

Review

Product-Oriented Phosphorus Recovery from Wastewater and Waste Streams: Sources, High-Value Products, Technologies, and Techno-Economic Assessment

Qidong Qian ¹, Kena Qin ^{1,*}, Xiaoting Sun ², Yanbo Chu ¹, Zewen Li ¹, Jue Wang ¹, Xiaoyang Liu ¹, Zheng Tan ¹ and Jun Zhang ^{1,*}

¹ School of Civil Engineering, Heilongjiang University, Harbin 150080, China; qianqidong0419@163.com (Q.Q.); chuq019@gmail.com (Y.C.); 13945936388@163.com (Z.L.); wangjue021117@126.com (J.W.); l2074073742@163.com (X.L.); gucao869365039@outlook.com (Z.T.)
² Beijing Drainage Group Co., Ltd., Beijing 100044, China; xt2986250884@163.com
* Correspondence: qinkena@hlju.edu.cn (K.Q.); zhangjun@hlju.edu.cn (J.Z.)

Abstract

Phosphorus recovery from wastewater and waste streams has become increasingly critical for addressing phosphate-rock supply insecurity and eutrophication control. Building on previous reviews of phosphorus recovery technologies and product applications, this review presents a product-oriented perspective for evaluating phosphorus recovery, explicitly integrating phosphorus sources, process design, product quality, application requirements, regulatory considerations, and life-cycle assessment (LCA) or techno-economic assessment (TEA). Collectively, the available evidence indicates that phosphorus sources differ substantially in phosphorus concentration, speciation, and impurity profiles, underscoring the importance of source–product matching for effective phosphorus recovery. Different phosphorus sources, therefore, require tailored recovery pathways to produce products that satisfy specific quality and application requirements. Product quality is governed primarily by process design rather than by the recovered mineral itself, with purity, contaminant control, regulatory compliance, and end-use suitability ultimately determining the environmental and economic value of recovered phosphorus. A meaningful comparison of recovery pathways further requires harmonized LCA/TEA, as environmental and economic outcomes are highly sensitive to system boundaries, functional units, and allocation assumptions. In addition, regulatory requirements are emerging as a key determinant of product commercialization and should therefore be incorporated throughout process design and technology development. Overall, this review highlights a shift from removal-oriented phosphorus recovery to product-oriented phosphorus recovery, emphasizing the production of high-quality, application-specific phosphorus products as the foundation for technology selection, product innovation, and the transition toward a circular phosphorus economy.

Keywords: phosphorus recovery; product-oriented; sources; technologies; LCA

Academic Editors: Jinsong Liang and Longyi Lv

Received: 25 June 2026

Revised: 19 July 2026

Accepted: 20 July 2026

Published: 22 July 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\) license](https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Phosphorus is an important nutrient for biological growth and agricultural production [1–3], but phosphate mineral resources are at risk of declining reserves, and low-

grade phosphate mining can damage the ecological environment [4]. Beyond resource security concerns, phosphorus losses from anthropogenic activities have become a major environmental challenge. Municipal wastewater, industrial effluents, livestock production, and agricultural runoff release large quantities of phosphorus into aquatic environments, accelerating eutrophication, harmful algal blooms, oxygen depletion, and ecosystem degradation [2,5,6].

Phosphorus recovery from wastewater and waste streams has received significant attention due to the potential to address resource scarcity and environmental damage simultaneously. It is evident that different phosphorus sources yield different recovery products. However, a systematic synthesis of how source characteristics relate to product outcomes is largely absent from existing reviews. Moreover, even for the same target product, such as magnesium ammonium phosphate hexahydrate (struvite; $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$), different recovery technologies and operating conditions can yield markedly different purities, which, in turn, affect compliance with product quality standards and market acceptance. Therefore, from a product-oriented perspective, the ultimate contribution to a circular economy depends not only on the quantity recovered but also on the effectiveness with which that product can re-enter productive cycles.

Numerous technologies have been developed for phosphorus recovery, including chemical precipitation, adsorption, membrane separation, and so on [7–9]. Previous reviews have comprehensively summarized these technologies and clarified the effects of key operational parameters, including pH, ion ratios, and competing ions. More recent reviews have begun to address product applications and life-cycle implications [10,11], signaling a growing recognition that recovery efficiency alone is insufficient. However, comparatively less attention has been devoted to systematically linking phosphorus source characteristics, recovery routes, product specifications, quality grades, and downstream utilization opportunities within a unified framework. Product quality standards, such as minimum P_2O_5 content, heavy metal thresholds, and pathogen limits, are rarely integrated into technology comparisons, even though they directly determine market access. Furthermore, although LCA and TEA studies have identified key drivers such as chemical consumption, energy demand, sludge management, and avoided fertilizer production [12–14], their conclusions are often difficult to compare because system boundaries, functional units, substitution assumptions, and product-use scenarios vary considerably among studies [15–17]. What remains insufficiently examined is how product purity grade, contaminant profiles, and downstream usability interact with environmental and economic performance across different phosphorus source types and how these interactions influence the viability of each recovery pathway.

This review adopts a product-oriented perspective as its central analytical framework. Rather than treating phosphorus recovery just as a pollutant-removal or resource-extraction process, the review focuses on how different phosphorus-bearing waste streams can be transformed into products with practical value. Specifically, (i) summarizes the characteristics of major phosphorus sources, including municipal wastewater and sludge, agricultural residues and industrial effluent; (ii) maps phosphorus sources of varying concentrations and types to corresponding recovery products, with emphasis on the purity and quality grades achievable by different process configurations; (iii) critically evaluates recovery technologies in terms of product quality, contaminant control, and compliance with end-use quality standards; (iv) synthesizes LCA- and TEA-based studies to clarify the environmental or economic priorities that distinguish each product pathway. By explicitly linking source characteristics, process engineering, product quality, and market compliance, this review aims to provide a more comprehensive framework to guide future phosphorus recovery research and support the transition toward a circular phosphorus economy.

2. Phosphorus Recovery: Sources and High-Value Products

The major anthropogenic sources amenable to phosphorus (P) recovery fall into three categories: municipal wastewater and sewage sludge, agricultural manure and crop residues, and industrial wastewater (e.g., from wineries, slaughterhouses, swine farms, and semiconductor manufacturing). As shown in Figure 1, phosphorus sources with distinct characteristics can yield a range of high-value products. These differences arise from variations in phosphorus concentration, the presence or absence of impurities (such as heavy metals, antibiotics, and competing ions), organic matter content, and overall matrix composition. Distinguishing phosphorus sources by their matrix properties helps to guide technology selection, product targeting, and downstream application strategies.

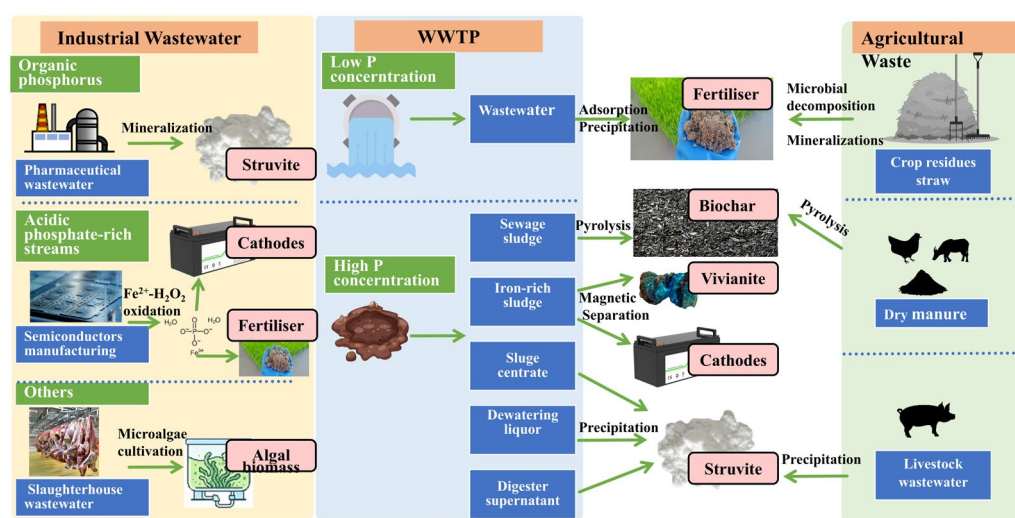


Figure 1. Source-specific pathways linking municipal, agricultural, and industrial phosphorus streams to high-value recovery products.

2.1. Phosphorus in Municipal Wastewater and Sewage Sludge

The phosphorus concentration in municipal wastewater is low (4–15 mg/L), but it is a continuous phosphorus source, mainly originating from human excreta, food residues, and residual detergent inputs [12,18]. For dilute municipal effluents, the product route focuses on phosphate adsorption and precipitation. Pap et al. developed a filtration/adsorption system using potassium hydroxide (KOH)-deacetylated, crab-carapace-based chitosan-calcite for phosphate recovery from rural wastewater effluent. Their comprehensive quality assessment confirmed the product's safety for agricultural use, with all contaminants (heavy metals, organic micropollutants, and pathogens) falling well below regulatory thresholds (Table 1) [19]. In contrast, Zhou et al. applied in situ CaCO_3 precipitation to recover P from urine sewage, achieving a product with substantially higher P_2O_5 content (17.4 wt%) and demonstrating strong agronomic effectiveness, as evidenced by a doubling of cowpea fresh biomass in pot trials (Table 1) [20]. Taken together, feedstocks with higher phosphorus concentrations tend to yield higher-grade products with more immediate fertilizer value. In contrast, dilute streams require adsorptive concentration and typically produce lower-P materials that function better as soil conditioners than as straight fertilizers.

As seen in Figure 1, for high-concentration phosphorus-containing liquids (above 50 mg/L) in wastewater treatment plant (WWTP) side streams, such as sludge dewatering liquor and sludge centrate, the target recovery product is struvite, a slow-release N-P-Mg fertilizer [21–23]. Research focuses on optimizing process parameters, such as pH and Mg^{2+} dosage [24]. Notably, Lew et al. challenged the prevailing assumption that higher pH universally improves struvite recovery; instead, they demonstrated that pH 7.4 and

the shortest hydraulic retention time tested (15 min) yield more homogeneous products ($\approx 85\%$ struvite) than the conventionally recommended alkaline conditions [25], underscoring the importance of wastewater-specific optimization over one-size-fits-all approaches. In contrast to these liquid-phase recovery approaches, thermal treatment offers an alternative pathway for phosphorus recovery from the solid fraction of municipal sludge. Through pyrolysis, sewage sludge solids are converted into sewage sludge biochar (SSB). Figueiredo et al. assessed SSB as a phosphorus fertilizer and showed that pyrolysis temperature and the choice of extractant critically affect P availability. They concluded that P-rich biochar should be regarded as a carbon-rich slow-release P product, whose fertilizer value depends on P speciation, plant availability, and contaminant control [26]. What emerges from this work is a recognition that biochar-P is not a single entity: lower pyrolysis temperatures ($\approx 300\text{ }^{\circ}\text{C}$) favor readily available P forms, whereas higher temperatures ($600\text{ }^{\circ}\text{C}$) produce more recalcitrant, slowly released P. This temperature-dependent tunability suggests that biochar can be engineered for specific agronomic outcomes but also explains why total P content alone is an unreliable indicator of fertilizer performance.

Beyond pyrolysis, phosphorus can also be recovered from iron-rich sludge solids in the form of vivianite ($\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$). This crystalline ferrous phosphate mineral has attracted growing interest as a recoverable P product. Nguyen et al. separated vivianite from digested sewage sludge using high-gradient magnetic separation, achieving an optimized magnetic recovery of about 80% after three recirculations [27]. The robustness of this magnetic separation approach is noteworthy (maintaining performance across sludge dry matter contents of 1.8–3.3%), as it suggests that physical separation can tolerate the inherent variability of sludge feedstocks better than chemically sensitive precipitation processes. This resilience makes magnetic recovery a more practically adaptable option for full-scale implementation across different wastewater treatment plant configurations. In a higher-value material route, Wang et al. used Fe-enhanced primary sedimentation, acidogenic fermentation, and selective Fe-P precipitation to recover more than 66% of sludge P as crystalline iron phosphate dihydrate ($\text{FePO}_4 \cdot 2\text{H}_2\text{O}$) with 99.3% purity, then prepared lithium iron phosphate/carbon (LiFePO_4/C) cathodes with an initial specific discharge capacity of 151 mAh/g [28]. The common limitation for P recovery from municipal wastewater and sewage sludge is that higher-value products require more selective enrichment, impurity removal, and product-quality control than ordinary P removal. This represents the most advanced entry in the product-value spectrum: while the process complexity and purity requirements far exceed those of fertilizer production, the resulting product commands a market price nearly an order of magnitude higher than phosphorus fertilizers, demonstrating that wastewater-derived phosphorus can be upgraded beyond agricultural uses.

2.2. Phosphorus in Agricultural Manure and Crop Residues

Agricultural phosphorus recovery differs from municipal recovery in that feedstocks, such as livestock manure, poultry litter, digestate, straw, and husks, etc., are nutrient-rich but heterogeneous [29–31]. Manures contain P, with N, K, and P occurring in both inorganic and organic forms, including phytate- and DNA-like hydrolyzable P and soluble or acid-extractable forms related to orthophosphate, magnesium phosphate (Mg-P), and calcium phosphate (Ca-P) species [32]. Crop residues contain less P but release large amounts of P through decomposition [29,32].

For liquid livestock wastewater, struvite is the most direct product because ammonium and phosphate coexist [33–35]. However, agricultural wastewater presents a more complex matrix than municipal streams: high concentrations of K^+ and Ca^{2+} compete with Mg^{2+} for phosphate, generating by-products such as potassium struvite and amorphous

calcium phosphate, which, together with the high suspended solids and organic matter content, consistently yield small, irregular, and low-strength crystals (mean size ca. 18–40 μm). This structural limitation, as shown in Table 1, is a recurring theme across agricultural P-recovery routes and distinguishes them from more controlled municipal or industrial settings. Consequently, proper selection of the magnesium source is critical. In metal-containing swine wastewater, Guan et al. compared MgCl_2 , MgO , and $\text{Mg}(\text{OH})_2$ and found that MgCl_2 achieved 94.55% P removal, while also precipitating 90.60% of Cu and 98.80% of Fe; alkaline magnesium sources caused Cu redissolution, making MgCl_2 preferable in technical, economic, and environmental assessments [36]. The co-precipitation of heavy metals during struvite formation, while potentially beneficial for wastewater polishing, introduces an additional quality-control challenge for the final product—one that requires case-by-case evaluation depending on the target end-use. Furthermore, the widespread use of veterinary antibiotics adds another layer of complexity: Chen et al. found that recovered struvite from swine wastewater contained tetracycline antibiotics (4.88–79.5 mg/kg) and their resistance genes (6.99×10^7 – 2.14×10^{11} copies/g), highlighting that agricultural P products carry not only inorganic impurities but also biological and chemical contaminants that may constrain their agronomic application [37].

Crop residues broaden the source base but generally require decomposition and microbial mineralization before released orthophosphate can enter precipitation, adsorption, or direct soil-reuse pathways [29]. As Table 1 summarizes, the P release patterns are strongly feedstock-dependent: green manure releases 56–74% of its initial P (5.1–5.6 kg/ha) within 52 weeks, sufficient to meet up to 62% of wheat P requirements, whereas wheat, pea, and canola residues contribute less than 1 kg/ha. This disparity reflects differences in residue quality, particularly in C/P and lignin/P ratios, and underscores the fact that crop residues are better viewed as a long-term soil fertility maintenance tool rather than a concentrated P source for immediate recovery [30].

Modified biochar provides a higher-value route for manure or residue solids. The pyrolysis approach demonstrated by Piash et al. represents a fundamental departure from wet-chemical recovery: rather than extracting and precipitating phosphorus as a mineral salt, this route transforms the entire manure matrix (including its organic carbon, nitrogen, and ash constituents) into a multifunctional soil amendment [31]. By incorporating Ca-bentonite during pyrolysis, readily soluble orthophosphate is converted to less-soluble Ca/Mg-phosphate forms, while K release is slowed by approximately 22% via cation exchange in the bentonite structure (Table 1). This engineering of nutrient release kinetics effectively repurposes a waste stream with high environmental risk (landfilling or over-application of raw manure) into a product whose value lies not only in its P content but in its combined contributions to soil organic matter, pH buffering, and water retention. The key distinction from the poultry-litter extraction route is that biochar-based fertilizers do not require a separate precipitation step; instead, nutrient retention is achieved through thermochemical transformation of the feedstock itself. This simplicity is attractive, though the final P_2O_5 equivalent is lower than that of struvite products, suggesting that biochar-based amendments are best suited for broad-acre soil conditioning rather than precision P fertilization.

2.3. Phosphorus in Industrial Wastewater and Other Organic Wastes

Reported phosphorus concentrations vary by industrial types: 35–77 mg/L (winery wastewater), 29–49 mg/L (abattoir wastewater), 194–780 mg/L swine wastewater, 0.4–21 mg/L (tannery wastewater) [3], 820 mg/L (acidic cheese wastewater) [38], and 320–600 mg/L (brewery side streams) [39]. These wide-ranging concentrations, together with the different chemical forms of phosphorus present, largely determine the appropriate recov-

ery strategy for each industrial stream. At higher concentrations, phosphorus is often present in organic forms and thus requires prior oxidation or mineralization to convert it to inorganic phosphate before mineral recovery. Pharmaceutical and organophosphorus chemical wastewater are examples of such high-strength streams. Qiu et al. used wet air oxidation to convert 99% of the total organic phosphorus (TOP) to inorganic phosphate in fosfomycin pharmaceutical wastewater and recovered it as hydroxyapatite (HAP; $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$) (at a Ca/P ratio of 2.0) or struvite at Mg/N/P of 1.1:1.0:1.0 [40]. Similarly, Chen et al. treated chlorpyrifos manufacturing wastewater with a TOP of 4700–4840 mg/L after peroxide-promoted catalytic wet air oxidation; struvite precipitation at $\text{Mg:NH}_4\text{:PO}_4 = 1.1:1.0:1.0$ recovered 97.2% of the phosphate [41].

Acidic phosphate-rich streams can be matched to iron phosphate products instead of being forced into struvite or Ca-P precipitation. Bahgat et al. recovered $\text{FePO}_4 \cdot 2\text{H}_2\text{O}$ from acidic high-strength phosphate wastewater: Fe(III) dosing recovered more than 95% P at initial pH 3 or higher but formed poorly settleable solids, whereas controlled $\text{Fe}^{2+}\text{-H}_2\text{O}_2$ oxidation maintained over 95% total P recovery and improved settleability, with an optimal Fe(II) oxidation rate of 4.7×10^{-4} mol/L/min and a volumetric index of 8 mL/g P [42]. This case illustrates that process optimization for acidic streams should focus not only on recovery efficiency but also on product separability, a factor often overlooked in conventional precipitation studies.

Other organic wastes expand the product range. Simple, low-technology procedures can be effective without complicated chemical or electrochemical processes. Chaudry et al. evaluated microalgae cultivation on slaughterhouse wastewater and estimated that ponds with nearly 80% water recycling could produce treated water with less than 1 mg/L N and 12 mg/L P, generate about 2 kg algal biomass per m^3 wastewater, and avoid 3.46–6.11 kg $\text{CO}_2\text{-eq}$ per m^3 treated depending on product credit [43]. This algal route is qualitatively different from the mineral-precipitation approaches discussed above: rather than producing a phosphorus-rich mineral concentrate, it assimilates both N and P into biomass, generating value primarily from the protein content of the harvested algae (Table 1). Overall, industrial and organic-waste P recovery must specify both source and product, because vivianite, recovered phosphoric acid, calcium phosphate, algal biomass, and carbon-assisted recovery have different purity requirements and market-entry criteria.

Table 1. Phosphorus characteristics from different sources, associated recovery routes, and product functions.

Sources	Influent Characteristics	Recovery Routes	Quality or Purity	Applications	Safety or Effectiveness	Ref.
Wastewater effluent	PO_4^{3-} 1.0 mg/L~7.0 mg/L	Filtration and adsorption	2.2–2.5 wt% P_2O_5	Soil amendment	$\text{Cd} < 0.12$ mg/kg, $\text{Pb} < 1.2$ mg/kg; No target pathogens	[19]
Urine sewage	~79.5 mg P/L	Adsorption and precipitation	17.4 wt% P_2O_5	Calcium-phosphate-based fertilizer	Cowpea fresh weight increase of ~100%	[20]
Sludge dewatering filtrate	~310 mg P/L	Chemical precipitation	Struvite purity: 85%	Slow-release fertilizer	~19% reduction in WWTP P load	[25]
Sewage sludge	TP: 2.1–3.7% (4.8–8.6% as P_2O_5)	Pyrolysis (200–600 °C)	P-NAC max at 300 °C (79% TP); P-CA max at 600 °C (53% TP);	Fertilizer/soil amendment	N.R.	[26]

Digested sewage sludge	Fe/P $\approx$ 1.6	High-gradient magnetic separation	Vivianite purity: 70–85%; Fe/P = 1.3	Precursor for LiFePO ₄ batteries	Robust to sludge dry matter variations (1.8–3.3%)	[27]
Fe-enhanced primary sludge	PO ₄ ³⁻ and HPO ₄ ²⁻ ; 149.0 $\pm$ 2.0 mg-P/L	Acidogenic fermentation followed by acidic oxidative Fe-P precipitation	FePO ₄ ·2H ₂ O purity: 99.3%; Fe/P = 0.96–1.0; particle size 200–250 nm	Precursor for LiFePO ₄ batteries	LiFePO ₄ /C cathode discharge capacity: 151 mAh/g; Carbon reduction: 413–495 kg CO ₂ -eq/t LiFePO ₄ /C cathode	[28]
Crop residues	P: 0.4–2.2 mg/g; C/P = 213–1248	Field decomposition	P release: green manure (5.1–5.6 kg/ha); pea: ~0.4 kg/ha; canola: ~0.8 kg/ha; wheat: ~0.4 kg/ha	P source for subsequent crops in rotation	Green manure P could meet up to 62% of wheat P requirements; other residues < 7%	[29]
Poultry litter	Aqueous PO ₄ ³⁻ : 943.4–1540.5 mg L ⁻¹	CO ₂ -assisted acid extraction	N:P:K = 2.0:1.0:0.1 (pH 8.5–9.0) or 0.9:1.0:0.2 (pH 10.5–11.0); crystal size ~100 μ m	Slow-release fertilizer	Overall P recovery: >70% in 45 min sequencing batch	[30]
Chicken manure	N.R.	Co-pyrolysis at 300 °C with Ca-bentonite	P release in clay loam: 32–40% (90 d)	Slow-release fertilizer/soil amendment	N.R.	[31]
Swine wastewater	O-P: 53.2–134.3 mg/L; NH ₄ -N: 79.9–2617 mg/L	Struvite crystallization	Struvite; P content: 12.3–19.7% (dry basis); P ₂ O ₅ : 28.2–45.1%	Fertilizer	Reduce chemical fertilizer consumption 6.4%, and CO ₂ reduction: 6522 t/y	[33]
Anaerobically digested poultry wastewater	PO ₄ ³⁻ 1397.0 mg/L	Air-lift electrolytic	Struvite purity: 88.5%; Fe/P $\approx$ 1.5; particle size 142.95 μ m	Fertilizer	No heavy metals detected	[34]
Anaerobically digested poultry litter supernatant	PO ₄ ³⁻ 4374.0 mg/L	Electrolytic struvite precipitation	Struvite purity: 90.5%	Fertilizer	TP removal: >99%; energy consumption: 18.4 kWh/m ³ ; space-time yield: 32 kg/m ³ h	[35]
Slaughterhouse wastewater	TP: 23–28 mg/L (PO ₄ ³⁻ -P); N/P mass ratio $\approx$ 7.1	Microalgae cultivation	Algal biomass yields $\approx$ 2 kg/m ³ of wastewater	Animal feed protein supplement (replacing soybean meal or fish-meal)	Carbon reduction: 3.46–6.11 kg CO ₂ -eq/m ³ wastewater; Economic feasibility: achieves positive NPV at $\geq$ 3700 m ³ /d scale	[43]
Chemical polishing wastewater	P: 2236 mg/L; pH 2.89; Ca ²⁺ 48.5 mg/L; Al ³⁺ 127 mg/L	Vivianite crystallization	Vivianite purity: 24.13%; optimal pH 7.0, Fe/P = 1.5, Fe ²⁺ = 500 mg/L	Fertilizer/precursor for LiFePO ₄ batteries	Cost analysis: \$0.925/kg P	[44]
Phosphogypsum leachate	TP: 4195 mg/L	Electrochemical recovery	Vivianite; Fe/P = 1.55; flower-like morphology	Precursor for LiFePO ₄ batteries	LiFePO ₄ /C cathode discharge capacity: 52.36–56.88 mAh g ⁻¹	[45]
Phosphogypsum leachate	PO ₄ ³⁻ : 2252 mg/L	Precipitation (MgSO ₄ + NH ₃ for PO ₄ ³⁻ at pH 8.5)	Struvite	Slow-release fertilizer	Meets GB15580-2011 discharge standard [46]; Profit: \$57.24/t PG	[47]

Lithium phosphate slag	Li: 15.1 wt%; P: 21.1 wt%; Al: 0.068 wt%	Al extraction → selective precipitation	$\text{FePO}_4 \cdot 2\text{H}_2\text{O}$ purity: 99.3%	Precursor for LiFePO_4 batteries	Al removal: 85% (Al < 25 mg/L); Li loss < 2.0%; Meets HG/T 4701-2021 [49]
------------------------	--	---	---	---	---

Note: N.R., not reported in the cited study; O-P, orthophosphate phosphorus; P-NAC, phosphorus soluble in neutral ammonium citrate; P-CA, phosphorus soluble in 2% citric acid; PG, phosphogypsum; TP, total phosphorus; NPV, net present value.

3. Phosphorus Recovery Technologies

As mentioned above, different phosphorus sources are suitable for producing different recovered products. However, even for the same target product, multiple recovery technologies may be applicable, and their performance varies. Crucially, the market viability of recovered phosphorus products is increasingly governed by regulatory frameworks that define quality thresholds and contaminant limits. In the European Union (EU), the Fertilizing Products Regulation (EU) 2019/1009 provides the overarching legal framework for recovered phosphate salts placed on the EU market. A key milestone is that recovered struvite has been approved for use in organic farming since 2023 (subject to source restrictions), setting a precedent for the use of recycled mineral fertilizers. In China, a tiered regulatory system governs phosphorus products across different value levels. Fertilizer-grade products must comply with general safety limits (GB 38400-2019 [50]) and product-specific standards, while battery-grade iron phosphate (FePO_4) recovered from waste streams must meet far stricter purity requirements under HG/T 4701-2021 [48], demonstrating that quality requirements scale with end-use value. In Japan, recovered struvite has been formally recognized under the Fertilizer Control Law as a distinct product category, making Japan one of the few countries to have established a dedicated legal status for recovered struvite. In Canada, the Fertilizers Act imposes comprehensive limits on heavy metals and pathogens. However, commercial-scale struvite recovery from municipal wastewater has yet to materialize, suggesting that regulatory frameworks alone do not guarantee market uptake.

These diverse and evolving regulatory requirements, as summarized in Table 2, define the quality benchmarks that recovered products must achieve and directly influence technology selection and process optimization. The overarching insight is that recovery alone is not enough; compliance with end-use quality standards must be embedded in process design from the outset. Therefore, this review, from a product-oriented perspective, critically evaluates recovery technologies with respect to principles, influencing factors, product quality, contaminant control, and downstream usability.

Table 2. Legal framework regarding P products in different countries.

Country/Region	Legislation/Regulations	P Products	Mass Fraction of Available Phosphorus (wt%)	Main Regulations/Restrictions mg/kg	Year
European Union	EU regulation 2019/1009: Fertilizer	Fertilizer	$\text{P}_2\text{O}_5 > 1.5$	Cd < 200, Cr < 2(VI) Cu < 600, Pb < 120, Ni < 100, Zn < 1500, As < 40	2019 [51]
China	GB/T 20412-2021	Fused calcium magnesium phosphate fertilizer	$\text{P}_2\text{O}_5 > 12$	Cd < 10, Hg < 5, As < 50, Pb < 200, Cr < 500, Ti < 2.5; Ascaris egg mortality 95%; Fecal Coliforms $\leq 100/\text{g}$ solid	2021 [50,52]
China	GB/T 18877-2020	Organic inorganic compound fertilizer	$\text{P}_2\text{O}_5 > 3.0$	As < 50, Cd < 10, Hg < 5, Pb < 150, Cr < 500	2020 [50,53]
Japan	No. 127/1950 (2019)	Struvite	$\text{P}_2\text{O}_5 > 20$	As < 0.2%, Cd < 0.0075%, Ni < 0.5%, Cr < 5%, Hg < 0.005%, Pb < 0.3%	2019 [54,55]

China	HG/T 4701-2021	Battery-grade iron phosphate (FePO ₄)	20.0 < P < 21.1, 35.7 < Fe < 36.7	Ca < 0.01%, Mg < 0.06%, Na < 0.02%, K < 0.02%, Cu < 0.02%, Zn < 0.003%, Mn < 0.015%, Al < 0.1%, Ti < 0.05%, Co < 0.18%, S < 0.03%	2021 [48]
Canada	Fertilizers act	Fertilizers	N.R.	As < 75, Cd < 20, Co < 1151, Pb < 505, Cr < 1060, Cu < 757, Hg < 5, Mo < 20, Ni < 181; Salmonella: Not detectable; Fecal Coliforms: 1000 MPN (Most Probable Number)/gram solid	2026 [56]
India	Fertilizer (Inorganic, Organic or Mixed) (Control) Order, 1985—Notification under Clause 20D, 2023	Nano diammonium phosphate fertilizer (liquid Nano DAP)	Water-soluble P ₂ O ₅ ≥ 16.0	Total N ≥ 6.0 wt%; pH 7.0–8.0; viscosity 1.2–1.3 cP; TEM particle size 10–20 nm (≥50%); DLS particle size 50–100 nm (≥50%); zeta potential: −9 to −12 mV	2023 [57]
Brazil	IN SDA/MAPA No. 39/2018, Annex I, updated in 2020	Diammonium phosphate fertilizer (DAP)	P ₂ O ₅ ≥ 45.0; water-soluble P ₂ O ₅ ≥ 38.0	Total N ≥ 17.0 wt%; nitrogen must be in ammoniacal form; produced by the reaction of phosphoric acid with ammonia	2020 [58]

Note: DAP, diammonium phosphate; DLS, dynamic light scattering; MPN, most probable number; N.R., not reported; TEM, transmission electron microscopy.

3.1. Chemical Struvite Precipitation and Electrochemical Struvite Precipitation

While the preceding sections have shown that different phosphorus sources demand distinct recovery routes and yield products of divergent value, the quality of a given product is not solely determined by its source, even for the same target product. Different recovery technologies and operating conditions can produce markedly different purities and, consequently, different market values. The two principal methods for recovering NH₃-N and PO₄^{3−} through struvite precipitation are chemical struvite precipitation (CSP), which entails the addition of magnesium salts (Mg(OH)₂, MgO, MgCl₂, MgCO₃, and MgSO₄) to a wastewater solution containing NH₄⁺ and PO₄^{3−} ions, and electrochemical struvite precipitation (ESP), which involves the introduction of Mg²⁺ ions into the solution by applying a modest electric current to a magnesium sacrificial electrode (as shown in Figure 2). Real wastewater contains competing ions (e.g., Ca²⁺, K⁺), carbonate, suspended solids, and organic matter, so the CSP production is usually a mixture of precipitated solids [22,23,59]. The overall fertilization quality of the precipitated solids depends primarily on the proportion of struvite in the mixture, whereas the crystallization process is significantly influenced by pH, magnesium dosage, and hydraulic retention time (HRT). Lew et al. investigated the effects of MgCl₂ dose, pH, and HRT on struvite recovery from sludge dewatering belt-press filtrate. The highest purity (approximately 85%) was achieved under 10 mM MgCl₂, pH 7.4, and an HRT of 15 min, producing the most homogeneous precipitate. While higher pH values and longer HRTs slightly increased the overall phosphorus precipitation, they simultaneously favored the co-precipitation of calcium phosphate and magnesium phosphate minerals [25]. Instead, X-ray diffraction (XRD) results showed that precipitates obtained at lower pH values were largely crystalline and morphologically similar to pure struvite, whereas precipitates formed at higher pH showed poorer peak definition and were less macrocrystalline [25]. These findings underscore a critical insight: product purity is not an intrinsic property of the target mineral but a direct consequence of process design choices, and conditions that maximize phosphorus recovery do not necessarily maximize struvite purity or fertilizer value.

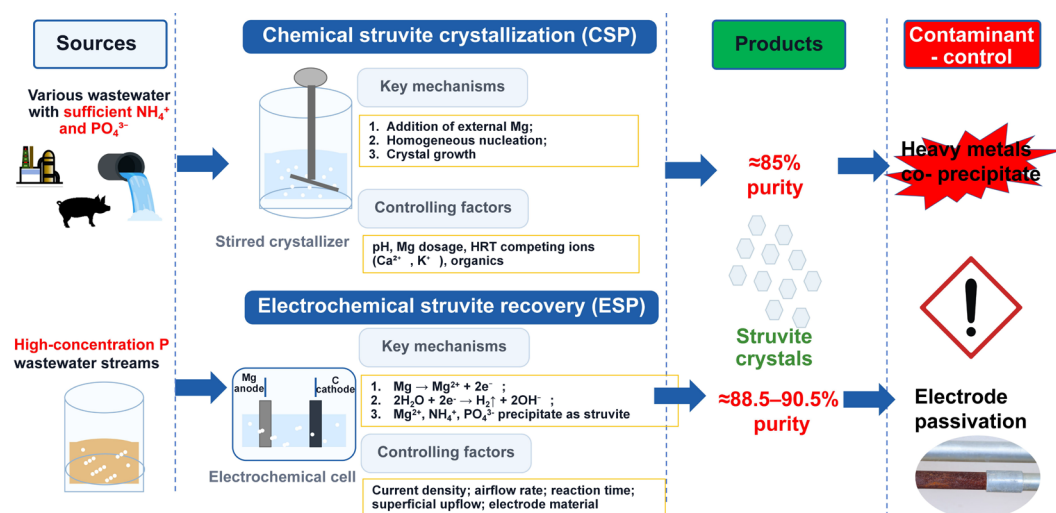


Figure 2. Chemical and electrochemical struvite precipitation.

Electrochemical struvite precipitation represents a distinct technological pathway that can achieve higher purity than conventional CSP under optimized conditions, although its performance is equally sensitive to operating parameters. Employing a magnesium sacrificial anode in ESP offers numerous advantages over CSP. The process can be readily automated, yields higher-purity struvite crystals, does not require chemical pH adjustment, generates minimal sludge, produces renewable hydrogen gas, and effectively reduces chemical oxygen demand (COD) levels in wastewater via oxidation and complexation. However, the purity outcome is by no means uniform across ESP configurations: in two separate studies, Aka et al. demonstrated that an integrated electrolytic precipitation-ammonia scrubbing setup (Mg-Mg electrodes, 4 A, 15 L/min air) achieved 90.5% struvite purity after 30 min [35], whereas an air-lift electrolytic reactor treating anaerobically digested poultry wastewater (12.4 A/m², 107.42 m/h superficial velocity) yielded 88.5% purity [34]. These values, while both exceeding the 85% achieved by Lew et al. via CSP, still differ from each other and fall short of the theoretical maximum, highlighting that even within the same technology class, purity is governed by current density, airflow rate, reaction time, and reactor hydrodynamics. Notably, Aka et al. also found that the mean particle size and its distribution increased linearly with the superficial upflow velocity [34]. From a product-oriented perspective, this variability in purity and particle size translates directly into differences in downstream handling, fertilizer efficacy, and ultimately market price, meaning that the choice between CSP and ESP, and the fine-tuning of operating conditions within either, must be evaluated not only by recovery efficiency but by the quality of the final product and its compliance with end-use specifications.

Furthermore, it is worth noting that research should pay close attention to reactor geometry design for struvite precipitation. According to Yinyan et al., larger particles settle faster and pose fewer challenges during downstream and end-user applications [60]. Therefore, it is necessary to tailor process design parameters and operating conditions to facilitate crystal growth and enhance product quality and recovery. When designing the reactor, special attention must be paid to its geometry. It is known that strong mechanical interactions between the formed struvite crystals and conventional mixing devices can lead to high levels of attrition and crystal breakage, resulting in excessive fines production. Consequently, such designs are unsuitable for scale-up, as large, narrow-size-distribution crystals are required for efficient nutrient recovery and fertilizer application [61].

3.2. Calcium Phosphate, HAP, and Adsorption/Enrichment Routes

Calcium phosphate recovery mainly includes adsorption/enrichment, amorphous Ca-P precipitation, brushite-like phases, and HAP formation. Compared with struvite precipitation, Ca-P routes do not require ammonium, making them more suitable for low-ammonium effluents and systems where calcium or carbonate can serve as both a reactant and a nucleation aid. Ca-P product quality is strongly affected by pH, Ca/P ratio, carbonate concentration, nucleation surface, competing ions, and the separation of fine solids during harvesting and drying [62]. From a product-oriented perspective, Ca-P recovery should consider whether the recovered solid is a low-density P carrier, a mixed Ca-P fertilizer, or a more crystalline HAP-rich product with higher value.

Adsorption and enrichment can provide a practical route when direct precipitation is limited by low phosphate concentration. Pap et al. reported a pilot reactor using KOH-deacetylated crab-carapace chitosan-calcite media. The reactor reduced residual effluent $\text{PO}_4\text{-P}$ to below 1 mg/L under low-phosphate conditions and harvested more than 50% of phosphate at higher $\text{PO}_4\text{-P}$ levels [19]. The recovered P-enriched medium contained about 2.5% P_2O_5 , trace levels of heavy metals, extremely low levels of organic micro-pollutants, and no detectable target bacterial pathogens [19]. This example shows the two-sided nature of adsorption/enrichment routes: they can produce a safe soil amendment and polish dilute wastewater, but the low P_2O_5 content limits transport value and fertilizer density, making them more suitable for local safe P capture than for producing a concentrated commercial fertilizer.

For more concentrated liquids, Ca-P precipitation can be directed toward a denser fertilizer product. Zhou et al. treated urine sewage containing about 79.5 mg-P/L in a 50 L pilot system for 20 batches. By adding CaCl_2 and Na_2CO_3 , CaCO_3 was generated in situ, providing both calcium supply and nucleation sites. The process produced 1012 g of P fertilizer from 1000 L of urine sewage, achieved 98.3% phosphate removal, and obtained a product containing 17.4 wt% P_2O_5 [20]. It indicates that carbonate is not always a competing ion; when deliberately introduced and controlled as CaCO_3 , it can facilitate Ca-P precipitation and improve product separation, yielding a product with P_2O_5 content approaching commercial fertilizer grades.

Bio-induced HAP provides another Ca-P route when biological phosphorus removal and mineral formation occur in the same reactor. Zhou et al. established a denitrifying biological phosphorus removal system in which phosphorus and nitrate removal efficiencies reached 99.3% and 45.1%, respectively [63]. The saturation index for HAP was above zero in the anaerobic and anoxic zones, and HAP cores accounted for approximately 66% of total P removal. The granular sludge at the reactor bottom contained inorganic matter and 15.4 wt% total phosphorus, of which 86.1% was chemical phosphorus precipitation [63]. However, HAP-rich granules must be separated from ordinary biological sludge before their full mineral value can be realized, and this additional purification step is a key factor that distinguishes bio-induced HAP from chemically precipitated products in terms of final product quality and processing cost.

3.3. Iron-Based Recovery: Vivianite, FePO_4 , and Electrochemical Fe-P Products

Iron-based phosphorus recovery is suitable for Fe-rich, reducing, or acidic P streams (Figure 3). The key factors controlling Fe-based recovery are $\text{Fe}^{2+}/\text{Fe}^{3+}$ state, pH, oxidation rate, impurity routing, magnetic separability, and final product grade [27,28,42,44,64], but the dominant factors are product-specific. Consequently, different iron-based routes, vivianite crystallization, FePO_4 precipitation, or electrochemical synthesis, yield products with distinct purities and market values, and the choice of process must be aligned with both the wastewater matrix and the required product specifications.

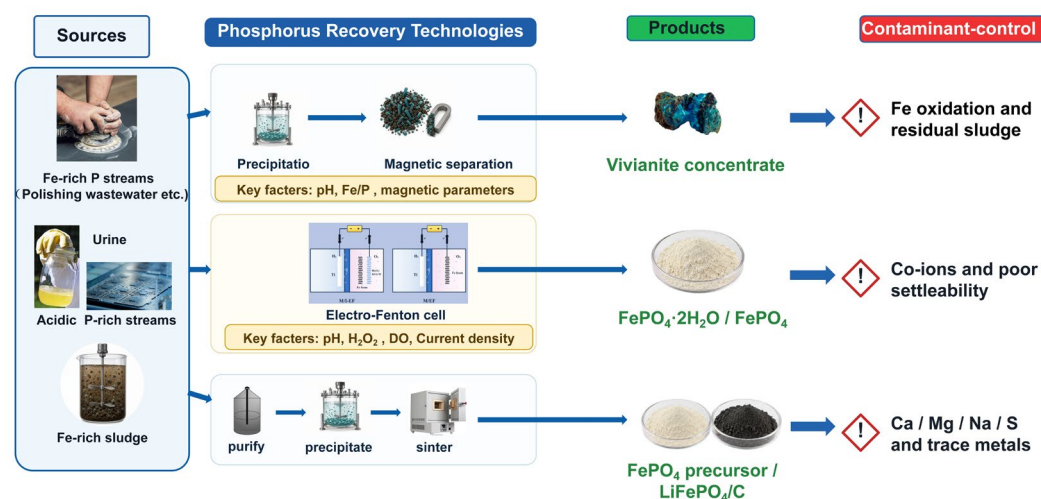


Figure 3. Iron-based P products recovery: preparation routes and effect factors.

For vivianite recovery, product separability is often as important as purity. Zhang et al. optimized precipitation from industrial wastewater at pH 7.0, 500 mg/L Fe²⁺, and an Fe/P molar ratio of 1.50, obtaining a vivianite purity of only 24.13% and an estimated recovery cost of 0.925 United States dollars (USD) per kg P [44]. Such purity falls far short of a refined chemical standard, indicating that direct precipitation alone is insufficient for high-value applications; however, vivianite is intrinsically magnetically separable, offering a potential pathway to upgrade the recovered material. Indeed, Nguyen et al. further showed that high-gradient magnetic separation could recover vivianite from digested sludge with 1.8–3.3% dry matter, and recovery reached about 80% after three recirculations; particles smaller than 10 µm were still recoverable [27].

For FePO₄·2H₂O and high-purity FePO₄ recovery, pH and oxidation conditions become more critical. Bahgat et al. studied acidic phosphate-rich waste streams and found that pH 3 was the best among pH 1.5, 3, 4, and 5, achieving about 96% P recovery with less pH adjustment than pH 4–5, whereas pH 1.5 recovered only about 60% [42]. They further showed that a controlled Fe²⁺-H₂O₂ oxidation rate of $4.7 \times 10^{-4} \text{ mol L}^{-1} \text{ min}^{-1}$ maintained more than 95% TP recovery and improved settleability to a volumetric index of 8 mL/g P [42]. Xu et al. used a field-induced electro-Fenton cell for P-rich urine and, under 10 mM H₂O₂, 10 mA/cm², initial pH 6.0, and 40 min, achieved 95.67% TP recovery and 98.41% FePO₄ purity [65]. These results demonstrate that FePO₄ precipitation can achieve much higher purity than vivianite under tightly controlled oxidation and pH conditions, but such purity comes at the cost of stricter process control and higher reagent consumption.

Compared to ordinary iron phosphate, higher-value Fe-P products require even stricter impurity control, as shown in Figure 3. Wang et al. recovered more than 66% of sludge P by acidogenic fermentation and acidic oxidative Fe-P precipitation; the resulting FePO₄ reached 99.3% purity, and the prepared LiFePO₄/C cathode showed an initial discharge capacity of 151 mAh/g [28]. Liu et al. recovered vivianite from phosphogypsum leachate by controlling dissolved oxygen and maintaining pH below 9, achieving up to 99.3% P recovery and reducing residual P to 3.9 mg/L [45]. Lou et al. used staged precipitation-electrodialysis-crystallization to recover fluoride at pH 4.7 (98.80% recovery), phosphate at pH 8.5 (99.91% recovery), and sulfate (99.89% recovery) [47]. Taken together, these cases show that when the target is battery-grade or high-purity chemical products, the recovery process must move beyond simple precipitation to include multi-step purification and impurity-specific separation, as the end-use specifications are far more demanding than those for fertilizer applications.

3.4. Thermochemical and Wet-Chemical Recovery from Phosphorus-Rich Ash

Thermochemical and wet-chemical recovery from phosphorus-rich ash differs from liquid-phase precipitation because phosphorus is already enriched in mineral ash phases rather than present as dilute dissolved phosphate in aqueous streams. The recovery objective is therefore not direct precipitation from solution, but the conversion or extraction of ash-bound phosphate phases, separation of co-dissolved metals and other ash-derived impurities, and production of specification-driven outputs such as citrate-soluble phosphate fertilizers, Ca-P/HAP products, purified phosphate streams, or technical-grade phosphoric acid. Because the starting material is a solid ash matrix rather than a homogeneous liquid, the achievable product purity and phase composition depend heavily on the chosen extraction or conversion route, and the final product must meet different quality benchmarks depending on its intended use—fertilizer, chemical feedstock, or battery material.

Thermochemical conversion improves the fertilizer value of poorly available ash-bound phosphates while removing volatile toxic metal compounds. Hermann and Schaaf described treating phosphate-rich ash with sodium- and/or potassium-based alkaline additives at temperatures above 900 °C [66]. The additives react with ash-borne phosphates to form ammonium-citrate-soluble alkaline phosphate compounds, while volatile As, Cd, and Pb compounds evaporate from the reactor bed and are captured from the cooled process gas [66]. This process produces calcined phosphorus or phosphorus-potassium (P-K) fertilizer materials from mono-incinerated, P-rich ash, with product quality depending on P bioavailability, additive inputs, and off-gas metal control. This route is well-suited for producing citrate-soluble fertilizer materials with minimal downstream purification, but it does not yield the high-purity phosphate streams required for chemical or battery applications.

Wet-chemical extraction releases ash phosphorus into acidic leachate, followed by separation from co-dissolved metals. Gao et al. investigated incinerated sewage sludge ash (ISSA) using wet-chemical extraction combined with cation exchange resin (CER) [67]. Increasing the H^+/P molar ratio from 2.97 to 5.94 increased extracted P from 33.31 ± 0.98 to 51.01 ± 2.55 mg/g ISSA, and P extraction efficiency from 63.91% to 97.81% [67]. Further increasing the H^+/P ratio to 29.72 only slightly increased extracted P to 51.26 ± 0.98 mg/g ISSA and extraction efficiency to 98.29%, showing a marginal benefit from excess acid [67]. Under the optimized conditions of H^+/P 5.94, liquid-to-solid ratio 10-, and 360 min reaction time, P extraction reached 98.34% [67]. The subsequent CER step separated phosphorus from co-dissolved metals; phosphorus was recovered as Ca-P/hydroxyapatite, while the Al-rich eluate was directed toward coagulant production [67]. Compared with thermochemical conversion, this wet-chemical route yields a purer Ca-P product and enables separate recovery of co-dissolved Al, but the acid consumption and cation-exchange steps add high operational costs.

Combined wet-thermochemical conversion addresses Fe/Al-rich ash by coupling acid leaching, P-bearing floc recovery, and thermal phase conversion. Fang et al. recovered P from Fe/Al-rich sewage sludge ash by adjusting the acid-leaching supernatant to pH 3.5, where 86.75% of P was recovered as Al-Fe-P flocs [68]. The flocs were then co-incinerated with $CaCl_2$ at 650, 750, and 850 °C to convert Fe-bound P into Ca-bound phosphate phases [68]. The apatite P content reached 65.32 mg/g at 750 °C, and thermogravimetric-differential scanning calorimetry (TG-DSC) analysis indicated that the main reaction between Al-Fe-P compounds and $CaCl_2$ occurred at about 540–690 °C [68]. Compared with conventional recovery, the wet-thermochemical products increased total P content by 34.14 mg/g and citric-acid-soluble P by 23.06 mg/g; Ca-P products prepared at 650–850 °C were reported to promote two rounds of ryegrass growth [68]. This hybrid approach bridges the gap between wet extraction and thermal conversion, producing plant-

available Ca-P phases from Fe/Al-rich ash that would otherwise be difficult to process. However, its multi-step nature and energy requirements make it more complex than the single-route method.

Acid-grade phosphoric acid production requires extraction followed by stronger purification and concentration. Donatello et al. used sulfuric acid washing of incinerator sewage sludge ash and reported 72–91% recovery of total P under optimized conditions; the filtrate was purified by cation exchange and concentrated to about 80% H_3PO_4 for comparison with technical-grade phosphoric acid specifications [69]. This route targets the highest-value product (technical-grade acid), but it also demands the most intensive purification, making it economically viable only when the ash feed is low in contaminants or when the acid product commands a sufficient market premium. Ash-based routes should therefore be selected based on product target, purification demand, and specification requirements: thermochemical conversion for citrate-soluble fertilizer materials; wet-chemical extraction for purified phosphate streams; combined wet-thermochemical treatment for plant-available Ca-P phases; and acid-grade routes for technical phosphoric acid production (Figure 4).

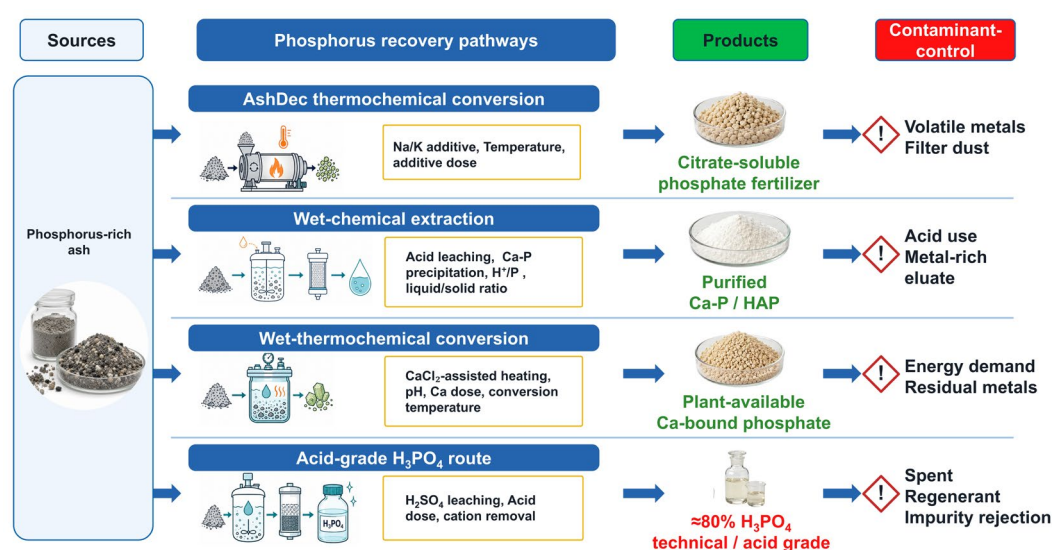


Figure 4. Thermochemical, wet-chemical, and acid-grade pathways and effect factors for phosphorus recovery from phosphorus-rich ash.

3.5. Biochar, Algal Biomass, and Carbon-Assisted Recovery

Biochar, algal biomass, and carbon-assisted routes usually recover phosphorus as a functional material rather than as pure mineral salt. Compared with precipitation routes, these technologies have a broader product boundary: the recovered product may be a slow-release mineral-carbon amendment, algal biomass, a regenerated adsorbent stream, or a phosphate precipitate obtained after pollutant mineralization. Therefore, when evaluating these routes, it is necessary to consider both nutrient recovery and the additional functions created by the process.

For sludge biochar, pyrolysis temperature is the key process parameter. Figueiredo et al. prepared sewage sludge-derived biochar at 200, 300, 500, and 600 °C and showed that higher temperatures increased pH, Brunauer–Emmett–Teller (BET) surface area, pore volume, ash content, fixed carbon, and mineral content [26]. These changes can improve material stability and contaminant immobilization, but they do not necessarily increase plant-available phosphorus. Neutral ammonium citrate plus water-extractable P (P-NAC) reached a maximum at 300 °C, accounting for 79% of total P, and then decreased at higher temperatures [26]. This result highlights a critical trade-off: higher-temperature biochar

may be more stable, but a 300 °C biochar may have greater immediately extractable fertilizer value. Thus, total P and available P should not be treated as equivalent indicators of product quality.

Modified manure biochar provides another example in which nutrient-release behavior determines product value. Piash et al. co-pyrolyzed chicken manure with 10–25% (*w/w*) Ca-bentonite to synthesize a slow-release biochar-based fertilizer [31]. The Ca-bentonite reduced soluble orthophosphate by forming less-soluble Ca/Mg phosphates, while exchange-site adsorption retarded K release by about 22% on average [31]. They also found that N release was 49% lower in coarser quartz sand than in clay loam because microbial activity was limited in the coarser medium [31]. Therefore, the value of biochar-based fertilizer depends not only on the feedstock and binder dose, but also on the receiving soil. A product that performs as a slow-release fertilizer in one soil may not show the same nutrient-delivery behavior in another.

Taken together, the sludge-biochar and manure-biochar examples define the first logic of this subsection: solid P-bearing wastes can be converted into mineral-carbon amendments, but their product value must be judged by plant-available P, nutrient-release behavior, and contaminant immobilization rather than by total P content alone [26,31]. The same product-function logic explains why microalgal and carbon-assisted systems are included here, although they do not produce conventional purified phosphate salts. In micro-algal treatment, dissolved N and P are transferred from wastewater into algal biomass while the water is simultaneously polished for reuse. Chaudry et al. modeled abattoir wastewater treatment with nearly 80% water recycling, producing effluent below 1 mg/L N and 12 mg/L P, about 2 kg biomass per m³ wastewater, and 3.46–6.11 kg CO₂-eq/m³ credited greenhouse-gas reduction depending on product credit [43]. The recovered P is therefore embedded in biomass, so its practical value depends on harvesting, dewatering, product safety, and the intended use of the algal product. Carbon-assisted recovery represents a third mode in which P recovery is coupled to pollutant destruction. Wang et al. used three-dimensional hierarchically porous carbon to adsorb more than 80% of dimethoate, desorbed and mineralized 90.8% of the adsorbed dimethoate to phosphate, and then recovered 99.8% of the released phosphate by CaCl₂ precipitation [70]. Thus, biochar, algal, and carbon-assisted routes are best understood as functional recovery pathways: they are most appropriate when the target is not only P recovery but also slow-release soil amendment, treated-water reuse, biomass valorization, or the destruction of organophosphorus pollutants (Figure 5).

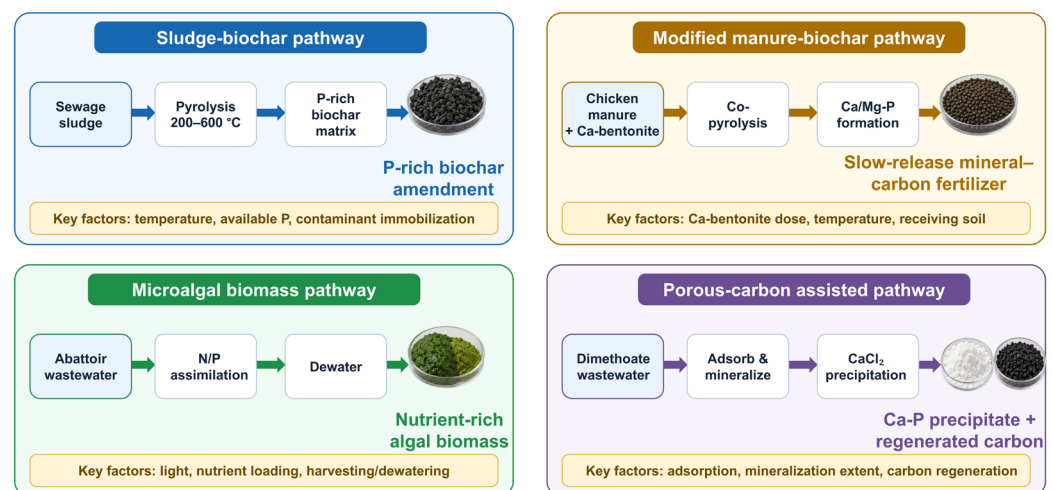


Figure 5. Biological and carbon-assisted phosphorus recovery routes grouped by product function.

3.6. Contaminant Fate and Product Safety

Product-oriented recovery requires an explicit risk analysis of the final material. A recovered P product is viable only when toxicity, contaminant mobility, hygienic safety, regulatory eligibility, and agronomic or industrial performance are acceptable for the intended use. Therefore, contaminant fate must be interpreted together with recovery efficiency: a process that removes P from wastewater may still fail if metals, antibiotics, antibiotic resistance genes (ARGs), pathogens, residual organics, or process salts remain in the marketed product [19,22,29,36,39,71].

For precipitation products, the main risk is co-precipitation or physical carry-over. Struvite and Ca-P can incorporate or entrain Ca, K, Fe, Cu, Zn, suspended solids, and organic matter; in swine wastewater, antibiotics and ARGs may partition differently from phosphate and can remain relevant even when P recovery is high [31,38]. Thus, swine-derived struvite should be assessed based on metal content, antibiotic residues, ARG indicators, pathogen control, crystal purity and size, and local fertilizer acceptance, rather than solely on O-P recovery [38,39,71].

For thermal products, pyrolysis and AshDec-type treatment reduce biological risk in different ways. Pyrolysis can destroy pathogens and many organic contaminants and may reduce the mobility or bioavailability of some metals, but metals are not eliminated and can be concentrated in the biochar matrix; the formation of polycyclic aromatic hydrocarbons (PAHs), H/C stability, and field release behavior therefore remain product gates [28,36,41,71]. AshDec treatment of sewage sludge ash improves the fertilizer value of mineral P and can volatilize part of the As, Cd, Pb, or related trace-element burden into off-gas or filter dust, so tail-gas capture, dust handling, and Component Material Category 13 (CMC 13) or national eligibility requirements are essential parts of the product assessment [29,32,71].

For Fe-P products and industrial streams, safety is linked to both impurity control and the target market. Vivianite, intended as a Fe-P resource, requires magnetic separability, dry-matter enrichment, and metal/organic impurity control, whereas FePO_4 or LiFePO_4/C precursor routes require Fe/P stoichiometry, low Ca/Na/Mg/ SO_4 and trace-metal impurities, controlled particle properties, washing and drying, and electrochemical validation. These stricter gates explain why a high-value industrial product can be less transferable than a fertilizer route unless purification and performance are demonstrated [26,33,45,47,66,71].

4. Life Cycle and Techno-Economic Assessment of Product-Oriented Phosphorus Recovery

4.1. Life Cycle Assessment Framework

LCA provides a framework for evaluating the direct and indirect environmental impacts of phosphorus recovery systems throughout their life cycles [72]. It can be used to assess anthropogenic P cycling, compare wastewater- and sludge-based recovery technologies, identify environmental hotspots, and examine trade-offs among recovery efficiency, emissions, energy demand, and product substitution [73–75]. Life cycle inventory (LCI) is the inventory-analysis phase of LCA rather than a separate method. After the goal and scope are defined, including the functional unit and system boundary, LCI compiles foreground inputs, outputs, recovered products, residuals, and direct emissions for each unit process. These flows are then translated into life cycle impact assessment (LCIA) indicators and interpreted in accordance with the study goal [73,75].

For wastewater-based P recovery, foreground inventory data typically includes chemical inputs, electricity and heat demand, transport, recovered P products, waste

streams, and direct emissions. Background processes can be modeled using LCA databases when required. For example, Amann et al. linked material flow analysis (MFA) and energy flow analysis (EFA) derived mass and energy flows with Ecoinvent 3.3 to calculate indirect emissions and indirect energy demand, while Xie et al. used open LCA with Ecoinvent 3.7 for background-system modeling [13,75]. Thus, Ecoinvent should be treated as a database choice in specific LCA models, not as an inherent component of LCI. The reliability of comparisons depends on transparent reporting of the functional unit, system boundary, multifunctionality treatment, and input-output inventory, especially for multifunctional systems such as P recovery from sewage sludge ash (SSA) [72,73,75].

Figure 6 illustrates how LCI can be constructed by combining material and energy flow analyses within the LCA workflow. MFA and SFA (substance flow analysis) track P, recovered products, residues, and pollutant flows from wastewater treatment inputs to final sinks or products, supporting the assessment of P recovery and depollution potential [12,74]. EFA quantifies the energy requirements for electricity, heat, fuel, transport, and treatment. These foreground mass and energy flows can then be connected to background datasets, such as Ecoinvent where used, to estimate indirect emissions and indirect energy demand and to support LCIA indicators such as cumulative energy demand (CED), global warming potential (GWP), and acidification potential (AP) [13].

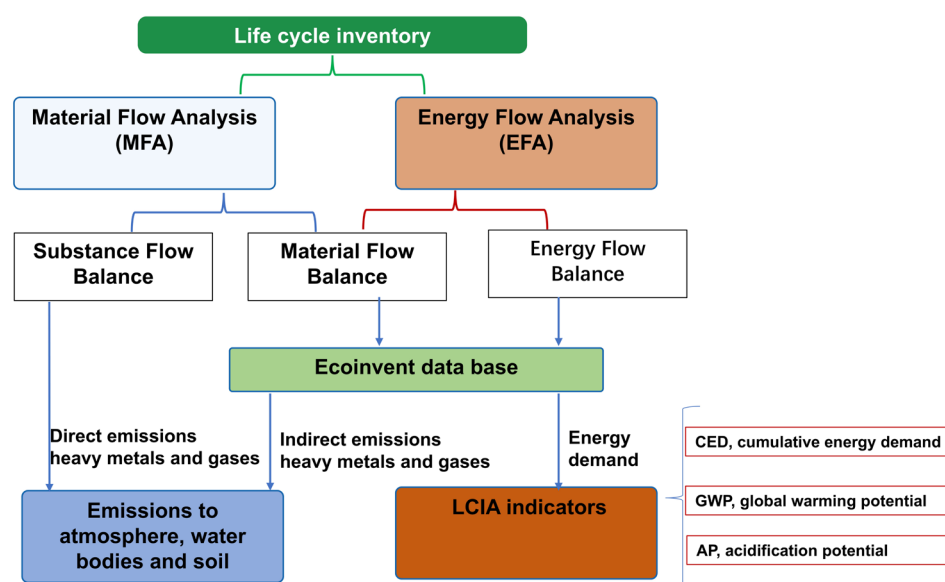


Figure 6. LCI development for phosphorus recovery scenarios using material/substance and energy flow analysis.

4.2. LCA-Based Techno-Economic Evaluation of P Recovery Scenarios

Given the significant divergence among phosphorus recovery studies in terms of research goals, functional units, system boundaries, multifunctionality allocation approaches, and cost accounting bases [15,72,73,75], a direct comparison of absolute techno-economic values across studies is neither valid nor meaningful. Consequently, this review does not aim to establish a universal ranking of technologies. Instead, we systematically delineate what the selected LCA and techno-economic studies evaluate, with the explicit goal of clarifying for the reader the essential inventory components and accounting dimensions that should be considered in such assessments, rather than encouraging inappropriate numerical benchmarking. The representative evaluation focuses, and key findings of published LCA and TEA studies are summarized in Table 3. Rather than comparing absolute numerical values across studies, the table highlights the different evaluation priorities adopted for different recovery products and application scenarios.

Table 3. Representative evaluation focuses, and key findings from published LCA and TEA studies for different phosphorus recovery pathways.

Method	Matched Recovery Route	Source	Product	Primary Evaluation Focus	Representative Findings	Ref.
LCA	Chemical struvite crystallization	WWTP	Struvite	Environmental impacts (LCIA)	Ostara reduced CED/GWP/AP by 20%/13%/24%; AirPrex reduced 31%/15%/21%, despite relatively low influent-P capture.	[10]
	AshDec thermochemical conversion	WWTP	Depolluted or P-rich ash	Environmental impacts (acidification)	AP decreased by 63–64% under AshDec scenarios.	[10]
	Microalgal recovery	Industrial wastewater	Algal biomass	Resource recovery and climate benefits	Biomass yield: ~2.0 kg m ⁻³ wastewater; avoided GHG emissions: 3.46–6.11 kg CO ₂ -eq m ⁻³ wastewater.	[39]
	Chemical struvite crystallization	Agricultural wastewater	Struvite	Climate benefits	Avoided greenhouse-gas emissions: 6522 t CO ₂ -eq yr ⁻¹ .	[47]
TEA	Electrochemical struvite	Agricultural wastewater	Struvite	Operational performance	Struvite purity: 88.5%; energy: 0.824 kWh/m ³ wastewater; operating cost: 3.87 USD/m ³ wastewater	[49]
	Acid extraction/phosphoric acid	WWTP	Ca-P or H ₃ PO ₄	Process phosphorus recovery	Process P recovery: LEACHPHOS 70%; EcoPhos 97%.	[60]
	Electrochemical struvite	WWTP	Struvite + H ₂	Energy demand and economic performance	Energy demand: 4.6 kWh kg ⁻¹ struvite; break-even value: 6.03 USD kg ⁻¹ struvite and 15.58 USD kg ⁻¹ H ₂ .	[62]
	Struvite/vivianite recovery scenarios	WWTP	Bioavailable P products	Life-cycle cost (societal, external, and net cost)	PR1: societal cost; PR2: external cost; PR3: net cost (5.5–7.7 USD kg ⁻¹ P).	[63]
Product quality and value assessment	Chemical FePO ₄ recovery	WWTP	FePO ₄ for LiFePO ₄ /C	Electrochemical performance	LiFePO ₄ /C capacity: 37.3–55.8 mAh/g	[76]
	Electrochemical Fe-P recovery	Industrial wastewater	vivianite; LiFePO ₄ /C	Electrochemical performance	LiFePO ₄ /C capacity: 52.36–56.88 mAh/g	[42,65]
	Fe-cycle FePO ₄ recovery	WWTP	Battery-grade FePO ₄	Product quality and techno-economics	FePO ₄ purity: 99.0%; recovery cost: 5.42 USD kg ⁻¹ P; emissions: 80.83 kg CO ₂ kg ⁻¹ P; LiFePO ₄ /C capacity: 84.6–100.2 mAh g ⁻¹ .	[77]

FePO ₄ recovery	WWTP	FePO ₄ ; LiFePO ₄ /C	Product quality and economic benefit	FePO ₄ purity: 98.5%; LiFePO ₄ /C capacity: 110.2 mAh g ⁻¹ ; recovery cost: 6.04 USD kg ⁻¹ P; net benefit: 3.68 USD kg ⁻¹ P.	[78]
----------------------------	------	---	--	---	------

Note: CED, cumulative energy demand; GWP, global warming potential; AP, acidification potential; PR1: struvite recovery scenario; PR2: vivianite recovery scenario; PR3: treated-sludge P-use scenario.

For WWTP side-stream and municipal liquid routes, LCA studies primarily assess environmental impacts associated with phosphorus recovery, including CED, GWP, AP, and plant operation. Electrochemical recovery routes further incorporate energy consumption and potential economic benefits from hydrogen co-production. Collectively, these studies indicate that the environmental performance of municipal phosphorus recovery depends on the overall treatment configuration and resource recovery strategy, rather than phosphorus recovery efficiency alone (Table 3).

For sludge and SSA pathways, the evaluation focus shifts from wastewater treatment performance to multifunctionality, functional-unit selection, chemical and energy inventories, heavy-metal management, and the agronomic value of recovered products. Consequently, different studies report societal costs, external costs, environmental impacts, or phosphorus recovery efficiencies, depending on their specific assessment objectives. This diversity highlights that comparisons among sludge-based recovery pathways are meaningful only when system boundaries and methodological assumptions are aligned (Table 3).

Agricultural and agro-industrial phosphorus recovery systems are evaluated from a different perspective. Instead of influent phosphorus capture, these studies emphasize operational performance, including nutrient removal, energy demand, operating costs, fertilizer substitution potential, water recycling, and greenhouse gas (GHG) mitigation. Such evaluation priorities reflect the dual objectives of agricultural waste management and nutrient recycling rather than maximizing phosphorus recovery alone (Table 3).

Industrial phosphorus recovery is predominantly product-oriented. Accordingly, LCA and TEA studies place greater emphasis on product quality, purity, recovery cost, electrochemical performance, and carbon emissions than on wastewater treatment efficiency. This is particularly evident for battery-grade FePO₄ products, where product specifications ultimately determine commercial value and market competitiveness. Consequently, environmental and economic assessments of industrial recovery pathways should be interpreted together with product quality requirements rather than recovery efficiency alone.

4.3. Synthesis: Value Creation and Circular-Economy Pathways of P Recovery

Municipal WWTP recovery should be evaluated through P capture, treatment-system effects, environmental indicators, and cost, whereas agricultural and livestock routes are better assessed through local nutrient recycling, fertilizer substitution, water reuse, and avoided emissions [79,80]. Industrial routes create value only when the recovered product meets a defined specification, such as vivianite/Ca-P resources or FePO₄-related materials, rather than a generic fertilizer claim [77,81].

For upstream of WWTPs or decentralized recovery, LCA/TEA should use source-specific functional units, such as a volume of separated wastewater, a mass of recovered

P, or a mass of recovered product [82,83]. The inventory should include separation or collection, storage, transport, Mg/alkali or electrode inputs, sanitization or product conditioning, and final fertilizer substitution [80,83].

Because liquid-phase or source-separated recovery can reduce local treatment burdens while capturing less city-wide P than SSA routes, local removal efficiency should be reported separately from total P capture across the wastewater system [79,84].

For sludge and SSA pathways, the assessment should combine treatment-function metrics with product metrics, as results depend on allocation or system expansion, avoided fertilizer or industrial products, changes in sludge disposal, energy and chemical demand, heavy-metal control, and product bioavailability [72,73].

These two pathways, therefore, answer different questions: decentralized LCA asks whether source separation justifies additional collection and conditioning, whereas centralized sludge- and ash-based LCA asks whether higher P capture from sludge/SSA offsets the burdens of concentration, incineration, ash treatment, chemical extraction, and product upgrading [79,83].

This distinction prevents a single universal hierarchy of technologies [79,80]. Electrochemical struvite is sensitive to electricity, electrode consumption, airflow, and break-even product values, while livestock wastewater routes are sensitive to operating costs, fertilizer substitution, and GHG credits [34,35,80]. SSA routes are sensitive to acid/alkali demand, energy use, purification requirements, and avoided products, whereas FePO_4 routes are sensitive to product purity, electrochemical performance, recovery cost, and carbon intensity [67,72,77].

To translate these qualitative insights into a practical tool for researchers and practitioners, Table 4 presents a decision matrix that links source characteristics, recovery routes, target products, and key LCA/TEA hotspots. The matrix follows a conditional logic: source category (P concentration, matrix complexity, impurity profile) determines feasible recovery routes and product options; the selected route determines which LCA/TEA hotspots dominate; and the product specification (fertilizer vs. battery) dictates purity and contaminant-control requirements.

Table 4. Decision matrix for P recovery route selection based on source characteristics, target product, and LCA/TEA hotspots.

Source	Key Characteristics	Feasible Recovery Routes	Target Product (Purity/Quality)	LCA/TEA Hotspots	Conditions/Limitations
Dilute municipal effluent (1–15 mg P/L)	Low P, high flow, low impurities	Adsorption	Soil amendment (2.2–2.5% P_2O_5)	Adsorbent production, regeneration, and breakthrough time	Low product value; viable only when water polishing is the primary objective
Concentrated municipal side streams (>50 mg P/L)	High P, high NH_4 , Ca^{2+} interference	Struvite crystallization (CSP/ESP)	Struvite fertilizer (85–90% purity)	Mg salt/electrode consumption; pH control; drying energy; purity vs. recovery trade-off	P-rich streams (>50 mg/L) are economically viable; pH < 8.0 and short HRT favor purity
Fe-rich digested sludge	Fe/P ~1.6, high organics, variable dry matter	High-gradient magnetic separation (HGMS)	Vivianite (70–85% purity)	Magnetic energy; recirculation number; sludge pre-treatment	Robust to sludge DM variations; <10 μm particles limit recovery
Acidic industrial streams (pH 1.5–5)	High P, acidic, contains F^- , SO_4^{2-} , heavy metals	Controlled Fe(II)- H_2O_2 precipitation	$\text{FePO}_4 \cdot 2\text{H}_2\text{O}$ (>95% recovery)	Fe salt; H_2O_2 dosing; pH adjustment; settleability	Fe(II) oxidation rate (4.7×10^{-4} mol/L/min) critical for settleability; avoids neutralization costs

Iron-enhanced primary sludge	Fe-P complexes, organic matrix, require fermentation	Fermentation → selective Fe-P precipitation (pH 2 + H ₂ O ₂) → sintering (700 °C)	Battery-grade FePO ₄ (99.3% purity; LFP precursor)	Fermentation; H ₂ O ₂ /acid consumption; sintering energy; multi-step purification	Strict impurity control required (Ca, Mg, Na, Cu, Zn, Mn, Al, Ti, S; magnetic < 0.00025%); high market value justifies complexity
Agricultural/livestock wastewater	High N/P, K ⁺ /Ca ²⁺ interference, antibiotics, ARGs, heavy metals	Struvite crystallization (CSP/ESP)	Struvite fertilizer (85–91% purity; 18–40 µm crystals)	Mg/electrode cost; antibiotic/ARG contamination; heavy metal co-precipitation	MgCl ₂ preferred to avoid Cu redissolution; product must meet local contaminant limits; antibiotics/ARGs may limit agricultural use
Crop residues/manures	P 0.4–2.2 mg/g, high C/P and lignin/P ratios	Pyrolysis (300–600 °C) with/without Ca-bentonite	Biochar-based slow-release fertilizer/soil amendment	Pyrolysis temperature; energy input; Ca-bentonite addition	Low temperature (300 °C) favors available P; high temperature (600 °C) favors slow-release P
Phosphogypsum leachate	Very high P (>4000 mg/L), acidic, F ⁻ , Ca ²⁺ , Mg ²⁺ , SO ₄ ²⁻	Electrochemical recovery (Fe anode; pH < 9, DO control); staged precipitation	Vivianite; multi-element recovery (F ⁻ , PO ₄ ³⁻ , SO ₄ ²⁻)	Electrode consumption; electricity; DO control; electrodialysis	Staged precipitation recovers F ⁻ at pH 4.7, PO ₄ ³⁻ at pH 8.5, SO ₄ ²⁻ via electrodialysis; residual P meets discharge standard (<10 mg/L)

A defensible decision rule is conditional: prioritize sludge/SSA recovery when high city-wide P capture and existing sludge/ash infrastructure are the management goal; use decentralized recovery for separately collected high-strength streams with quantified collection and hygiene burdens; select agricultural routes when local nutrient balance and fertilizer substitution dominate; and use industrial FePO₄ routes only when product-grade purity and material performance are demonstrated [80–82]. The matrix above provides a structured reference to guide these decisions by linking source conditions, technology options, product quality, and key LCA/TEA drivers.

Crucially, the same source category may yield different products depending on the applied technology, and the same target product may be produced from different sources with varying quality outcomes. The matrix is not intended to prescribe a single “best” choice, but to help users identify viable pathways and anticipate the dominant cost and environmental drivers for each option.

5. Conclusions

This review establishes a product-oriented framework for phosphorus recovery, demonstrating that recovery performance should not be evaluated solely by phosphorus removal efficiency, because product quality, safety, regulatory compliance, and end-use suitability ultimately determine the environmental and economic value of recovered phosphorus. Four main findings emerge from this review.

First, source-product matching is essential. Phosphorus sources differ substantially in concentration, speciation, and impurity profiles; therefore, different source types require different recovery pathways to produce products suitable for specific applications.

Second, product quality is determined not only by the source but also by process conditions. Even for the same product, such as struvite, vivianite, or FePO₄, different recovery technologies produce markedly different purities, which directly affect regulatory compliance, market acceptance, and product value.

Third, LCA/TEA results are context-dependent and not directly comparable across studies. Differences in system boundaries, functional units, and allocation methods mean that upstream, decentralized, sludge-based, and industrial recovery pathways address different management objectives and therefore require product-specific evaluation criteria.

Fourth, regulatory compliance must be embedded in process design. Compliance with contaminant limits and product-quality standards should therefore be integrated into process design from the outset rather than considered only after product recovery.

Despite the diversity of available technologies, fertilizer remains the dominant end-use for recovered phosphorus, indicating that product diversification has lagged advances in recovery technologies. Future progress will depend less on further increasing recovery efficiency and more on developing higher-value products, particularly battery-grade FePO_4 and application-specific fertilizers that better match market demand.

Future research should prioritize: (1) standardized quality criteria for recovered products; (2) long-term validation of fertilizer performance and battery precursors; (3) harmonized LCA/TEA methodologies that explicitly incorporate product specifications; (4) pilot- and full-scale demonstrations under realistic wastewater conditions.

Overall, the central question in phosphorus recovery is no longer “how much phosphorus can be recovered”, but rather “what products can be produced, for which applications, and at what environmental and economic cost”. Such a transition will facilitate the development of reliable fertilizers, industrial phosphates, and other high-value phosphorus products, thereby accelerating the transition toward a circular phosphorus economy.

Author Contributions: Data collection and summary, Q.Q., K.Q., X.S., Y.C. and Z.L.; Manuscript preparation, Q.Q., J.W., X.L., Z.T. and J.Z.; Supervision, K.Q. and J.Z.; Funding Acquisition, K.Q. and J.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Heilongjiang Provincial College Student Innovation and Entrepreneurship Training Program (S202410212086), the Outstanding Young Teachers Support Program of Provincial Universities in Heilongjiang Province (YQJH2024194), the National Natural Science Foundation of China (22206048), the National Natural Science Foundation of Heilongjiang (LH2024E110), and the Basic Research Funds for Heilongjiang Provincial Universities (2025-KYYWF-ZR0392).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: Author Xiaoting Sun was employed by Beijing Drainage Group Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. U.S. Geological Survey. *Mineral Commodity Summaries 2025, Version 1.2*; U.S. Geological Survey: Reston, VA, USA, 2025.
2. Demay, J.; Ringeval, B.; Pellerin, S.; Nesme, T. Half of global agricultural soil phosphorus fertility derived from anthropogenic sources. *Nat. Geosci.* **2023**, *16*, 69–74.
3. Zhu, F.; Cakmak, E.K.; Cetecioglu, Z. Phosphorus recovery for circular Economy: Application potential of feasible resources and engineering processes in Europe. *Chem. Eng. J.* **2023**, *454*, 140153.
4. Li, Q.; Xiang, P.; Li, L.; Zhang, T.; Wu, Q.; Bao, Z.; Tu, W.; Zhao, C. Phosphorus mining activities alter endophytic bacterial communities and metabolic functions of surrounding vegetables and crops. *Plant Soil* **2024**, *497*, 155–174.

5. Baker, J.; Schunk, N.; Scholz, M.; Merck, A.; Muenich, R.L.; Westerhoff, P.; Elser, J.J.; Duckworth, O.W.; Gatiboni, L.; Islam, M.; et al. Global-to-Local Dependencies in Phosphorus Mass Flows and Markets: Pathways to Improving System Resiliency in Response to Exogenous Shocks. *Environ. Sci. Technol. Lett.* **2024**, *11*, 493–502.
6. Zheng, M.; Hu, Z.; Liu, T.; Sperandio, M.; Volcke, E.I.P.; Wang, Z.; Hao, X.; Duan, H.; Vlaeminck, S.E.; Xu, K.; et al. Pathways to advanced resource recovery from sewage. *Nat. Sustain.* **2024**, *7*, 1395–1404.
7. Perera, M.K.; Englehardt, J.D.; Dvorak, A.C. Technologies for Recovering Nutrients from Wastewater: A Critical Review. *Environ. Eng. Sci.* **2019**, *36*, 511–529.
8. Zheng, Y.; Wan, Y.; Zhang, Y.; Huang, J.; Yang, Y.; Tsang, D.C.W.; Wang, H.; Chen, H.; Gao, B. Recovery of phosphorus from wastewater: A review based on current phosphorous removal technologies. *Crit. Rev. Environ. Sci. Technol.* **2023**, *53*, 1148–1172.
9. Vu, M.T.; Duong, H.C.; Wang, Q.; Ansari, A.; Cai, Z.; Hoang, N.B.; Nghiem, L.D. Recent technological developments and challenges for phosphorus removal and recovery toward a circular economy. *Environ. Technol. Innov.* **2023**, *30*, 103114.
10. Śniatała, B.; Al-Hazmi, H.E.; Sobotka, D.; Zhai, J.; Mąkinia, J. Advancing sustainable wastewater management: A comprehensive review of nutrient recovery products and their applications. *Sci. Total Environ.* **2024**, *937*, 173446.
11. Walsh, M.; Schenk, G.; Schmidt, S. Realising the circular phosphorus economy delivers for sustainable development goals. *npj Sustain. Agric.* **2023**, *1*, 2.
12. Egle, L.; Rechberger, H.; Krampe, J.; Zessner, M. Phosphorus recovery from municipal wastewater: An integrated comparative technological, environmental and economic assessment of P recovery technologies. *Sci. Total Environ.* **2016**, *571*, 522–542.
13. Amann, A.; Zoboli, O.; Krampe, J.; Rechberger, H.; Zessner, M.; Egle, L. Environmental impacts of phosphorus recovery from municipal wastewater. *Resour. Conserv. Recycl.* **2018**, *130*, 127–139.
14. Clack, K.; Rajagopal, D.; Hoek, E.M. Life cycle and techno-economic assessment of bioresource production from wastewater. *npj Clean Water* **2024**, *7*, 22.
15. Lam, K.L.; Solon, K.; Jia, M.; Volcke, E.I.P.; van der Hoek, J.P. Life Cycle Environmental Impacts of Wastewater-Derived Phosphorus Products: An Agricultural End-User Perspective. *Environ. Sci. Technol.* **2022**, *56*, 10289–10298.
16. Bagheri, M.; Gómez-Sanabria, A.; Höglund-Isaksson, L. Economic feasibility and direct greenhouse gas emissions from different phosphorus recovery methods in Swedish wastewater treatment plants. *Sustain. Prod. Consum.* **2024**, *49*, 462–473.
17. Serrano-Gomez, J.; Metson, G.S.; Neset, T.S.; Santner, J.; Hermann, L.; Zessner, M. EU-compliant wastewater recycled phosphorus: How much national cereal demand can it meet? *J. Clean. Prod.* **2023**, *429*, 139482.
18. Chrispim, M.C.; Scholz, M.; Nolasco, M.A. Phosphorus recovery from municipal wastewater treatment: Critical review of challenges and opportunities for developing countries. *J. Environ. Manag.* **2019**, *248*, 109268.
19. Pap, S.; Zhang, H.; Bogdan, A.; Elsby, D.T.; Gibb, S.W.; Bremner, B.; Taggart, M.A. Pilot-scale phosphate recovery from wastewater to create a fertiliser product: An integrated assessment of adsorbent performance and quality. *Water Res.* **2023**, *228*, 119369.
20. Zhou, J.; Dong, K.; Yu, Z.; Li, Z. Pilot-scale phosphorus recovery from urine sewage by in-situ formed calcium carbonate. *Desalin. Water Treat.* **2024**, *320*, 100881.
21. Gao, D.; Li, B.; Huang, X.; Liu, X.; Li, R.; Ye, Z.; Wu, X.; Huang, Y.; Wang, G. A review of the migration mechanism of antibiotics during struvite recovery from wastewater. *Chem. Eng. J.* **2023**, *466*, 142983.
22. Yan, Y.; Kallikazarou, N.I.; Nisiforou, O.; Shang, Q.; Fu, D.; Antoniou, M.G.; Fotidis, I.A. Phosphorus recovery through struvite crystallization from real wastewater: Bridging gaps from lab to market. *Bioresour. Technol.* **2025**, *427*, 132408.
23. Guan, Q.; Li, Y.; Zhong, Y.; Liu, W.; Zhang, J.; Yu, X.; Ou, R.; Zeng, G. A review of struvite crystallization for nutrient source recovery from wastewater. *J. Environ. Manag.* **2023**, *344*, 118383.
24. Ramaswamy, J.; Solaiappan, V.; Albasher, G.; Alamri, O.; Alsultan, N.; Sathiasivan, K. Process optimization of struvite recovered from slaughterhouse wastewater and its fertilizing efficacy in amendment of biofertilizer. *Environ. Res.* **2022**, *211*, 113011.
25. Iftikhar, A.; Tao, W. Production of natural fertilizers with sludge digestate by mineral-based struvite crystallization and organic binding. *J. Clean. Prod.* **2025**, *525*, 146599.
26. Figueiredo, C.C.D.; Reis, A.D.S.P.J.; Araujo, A.S.D.; Blum, L.E.B.; Shah, K.; Paz-Ferreiro, J. Assessing the potential of sewage sludge-derived biochar as a novel phosphorus fertilizer: Influence of extractant solutions and pyrolysis temperatures. *Waste Manag.* **2021**, *124*, 144–153.
27. Nguyen, H.; Prot, T.; Wijdeveld, W.; Korving, L.; Dugulan, A.; Brück, E.; Haarala, A.; van Loosdrecht, M. Robust magnetic vivianite recovery from digested sewage sludge: Evaluating resilience to sludge dry matter and particle size variations. *Water Res.* **2024**, *266*, 122407.
28. Wang, X.; Chang, Y.; Liang, Z.; Li, A.; Wu, Y.; Wen, B.; Li, B.; Sun, F.; Li, X.Y.; Logan, B.E.; et al. Sustainable production of high-purity crystalline FePO₄ from sludge for battery electrodes. *Water Res.* **2026**, *289*, 124885.

29. Raniero, H.R.; Hernandez-Mora, A.; Duboc, O.; Staudinger, C.; Santner, J. Phosphorus Release Dynamics from Cover Crop Residues: A Comparison between Single Species and Mixtures. *Soil Use Manag.* **2025**, *41*, e70082.
30. Shashvatt, U.; Benoit, J.; Aris, H.; Blaney, L. CO₂-assisted phosphorus extraction from poultry litter and selective recovery of struvite and potassium struvite. *Water Res.* **2018**, *143*, 19–27.
31. Piash, M.I.; Iwabuchi, K.; Itoh, T. Synthesizing biochar-based fertilizer with sustained phosphorus and potassium release: Co-pyrolysis of nutrient-rich chicken manure and Ca-bentonite. *Sci. Total Environ.* **2022**, *822*, 153509.
32. Ran, X.; Uppuluri, N.S.T.; Deng, Y.; Zheng, Y.; Dong, R.; Müller, J.; Oechsner, H.; Li, B.; Guo, J. Comparison of phosphorus species in livestock manure and digestate by different detection techniques. *Sci. Total Environ.* **2023**, *874*, 162547.
33. Shim, S.; Reza, A.; Kim, S.; Won, S.; Ra, C. Nutrient recovery from swine wastewater at full-scale: An integrated technical, economic and environmental feasibility assessment. *Chemosphere* **2021**, *277*, 130309.
34. Aka, R.J.N.; Hossain, M.; Yuan, Y.; Agyekum-Oduro, E.; Zhan, Y.; Zhu, J.; Wu, S. Nutrient recovery through struvite precipitation from anaerobically digested poultry wastewater in an air-lift electrolytic reactor: Process modeling and cost analysis. *Chem. Eng. J.* **2023**, *465*, 142825.
35. Ndeddy Aka, R.J.; Agyekum-Oduro, E.; Zhu, J.; Wu, S. Integrating electrolytic struvite precipitation with ammonia scrubbing toward complete recovery of nitrogen and phosphorus from anaerobic digestate of poultry litter. *Sep. Purif. Technol.* **2025**, *370*, 133287.
36. Guan, Q.; Zeng, G.; Gong, B.; Li, Y.; Ji, H.; Zhang, J.; Song, J.; Liu, C.; Wang, Z.; Deng, C. Phosphorus recovery and iron, copper precipitation from swine wastewater via struvite crystallization using various magnesium compounds. *J. Clean. Prod.* **2021**, *328*, 129588.
37. Cai, J.; Ye, Z.L.; Ye, C.; Ye, X.; Chen, S. Struvite crystallization induced the discrepant transports of antibiotics and antibiotic resistance genes in phosphorus recovery from swine wastewater. *Environ. Pollut.* **2020**, *266*, 115361.
38. Lei, Y.; Zhan, Z.; Saakes, M.; van der Weijden, R.D.; Buisman, C.J.N. Electrochemical Recovery of Phosphorus from Acidic Cheese Wastewater: Feasibility, Quality of Products, and Comparison with Chemical Precipitation. *ACS ES&T Water* **2021**, *1*, 1002–1013.
39. Hultberg, M.; Bodin, H. Fungi-based treatment of real brewery waste streams and its effects on water quality. *Bioprocess Biosyst. Eng.* **2019**, *42*, 1317–1324.
40. Tian, F.; Qiao, J.; Zheng, W.; Lei, Y.; Jiang, S.; Liu, Y. Flow-through electrochemical organophosphorus degradation and phosphorus recovery: The essential role of chlorine radical. *Environ. Res.* **2023**, *236*, 116867.
41. Chen, F.; Zeng, S.; Ma, J.; Zhu, Q.; Zhang, S. Treatment of chlorpyrifos manufacturing wastewater by peroxide promoted-catalytic wet air oxidation, struvite precipitation, and biological aerated biofilter. *Environ. Sci. Pollut. Res.* **2019**, *26*, 26721–26732.
42. Bahgat, N.T.; Siddiqui, A.; Wilfert, P.; Korving, L.; van Loosdrecht, M.C. FePO₄·2H₂O recovery from acidic phosphate-rich waste streams. *Water Res.* **2024**, *260*, 121905.
43. Chaudry, S.; Alavianghavanini, A.; Darvehei, P.; Moheimani, N.R.; Bahri, P.A. Feasibility of Nutrient Removal and Recovery from Abattoir Wastewater Using Microalgae. *Energies* **2024**, *17*, 308.
44. Zhang, Y.; Qin, J.; Chen, Z.; Chen, Y.; Zheng, X.; Guo, L.; Wang, X. Efficient removal and recovery of phosphorus from industrial wastewater in the form of vivianite. *Environ. Res.* **2023**, *228*, 115848.
45. Liu, S.; Lou, X.Y.; Shi, W.; Liu, P.; Gu, X.; Feng, X.; Yang, S.; Shangguan, Y.; Fan, H.; Zhou, H.; et al. Efficient Electrochemical Recovery of Phosphate from Phosphogypsum Leachate for Lithium-Ion Battery Cathode Application. *ACS ES&T Eng.* **2025**, *5*, 1670–1682.
46. GB 15580-2011; Discharge Standard of Water Pollutants for Phosphate Fertilizer Industry. China Environmental Science Press: Beijing, China, 2011.
47. Lou, X.Y.; Wang, J.; Liang, J.; Liu, S.; Wang, R.; Deng, L.; Li, D.; Hu, X.; Chen, H. Sequence closed-loop recovery of fluoride, phosphate, and sulfate anions from phosphogypsum leachate via precipitation-electrodialysis-crystallization approaches. *Sep. Purif. Technol.* **2024**, *342*, 127014.
48. HG/T 4701-2021; Iron Phosphate for Battery. Ministry of Industry and Information Technology of the People's Republic of China: Beijing, China, 2021. Available online: <https://std.samr.gov.cn/hb/search/stdHBDetailed?id=D7B6988FD9D1AA-BEE05397BE0A0A1B36> (accessed on 24 June 2026).
49. Jiang, Y.; Zhang, G.; Zhou, K.; Peng, C.; Salih, K.A.; Zhou, H.; Wu, Y.; Chen, W. Sequential separation and recovery of phosphorus and lithium from lithium phosphate slag by selective extraction-precipitation. *Sep. Purif. Technol.* **2024**, *333*, 125907.
50. GB 38400-2019; Limitation Requirements of Toxic and Harmful Substance in Fertilizers. State Administration for Market Regulation of China; Standardization Administration of China: Beijing, China, 2019. Available online: <https://openstd.samr.gov.cn/bzgk/std/newGbInfo?hcno=76E30A68743B8F552A3EBE6334C7BC07> (accessed on 24 June 2026).

51. European Parliament and Council of the European Union. Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 Laying Down Rules on the Making Available on the Market of EU Fertilising Products and Amending Regulations (EC) No. 1069/2009 and (EC) No. 1107/2009 and Repealing Regulation (EC) No. 2003/2003. Available online: <https://eur-lex.europa.eu/eli/reg/2019/1009/oj> (accessed on 24 June 2026).
52. Standardization Administration of China. GB/T 20412-2021: Fused Calcium Magnesium Phosphate Fertilizer. Available online: <https://openstd.samr.gov.cn/bzgk/std/newGbInfo?hcno=990228647057835B1401114CD1A584BB> (accessed on 24 June 2026).
53. Standardization Administration of China. GB/T 18877-2020: Organic–Inorganic Compound Fertilizer. Available online: <https://openstd.samr.gov.cn/bzgk/std/newGbInfo?hcno=1D058CB95DC9BD89C0CFDFEF9B9A2DDE> (accessed on 24 June 2026).
54. Government of Japan. Act on the Quality Control of Fertilizer, Act No. 127 of 1950. Available online: <https://www.japaneselaw-translation.go.jp/en/laws/view/4446/en> (accessed on 24 June 2026).
55. Ministry of Agriculture, Forestry and Fisheries of Japan. Overview of the Fertilizer Regulatory System and Official Specifications for Fertilizers. Available online: https://www.maff.go.jp/j/syouan/nouan/kome/k_hiryo/attach/pdf/220706hiryo_setsume-10.pdf (accessed on 24 June 2026).
56. Canadian Food Inspection Agency. Guide to Submitting Applications for Registration under the Fertilizers Act. Available online: <https://inspection.canada.ca/en/plant-health/fertilizers/registration-overview/guide#a43> (accessed on 24 June 2026).
57. Government of India, Ministry of Agriculture and Farmers Welfare. Specifications for Nano Di-Ammonium Phosphate Fertilizer (Liquid) Under Clause 20D of the Fertiliser (Inorganic, Organic or Mixed) (Control) Order, 1985. Available online: <https://egazette.gov.in/WriteReadData/2023/250317.pdf> (accessed on 24 June 2026).
58. Ministry of Agriculture, Livestock and Food Supply of Brazil. Annex I—Specifications for Mineral Fertilizers, as Updated in 2020. Available online: <https://www.gov.br/agricultura/pt-br/assuntos/insumos-agropecuarios/insumos-agricolas/fertilizantes/legislacao/anexo-i-in-39-2018-altera-dioxido-de-silicio-12-06-20.pdf> (accessed on 24 June 2026).
59. Peng, L.; Dai, H.; Wu, Y.; Peng, Y.; Lu, X. A comprehensive review of phosphorus recovery from wastewater by crystallization processes. *Chemosphere* **2018**, *197*, 768–781.
60. Yinyan, S.; Man, C.; Xiaochan, W.; Odhiambo, M.O.; Weimin, D. Numerical simulation of spreading performance and distribution pattern of centrifugal variable-rate fertilizer applicator based on DEM software. *Comput. Electron. Agric.* **2018**, *144*, 249–259.
61. Liu, Z.-G.; Min, X.-B.; Feng, F.; Tang, X.; Li, W.-C.; Peng, C.; Gao, T.-Y.; Chai, X.-L.; Tang, C.-J. Development and simulation of a struvite crystallization fluidized bed reactor with enhanced external recirculation for phosphorous and ammonium recovery. *Sci. Total Environ.* **2021**, *760*, 144311.
62. Deng, L.; Dhar, B.R. Phosphorus recovery from wastewater via calcium phosphate precipitation: A critical review of methods, progress, and insights. *Chemosphere* **2023**, *330*, 138685.
63. Zhou, M.; Han, Y.; Zhuo, Y.; Pu, B.; Li, L.; Liu, Y.; Peng, D. Bioinduced phosphorus precipitation in granular sludge undergoing denitrifying biological phosphorus removal: Phosphorus recovery from sewage as hydroxyapatite. *Water Res.* **2025**, *281*, 123590.
64. Wu, Y.; Luo, J.; Zhang, Q.; Aleem, M.; Fang, F.; Xue, Z.; Cao, J. Potentials and challenges of phosphorus recovery as vivianite from wastewater: A review. *Chemosphere* **2019**, *226*, 246–258.
65. Xu, H.; Lv, M.; Yang, M.; Huang, L.; Fang, Y.; Li, Y.; Yang, H.; Li, G. Battery-grade FePO₄ recovery from P-rich urine via field-induced electro-Fenton in a compartmental electrolytic cell. *Environ. Res.* **2026**, *295*, 123993.
66. Hermann, L.; Schaaf, T. Outotec (AshDec) Process for P Fertilizers from Sludge Ash. In *Phosphorus Recovery and Recycling*; Ohtake, H., Tsuneda, S., Eds.; Springer: Singapore, 2019; pp. 221–233.
67. Gao, J.; Yang, D.; Liu, Z.; Chen, X.; Wang, X.; Gong, H.; Dai, X. Enhanced simultaneous recovery of phosphorus and metals from incinerated sewage sludge ash via combined wet-chemical extraction and cation exchange resin. *Chem. Eng. J.* **2025**, *509*, 161360.
68. Fang, Y.; Liu, A.; Li, N.; Jiang, N.; Qian, G.; Xu, Y. Phosphorus recovery from Fe/Al-rich sewage sludge ash: Combining wet and thermochemical methods. *Sep. Purif. Technol.* **2025**, *363*, 131823.
69. Baldi, M.; Martinotti, A.; Sorlini, S.; Katsoyiannis, I.A.; Abbà, A.; Carnevale Miino, M.; Collivignarelli, M.C. Extraction and Purification of Phosphorus from the Ashes of Incinerated Biological Sewage Sludge. *Water* **2021**, *13*, 1102.
70. Wang, S.; Shen, Z.; Gao, J.; Qiu, Y.; Li, J.; Wang, Z.; Lyu, J. Adsorption-regeneration process for removing dimethoate and recovering phosphorus with three-dimensional hierarchically porous carbon. *J. Environ. Chem. Eng.* **2022**, *10*, 107716.
71. Dong, K.; Xiang, X.; Zhou, J.; Li, Z. Efficient fertilizer production from low phosphate water using in situ-formed vaterite/calcite calcium carbonate composite microspheres. *Sci. Total Environ.* **2022**, *822*, 153620.
72. Abdolrezayi, A.; Puricelli, S.; Dolci, G.; Turolla, A.; Canziani, R.; Rigamonti, L. Phosphorus recovery from sewage sludge ash: Life cycle inventory and critical review of LCA case studies. *J. Environ. Manag.* **2025**, *389*, 125620.

73. Manoukian, L.; Metson, G.; Hernández, E.M.; Vaneekhaute, C.; Frigon, D.; Omelon, S. Forging a cohesive path: Integrating life cycle assessments of primary-origin phosphorus fertilizer production and secondary-origin recovery from municipal wastewater. *Resour. Conserv. Recycl.* **2023**, *199*, 107260.
74. Morrissey, K.G.; English, L.; Thoma, G.; Popp, J. Prospective Life Cycle Assessment and Cost Analysis of Novel Electrochemical Struvite Recovery in a U.S. Wastewater Treatment Plant. *Sustainability* **2022**, *14*, 13657.
75. Xie, J.; Zhuge, X.; Liu, X.; Zhang, Q.; Liu, Y.; Sun, P.; Zhao, Y.; Tong, Y. Environmental sustainability opportunity and socio-economic cost analyses of phosphorus recovery from sewage sludge. *Environ. Sci. Ecotechnol.* **2023**, *16*, 100258.
76. Zheng, K.; Wang, Y.; Xiang, L.; Huang, C.; Zhang, H.; Li, J. A dual-cycle regeneration to recover high-value and high-purity FePO₄ from real wastewater for Li-battery application. *Water Res.* **2023**, *242*, 120300.
77. Wang, Y.; Fei, R.; Yuan, Z.; Li, Y.; Zhang, H.; Li, J. Low-carbon emitting Fe-cycle recovery of battery-grade FePO₄ from biogas slurry for Li-battery application. *Chem. Eng. J.* **2024**, *496*, 154131.
78. Bai, G.; Xu, K.; Xu, T.; Li, J.; Zheng, M.; Wang, C. Recovery of iron phosphate from waste activated sludge as a precursor for lithium-ion battery cathode materials. *Resour. Conserv. Recycl.* **2026**, *225*, 108596.
79. Pausta, C.M.; Kalbar, P.; Saroj, D. Life cycle assessment of nutrient recovery strategies from domestic wastewaters to quantify environmental performance and identification of trade-offs. *Sci. Rep.* **2024**, *14*, 3678.
80. Mayor, Á.; Vinardell, S.; Ganesan, K.; Bacardí, C.; Cortina, J.L.; Valderrama, C. Life-cycle assessment and techno-economic evaluation of the value chain in nutrient recovery from wastewater treatment plants for agricultural application. *Sci. Total Environ.* **2023**, *892*, 164452.
81. Randall, D.G.; Jalava, J.; Vinnerås, B.; Simha, P. Phosphorus recovery as vivianite and amorphous calcium phosphate from high-load industrial wastewater. *Front. Environ. Sci.* **2024**, *12*, 1491220.
82. Wang, Z.; Skerlos, S.J.; Novak, P.J. Nitrogen and Phosphorus Recovery from Anthropogenic Liquid Waste Streams. *Annu. Rev. Environ. Resour.* **2024**, *49*, 281–307.
83. Wang, X.; Chen, J.; Li, Z.; Cheng, S.; Mang, H.P.; Zheng, L.; Jan, I.; Harada, H. Nutrient recovery technologies for management of blackwater: A review. *Front. Environ. Sci.* **2023**, *10*, 1080536.
84. Rufí-Salís, M.; Petit-Boix, A.; Leipold, S.; Villalba, G.; Rieradevall, J.; Moliné, E.; Gabarrell, X.; Carrera, J.; Suárez-Ojeda, M.E. Increasing resource circularity in wastewater treatment: Environmental implications of technological upgrades. *Sci. Total Environ.* **2022**, *838*, 156422.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.