniting omics driven discovery, rational community design, and synthetic biology, researchers are developing next generation adaptive biofertilizers. These systems can dynamically respond to soil and plant signals through feedback regulation, maintaining consistent performance across diverse environments. Such intelligent inoculants not only improve phosphorus use efficiency but also advance the broader goals of the circular bioeconomy by

reducing chemical fertilizer dependence, minimizing nutrient loss, and promoting long term soil vitality. The convergence of omics technologies, microbial engineering, and systems ecology represents a decisive step toward precision microbiome management for sustainable phosphorus cycling and resilient agroecosystems.

## 4.2 Biotechnological innovations for P recovery

From a global perspective, and considering the transformations of phosphorus (P) within ecosystems, it is important to differentiate between P elimination and P recovery mechanisms. Initially, P elimination focused on preventing eutrophication. Later, attention shifted to the potential reuse of P rich sludge in agriculture (Cornel and Schaum, 2009). Consequently, sustainable P management emerged, emphasizing both the elimination of excess P and its potential recovery.

The conventional approach of sourcing P through mining phosphate rock (PR) is increasingly recognized as unsustainable, given the finite nature of PR reserves and the significant environmental impacts of mining activities. This has led to a growing interest in sustainable P recycling techniques that recover P from various waste streams, reduce dependence on PR, and help mitigate environmental pollution. In this context, second generation P recovery refers to environmentally sustainable methods of extracting P from waste materials, in contrast to the traditional first generation approach of mining PR. These innovative recovery strategies include biological, chemical, technological, and electrochemical processes applied to solid, semi solid, or liquid waste byproducts (Ogwu et al., 2025).

Generally, P recovery involves designing systems and implementing techniques to produce reusable P rich products

(Desmidt et al., 2015; Venkiteshwaran et al., 2018). It is worth noting that not all removed P is recovered. For instance, Guisasaola et al. (2019) achieved 98% P removal using a biological reactor but only recovered about 60% through supernatant extraction from an anaerobic system. Currently, phosphorus is primarily recovered from nutrient rich streams resulting from the anaerobic digestion of various feedstocks, including sewage sludge, food waste, agricultural residues, and wastewater from animal farming (Vu et al., 2022; Salkunić et al., 2022; Ganesapillai et al., 2021).

Enhanced biological phosphorus removal (EBPR) has emerged as a highly effective P removal process in municipal and industrial wastewater treatment. For many years, EBPR has been regarded as a cost effective and environmentally sustainable alternative to chemical treatments (Acevedo et al., 2012; Nguyen et al., 2013).

In biological nutrient removal (BNR) systems, EBPR relies on a specialized group of microorganisms known as polyphosphate accumulating organisms (PAOs). These organisms take up phosphate from wastewater in excess of their growth requirements under alternating anaerobic and aerobic/anoxic conditions (Tchobanoglous et al., 2003). Accumulibacter is the most widely studied PAO and forms the basis of most metabolic models (Martin et al., 2006; Oehmen et al., 2007). It is considered the dominant PAO in effective EBPR systems (López-Vázquez et al., 2008; Zeng et al., 2003).

For two decades, Acinetobacter species were mistakenly identified as the primary PAOs responsible for EBPR (Crocetti et al., 2000; Li et al., 2003; Nguyen et al., 2011). Later studies disproved this, confirming Accumulibacter as the main PAO. However, Tetrasphaera related Actinobacteria have also been found in high abundance in well performing P removal systems and have demonstrated the capacity for luxury P uptake (Nguyen et al., 2011; Oehmen et al., 2007).

Other predictive PAOs, including Pseudomonas sp., Paracoccus sp., and some Enterobacter species, have been detected at low levels in P removal plants (Krishnaswamy et al., 2009; Li et al., 2003). Notably, certain PAOs can perform simultaneous P accumulation and denitrification under alternating anaerobic anoxic conditions (López-Vázquez et al., 2008).

Denitrifying PAOs (DPAOs) utilize alternative electron acceptors (nitrate or nitrite) to metabolize intracellular organic compounds under anoxic conditions, enabling simultaneous P uptake and denitrification (Barnard et al., 2017; Nielsen et al., 2019, 2012). Promoting DPAOs in wastewater treatment plants (WWTPs) offers potential benefits, such as energy savings, by integrating P and nitrogen (N) removal (Oehmen et al., 2007).

A significant advance in understanding EBPR microbiology was the discovery of new PAOs capable of simultaneous P and N removal under anoxic conditions. The genus Tetrasphaera, recently identified as a putative PAO, was first characterized through isolated strains (Hanada et al., 2002; Maszenan et al., 2000). Tetrasphaera representatives are often predominant in full scale WWTPs (Fernando et al., 2019; Stokholm-Bjerregaard et al., 2017). They exhibit versatile metabolic capabilities, including the fermentation of glucose and amino acids to produce volatile fatty

acids (VFAs) in anaerobic zones, thereby enriching substrate pools for EBPR. Unlike typical PAOs that primarily store polyhydroxyalkanoates (PHAs), Tetrasphaera can store other intracellular compounds and use nitrate (but not nitrite) in addition to dissolved oxygen as electron acceptors (Metcalf et al., 1991). This has drawn attention to their interactions and competition with Accumulibacter (Nielsen et al., 2012; Seviour et al., 2003).

In recent years, several new genera have been proposed as potential PAOs, such as Dechloromonas and Candidatus Microthrix. However, only the betaproteobacterial genera Ca. Accumulibacter (Fernando et al., 2019) and the actinobacterial genus Tetrasphaera have consistently been found in high abundances in full scale EBPR systems (Stokholm-Bjerregaard et al., 2017). For example, in Danish WWTPs, 24-70% of total P removal was attributed directly to Ca. Accumulibacter and Tetrasphaera (Fernando et al., 2019). Other PAOs generally have much lower relative abundances, with Acinetobacter reaching only 1.2% and Dechloromonas below 1% (Petriglieri et al., 2021; Seviour and McIlroy, 2008).

Recent progress in microbial ecology has revealed that the efficiency of phosphorus (P) recovery in enhanced biological phosphorus removal (EBPR) systems depends closely on the structure, activity, and functional diversity of their microbial communities. The interaction among phosphorus accumulating organisms (PAOs), denitrifying PAOs (DPAOs), and competing guilds such as glycogen accumulating organisms (GAOs) and nitrifiers determines not only phosphorus removal performance but also the stability and resilience of reactors operating under changing environmental and process conditions (Lv et al., 2014; Wang et al., 2020; Roy et al., 2021; Lin et al., 2023).

Advances in metagenomics, metatranscriptomics, and single cell genomics have enabled a much deeper characterization of the genetic potential and metabolic activity of PAO and DPAO populations within these mixed microbial systems. Such approaches identify key functional genes and reveal how their expression patterns respond to operational changes. Insights at this molecular scale help clarify how variations in nutrient loading, oxygen concentration, and carbon availability influence community function. Incorporating omics data into real time control frameworks now allows proactive adjustment of reactor operation, helping maintain microbial balance, stabilize performance, and improve phosphorus recovery efficiency. This integration is reshaping EBPR plants into adaptive, self regulating bioprocesses that combine higher stability with lower energy demand (Shakya et al., 2019; Mickol et al., 2021; Pelevina et al., 2023; Sabba et al., 2023; Zhou et al., 2023). Understanding the ecological relationships among PAOs, DPAOs, GAOs, and nitrifiers remains central to process optimization. Whereas PAOs and DPAOs are primarily responsible for phosphorus storage and release under aerobic and anoxic conditions, GAOs often compete for the same carbon sources without contributing to phosphorus removal, thereby affecting system stability. Omics guided community profiling, combined with metabolic and

network modeling, helps to untangle these cooperative and competitive interactions. The resulting knowledge informs operational strategies; such as adjusting carbon inputs, dissolved oxygen levels, and aeration cycles; to maximize phosphorus uptake while limiting microbial competition and minimizing energy costs (Zou Haiming et al., 2014; Li et al., 2020b; Gao et al., 2022).

At the same time, engineering innovations are advancing in parallel with biological insights. Modern bioreactor systems integrate sensor based monitoring, machine learning, and automated feedback control with omics informed microbial management to achieve closed loop regulation of community function. Hybrid configurations that combine EBPR with electrochemical recovery, membrane technologies, or anaerobic digestion are being developed to achieve nutrient removal, recovery, and reuse in a single process. These integrated designs reflect the core principles of a circular nutrient economy, transforming conventional wastewater treatment facilities into multifunctional bioresource recovery centers that generate valuable outputs such as struvite and biofertilizers.

Recent technological advancements have significantly improved P-removal efficiency. For instance, Yang et al. (2010) developed a sequencing batch moving bed membrane bioreactor system, achieving a total P removal rate of 84%. A novel development in granular sludge systems is the operation under anaerobic-anoxic conditions, known as AnoxAn technology. This approach aims to achieve simultaneous multi nutrient removal. Total P removal rates of up to 89% have been reported using AnoxAn reactors, without compromising N removal, albeit requiring mechanical mixing (Díez-Montero et al., 2016).

Membrane aerated biofilm reactors (MABRs), a novel modification of membrane bioreactor (MBR) technology, utilize gaseous electron donors or acceptors transferred across a hydrophobic membrane (Ivanovic and Leiknes, 2012; Nerenberg, 2016). While only recently commercialized and not yet widely established in nutrient removal markets (Martin and Nerenberg, 2012), MABRs have demonstrated promising results. They behave differently from conventional biofilms due to gas exchange, adding operational complexity. Nonetheless, total P removal of up to 90% has been achieved when used with sequencing batch reactors (SBRs) (Sun et al., 2015).

## 5 Integrating microbial and biotechnological solutions into crop production

### 5.1 Field application strategies

Contemporary agriculture must feed a growing population while safeguarding the environment. A central challenge in this balance is phosphorus (P) management. Although vital for plant growth, much of the phosphorus in soils exists in forms unavailable to crops. Dependence on chemical fertilizers has not solved this

problem; instead, it has contributed to inefficient nutrient use, losses to waterways, and ecological issues such as eutrophication (Cordell and White, 2013; Blackwell et al., 2019; Dixon et al., 2020).

Biological approaches, especially the use of phosphate solubilizing microorganisms (PSMs), are emerging as an effective alternative. These microbes; spanning bacteria, fungi, and Actinobacteria; convert insoluble phosphorus into plant accessible forms by releasing organic acids, protons, and enzymes such as phosphatases and phytases (Ma et al., 2025). Well studied genera include *Pseudomonas*, *Bacillus*, *Rhizobium*, *Aspergillus*, and *Trichoderma*, which colonize the rhizosphere and improve nutrient availability (Sharma et al., 2013; Billah et al., 2019; Elhaisoufi et al., 2022; Timofeeva et al., 2022; Zhu et al., 2024; Ughamba et al., 2025). Many also produce growth promoting hormones, increase nutrient uptake efficiency, and help plants withstand environmental stresses. Mycorrhizal fungi are particularly valuable, expanding the functional root network and enhancing phosphorus acquisition in nutrient poor soils.

Effective deployment of these microbial agents depends on careful strain selection, suitable formulation, and appropriate application methods (Kumar et al., 2022; Díaz-Urbano et al., 2023; Chukwudi et al., 2025). Inoculants are typically delivered in solid carriers like peat, talc, or vermiculite, or as liquid suspensions enhanced with stabilizers. Encapsulation technologies have further improved shelf life, microbial survival, and controlled nutrient release (Gopalakrishnan et al., 2016; Lobo et al., 2019; Vassilev et al., 2020; Khan et al., 2023b). On the production side, advances in fermentation techniques now yield concentrated, stable preparations at commercial scale (Stamenković et al., 2018; Golzar-Ahmadi et al., 2024; Díaz-Rodríguez et al., 2025).

Field success also relies on matching microbial species to soil types, crop varieties, and local agricultural practices, as well as timing applications to crop growth stages. Techniques range from seed coating to soil drenching and foliar spraying, chosen according to the crop and formulation (Ibáñez et al., 2023; Chukwudi et al., 2025; Yusuf et al., 2025; Dixon and Vivanco, 2025). Regulatory oversight is evolving to ensure quality and safety, with countries such as Brazil, India, Canada, and Australia setting standards for microbial content, concentration, and approved uses (Dos Reis et al., 2024).

From an ecological perspective, microbial phosphorus strategies minimize runoff and mitigate the risk of nutrient driven water pollution. Unlike synthetic fertilizers, which often accumulate in soils and leach away, PSMs improve phosphorus uptake and stability, protecting waterways. They also enhance soil structure, promote biodiversity, and lower erosion risks (Chowdhury et al., 2017; Khan et al., 2024c; Liang et al., 2025; Nuruzzaman et al., 2025). Beyond environmental protection, these microbes help build resilient agroecosystems by increasing microbial biomass, enzyme activity, and beneficial soil interactions. Many strains tolerate harsh conditions, making them valuable for restoring degraded land and supporting climate adapted agriculture (Koskey et al., 2021; Samantaray et al., 2024; Asante et al., 2025; Díaz-Rodríguez et al., 2025).

## 5.2 Sustainability benefits

A major sustainability advantage in modern agriculture is reducing dependence on non renewable phosphate rock. Naturally occurring microorganisms, such as phosphate solubilizing bacteria and polyphosphate accumulating organisms, help unlock phosphorus bound in soils or organic matter, transforming it into plant accessible orthophosphate. This biological mechanism lowers the need for synthetic phosphorus fertilizers, safeguarding finite reserves for future use (Cordell and White, 2013; Silva et al., 2023; Colombo et al., 2024). Microbial inoculants enhance phosphorus uptake by increasing its availability in the soil and improving plant absorption. Field studies have documented up to a 25% rise in phosphorus bioavailability and corresponding yield improvements when microbial treatments are applied, pointing to a more efficient and productive farming model (Bargaz et al., 2018; O'Callaghan et al., 2022; Bargaz et al., 2021; Sande et al., 2024). Biological phosphorus strategies also help reduce environmental contamination. Unlike traditional fertilizers, which often leach into waterways and trigger eutrophication, microbial interventions promote better soil structure and nutrient retention. Research has shown a 30% decline in soil pathogens and enhanced water retention in treated areas, contributing to healthier soils and ecosystems (Singh et al., 2024; Khan et al., 2024a, c; Xing et al., 2025).

In circular agriculture systems, microbial technologies support closed loop nutrient cycles. Microbes that store phosphorus as polyphosphate can later release it for plant use, forming a renewable reservoir of bioavailable nutrients. This dynamic process reduces external fertilizer requirements and promotes internal nutrient recycling (Ayeyemi et al., 2023; Babcock-Jackson et al., 2023; Lemos Junior et al., 2024). Recent advances in biotechnology further optimize these systems.

Recent developments in biotechnology are enhancing these systems through the use of advanced analytical methods, including single cell Raman spectroscopy (SCRS) and nuclear magnetic resonance (NMR) spectroscopy. SCRS provides a non destructive way to study the biochemical profile and metabolic state of individual microbial cells, allowing scientists to pinpoint in real time which organisms are actively storing or releasing phosphorus. NMR, on the other hand, offers precise identification and quantification of various phosphorus compounds present in soils, biofilms, and plant tissues. When applied together, these techniques make it possible to design and introduce microbial consortia that are well matched to specific soils, crop requirements, and environmental settings. Such precision ensures that phosphorus recovery and plant absorption are maximized, while unnecessary nutrient losses and environmental impacts are kept to a minimum. In this way, biotechnology driven, data guided microbial management supports a more efficient agricultural system one that reduces dependence on mined phosphate rock and operates in harmony with circular nutrient use principles (Wang et al., 2021; Jing et al., 2025).

Biotechnological innovations are expanding the potential of microbial applications. Through genome sequencing, metabolic mapping, and synthetic community design, scientists are tailoring microbial consortia for specific crops, soil types, and stressors. By integrating functions like nitrogen fixation, stress resilience, and disease suppression, these engineered formulations will offer reliable, multi benefit tools for sustainable farming (Sudheer et al., 2020; Ibrahim et al., 2021; Argente-Martínez et al., 2024).

## 5.3 Future directions and challenges

In the face of escalating global food demands and mounting environmental pressures, the recovery and sustainable reuse of phosphorus have become critical elements of future oriented agricultural strategies. Advances in microbial and biotechnological approaches have introduced promising methods for enhancing phosphorus recycling and reducing dependency on finite mineral resources. Nonetheless, the practical implementation of these innovations remains constrained by a range of scientific, technical, and logistical challenges that must be addressed to enable large scale adoption. Among the leading priorities is enhancing the functionality of microbial consortia. Although individual phosphate solubilizing microorganisms (PSM) have demonstrated notable capabilities in controlled settings, their efficacy often declines under open field conditions, largely due to environmental unpredictability. To address this, efforts are shifting toward assembling diverse microbial groups with complementary functions, matched to particular crops and soil characteristics. Developments in areas such as genome analysis, synthetic biology, and metabolic engineering are opening possibilities for tailored microbial solutions that combine nutrient mobilization, stress resistance, and other beneficial traits.

Equally pressing is the need for accurate and scalable phosphorus monitoring systems. Managing P efficiently requires insight into its chemical forms and movement within soil and plant systems. Technologies provide sophisticated diagnostics, though their adoption is hindered by cost, complexity, and accessibility. Integrating machine learning into these platforms may enhance real time decision making, offering adaptive strategies for fertilizer application and soil management.

Bringing these microbial technologies from research environments into practical agricultural use is still a considerable hurdle. Field variability, native microbial competition, and environmental stressors can undermine the viability of introduced organisms. Approaches such as encapsulated microbial carriers or pairing with organic amendments may help improve persistence and functionality in the field, especially under challenging conditions.

Wider adoption also depends heavily on regulatory and economic conditions. Incentives that reward sustainable phosphorus practices, together with standardized guidelines for biobased products, are essential to encourage uptake.

Infrastructure investments, particularly in regions vulnerable to phosphorus scarcity, will be necessary to implement these innovations at scale.

Awareness and education remain central to bridging the gap between technology and end users. Many farmers are unfamiliar with microbial based products or remain doubtful of their benefits. Demonstration projects, knowledge sharing networks, and transparent reporting of agronomic and economic outcomes will play a critical role in increasing acceptance and proper application.

A broader systems approach is also required. Embedding phosphorus recovery into circular bioeconomy frameworks; through linkages with food waste recycling, wastewater treatment, and composting; can close nutrient loops and reduce reliance on mined phosphorus. For example, combining struvite precipitation with microbial strategies enables efficient nutrient recovery from organic waste streams. Achieving this vision, however, will require collaboration across sectors and alignment of policies at both local and global scales.

Microorganisms capable of converting insoluble phosphorus compounds into plant available forms continue to show great potential in improving nutrient use efficiency. Continued research is needed to isolate strains with high functional resilience and to formulate products that perform consistently across diverse agricultural settings.

Organo mineral fertilizers (OMF) represent another promising solution. By combining mineral inputs with organic matter; such as compost, biochar, or recovered phosphorus; they can enhance soil structure and nutrient retention, reducing phosphorus runoff. Yet, the challenge lies in developing standardized methods for producing OMF at scale, considering variability in raw material quality and regional regulations.

Advanced tools; including ICP-MS, NMR, and Raman spectroscopy; are expanding our understanding of phosphorus behavior at micro and molecular levels. These technologies enable more precise nutrient management strategies but are often inaccessible to smallholder farmers due to expense and technical demands.

Sustainable phosphorus management calls for a paradigm shift in how nutrients are managed. This includes reducing losses, aligning input use with crop requirements, and fostering nutrient circularity. Supportive policy, strategic investment in research, and international collaboration will be key to achieving these goals.

Changing climate conditions further complicate phosphorus dynamics by altering soil processes and biological activity. Resilient strategies must be developed to adapt phosphorus management practices to evolving environmental patterns, ensuring food security and ecological health in the years to come.

The feasibility of adopting circular phosphorus (P) practices is largely determined by regional contexts and socio-economic conditions. This is especially evident in low income settings, where limited access to fertilizers and underdeveloped waste management systems make nutrient recovery both essential and difficult to achieve. In South Asia, affordability remains a dominant constraint. Farmers in India, Nepal, and Bangladesh face escalating fertilizer prices alongside a staggering regional infrastructure deficit,

estimated at US\$1.7–2.5 trillion. Such gaps affect not only transportation and markets but also the delivery of agricultural services, leaving smallholder farmers with restricted access to affordable inputs. Under these circumstances, localized nutrient recycling methods; such as applying animal manure, recycling crop residues, or using biochar; serve as important alternatives to improve soil fertility and reduce reliance on costly imports (Dan et al., 2014).

In contrast, high income regions such as the European Union demonstrate how supportive policy frameworks and sustained investment in technology can enable more advanced nutrient recovery systems. Struvite precipitation, for instance, has transitioned from experimental trials to full scale commercial deployment in several EU member states through initiatives like ManureEcoMine and municipal wastewater recovery projects. Regulatory measures aligned with sustainability targets and market incentives for recycled products have accelerated adoption of struvite, animal bone biochar, and incinerated sewage sludge ash (ISSA) fertilizers. These experiences underscore the importance of regulatory stability and financial support in fostering successful circular P strategies (Nardy, 2025).

By comparison, Africa and much of Latin America continue to face profound governance and infrastructure constraints. In Africa, crop yields remain at roughly one third of potential despite strong fertilizer response rates. Regional programs offering subsidies and credit guarantees, such as the African Fertilizer and Agribusiness Partnership (AFAP) in Ghana, Mozambique, and Tanzania, have expanded access, yet fragmented fertilizer policies and weak regional trade continue to drive up costs and hinder widespread use. Meanwhile, untreated sewage in rapidly urbanizing African cities frequently discharges into waterways, creating both ecological risks and missed opportunities for nutrient recovery. In these contexts, decentralized and low cost options; such as composting or co-composting of organic waste; can simultaneously support soil fertility and improve sanitation. In rural areas, more localized practices, including direct manure application and biochar production, remain the most viable solutions given the high costs associated with transport and collection (UNECA and AFFM, 2018).

These regional contrasts illustrate that while the principles of circular P management are globally relevant, effective implementation must reflect local socio-economic conditions and infrastructural realities. South Asia highlights affordability as the primary obstacle, the European Union demonstrates the role of policy and investment in advancing technological solutions, and Africa illustrates the pressing need to address yield gaps while overcoming governance challenges. Collectively, these cases confirm that circular P strategies cannot follow a universal blueprint but instead must be adapted to the unique opportunities and constraints of each region.

The sustainable management of phosphorus (P) in the coming decades will depend on bringing together microbial innovation, resource recovery, and supportive policy under a cohesive circular bioeconomy model. This approach goes beyond developing isolated technologies; it requires understanding how biological,

environmental, and socio-economic systems interact to reinforce nutrient security across different scales. Future research should therefore move past identifying single priorities and instead examine the dynamic relationships among microbial activity, recovery systems, and governance structures that together shape the resilience and circularity of phosphorus use. On the biological side, microorganisms play a vital role in maintaining phosphorus availability within both agricultural soils and waste management systems. The next wave of bio-based solutions should focus on building diverse, ecologically balanced microbial communities that can continue to solubilize, mobilize, and absorb phosphorus under changing environmental conditions. Advances in genomics, synthetic biology, and bioinformatics now make it possible to deliberately design these microbial networks to perform complementary functions; linking phosphorus cycling with plant growth support, stress resistance, and disease suppression. Such engineered consortia could operate as adaptive biological systems, responding to environmental fluctuations while maintaining efficient nutrient turnover and boosting agricultural productivity.

Waste valorization forms the second major foundation of a circular phosphorus strategy. Organic residues from farms, food industries, and municipal systems should be treated not as waste but as valuable nutrient sources. Combining biological and chemical recovery methods allows these materials to be converted into fertilizers and soil amendments with high agronomic worth. Microbial processes further enhance these recovery routes by speeding up organic matter breakdown, stabilizing phosphorus compounds, and lowering contaminant levels. These interactions between microbial transformation and resource recovery create a more efficient and sustainable nutrient cycle, effectively linking waste generation with fertilizer production.

Scaling these innovations, however, requires enabling policies and systemic integration. Regulatory frameworks that define, test, and certify recycled phosphorus products are necessary to ensure their safety, quality, and market trust. Economic incentives can also encourage investment and adoption, particularly in regions with limited resources. Equally important are knowledge-sharing networks that connect scientists, policymakers, industry, and farmers, facilitating the translation of laboratory findings into practical applications. Through these collective efforts, phosphorus management can evolve from a set of separate technical measures into a holistic, circular system that unites innovation, sustainability, and social equity.

## 6 Conclusion

Phosphorus (P) is an essential element for agriculture, underpinning plant growth and global food production. Its significance continues to rise as population growth and intensifying demand for natural resources place mounting pressure on finite phosphate rock reserves. Current reliance on these non renewable inputs, combined with inefficient fertilizer use and the environmental risks of nutrient runoff and eutrophication, underscores the urgent need for more sustainable management

approaches. Advances in microbiology, biotechnology, and materials science are beginning to reshape phosphorus stewardship, offering pathways to reduce dependence on mined reserves while enhancing soil health and mitigating agriculture's ecological footprint.

Central to this transition is the shift toward circular nutrient systems, which prioritize resource recovery, efficient use, and equitable distribution. Efforts to recover phosphorus from organic wastes, alongside the development of organo-mineral fertilizers, have shown promise in reducing environmental losses and improving nutrient availability. Blending recovered materials such as struvite, hydroxyapatite, or incinerated sewage sludge ash (ISSA) with compost or biochar can create fertilizers that release nutrients gradually while contributing carbon and micronutrients to soils. Tailoring these formulations to specific soil and crop conditions represents a critical research frontier. Complementary strategies, such as breeding crop varieties with enhanced root traits for mobilizing P from low solubility sources, or employing microbial consortia of phosphate solubilizing microbes, *Bacillus*, and *Trichoderma*, can further boost nutrient uptake, particularly in low input farming systems.

Despite the technical potential, widespread adoption faces persistent challenges. High costs, fragmented policy support, and technical uncertainties limit scaling, particularly in low income regions. Affordable recovery technologies, such as optimizing struvite precipitation using locally available magnesium sources (magnesite, bittern, or ash) combined with passive pH management, are needed to make phosphorus recycling viable in diverse contexts. Decentralized recovery systems for peri-urban areas require evaluation not only for efficiency but also for safety, pathogen control, and farmer acceptance. Standardized protocols, open source process designs, and affordable diagnostic kits for testing nutrients, contaminants, and pathogens will be critical in building trust, ensuring quality, and facilitating safe trade in recycled fertilizers.

Policy support is equally vital to drive the transition from innovation to widespread practice. Expanding subsidy schemes and public procurement to include certified recycled fertilizers could lower barriers to adoption. Regulatory frameworks must establish clear standards for microbial inoculants and recycled fertilizer products, ensuring consistency, safety, and market confidence. International cooperation, through mechanisms such as mutual recognition agreements, could also promote cross border trade in recycled phosphorus products while safeguarding environmental and public health. Urban planning and sanitation policies that incorporate source separating systems would help integrate food security with wastewater management, reinforcing broader sustainable development goals.

Industry engagement plays a decisive role in aligning innovations with local realities. Regional adaptation of organo-mineral formulations, cost reductions through the use of local byproducts, and innovative payment schemes for smallholders can make recycled fertilizers more competitive. Certification and eco-labeling systems would enhance market transparency and consumer trust, opening access to institutional buyers. Integrated biorefinery hubs, capable of processing agricultural, food, and wastewater streams through

technologies such as struvite precipitation, offer opportunities for regional scale phosphorus recovery.

To operationalize these strategies, several priorities stand out. First, field ready microbial consortia must be developed and tailored to specific soils and crops. Second, harmonized production protocols and farmer training are required to support the effective use of organo-mineral fertilizers. Third, investments in monitoring systems and indicators; such as substitution rates of mineral P, reductions in leachable P, recovery costs, and improvements in soil microbial diversity; are needed to track progress and inform adaptive management. Finally, multi stakeholder platforms that bring together researchers, policymakers, agribusinesses, and farmers are crucial for overcoming technical barriers, aligning incentives, and accelerating adoption at scale.

Taken together, these measures illustrate that sustainable phosphorus management is not only a technical challenge but also a socio-political and economic one. Through integrated research, policy alignment, and cross sector collaboration, it is possible to transform phosphorus from a source of environmental concern into the foundation of resilient, resource efficient, and climate smart food systems.

## Author contributions

MO: Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. KR: Data curation, Investigation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. MH: Conceptualization, Data curation, Investigation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. JA: Conceptualization, Formal analysis, Project administration, Resources, Supervision, Validation, Writing – review & editing.

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## Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fagro.2025.1686198/full#supplementary-material>

### SUPPLEMENTARY TABLE 1

Relevant phosphate solubilizing microbe species (PSMs) in the soil.

### SUPPLEMENTARY FIGURE 1

Sankey Diagram represents the main plant subfamilies in this study along with the associated plant genus and species.

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