Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Review

Advancements and feasibility of synergistic approaches in phosphorus recovery from wastewater: A critical review

Parminder Kaur [a], Małgorzata Szlachta [b,*], Junhua Xu [a], Jouko Vepsäläinen [c], Reijo Lappalainen [d], Farihahusnah Hussin [e], Mohamed Kheireddine Aroua [e,f]

[a] Circular Economy Solutions Unit, Geological Survey of Finland, P.O. Box 96, FI-02151, Espoo, Finland
[b] Faculty of Engineering and Natural Sciences, Tampere University, P.O. Box 541, FI-33104, Tampere, Finland
[c] School of Pharmacy, University of Eastern Finland, P.O. Box 1627, FI-70211, Kuopio, Finland
[d] Department of Technical Physics, University of Eastern Finland, P.O. Box 1627, FI-70211, Kuopio, Finland
[e] School of Engineering and Technology, Sunway University, No. 5 Jalan Universiti, Bandar Sunway, 47500, Petaling Jaya, Selangor, Malaysia
[f] School of Engineering, Lancaster University, Lancaster, LA1 4YW, United Kingdom

ARTICLE INFO

Keywords:
Phosphorus
Resources recovery
Synergetic technologies
Wastewater
Techno-economic assessment
Environmental implications

ABSTRACT

This review explores the potential and challenges of synergetic approaches, such as coupling, hybrid, and sequential methods, to enhance phosphorus recovery while minimizing environmental impacts. It emphasizes phosphorus recovery's economic and ecological dimensions, stressing the imperative for ongoing research and development to bolster economic viability and scalability. This review also discusses factors for improvement and outlines the exploration of innovative technologies and comprehensive techno-economic assessments to bridge the gap between advancements and real-world implementation. Its highlights include global efforts for phosphorus recovery, the need for synergetic approaches, an understanding of the difference between efficiency and performance approaches, required innovation in the future, and the environmental and economic implications.

1. Introduction

Phosphorus (P), an essential nutrient for the sustainability of life, plays a critical role in various biological and environmental processes. Its unique properties and extensive application make it the most important non-renewable resource (Carrillo et al., 2020). Phosphorus naturally occurs in phosphate rocks or phosphorite deposits, which are distributed differently worldwide. The European Commission classifies phosphate rock as a critical raw material (Blengini et al., 2017).

Nations without P deposits heavily rely on imports, leaving them susceptible to market fluctuations in fertilizer and mineral P prices (Cordell et al., 2015). Over the years, the importance of P has increased due to the depletion of mineral reserves, and globally, approximately 95 % of the extracted P is primarily utilized in agriculture (Mekonnen and Hoekstra, 2018; Walsh et al., 2023).

An approach to minimizing dependency involves extracting P from readily accessible but often overlooked domestic sources, such as wastewater (Schoumans et al., 2015). National P budgets in Central Europe indicate that wastewater harbors a P load that could theoretically substitute for 40 %–50 % of the mineral P fertilizer annually applied in agriculture (Egle et al., 2016; Muntwyler et al., 2024; Stamm et al., 2022). It is estimated that around 359.4 × 10^9 m^3 of municipal wastewater is produced yearly, implying a potential of over 3.6 million metric tons of P that could be recovered from this source (Snyder and Morales-Guio, 2024). To close the nutrient cycle, phosphate must be reclaimed from these wastewater sources by upgrading existing wastewater facilities and implementing innovative, modular phosphate recovery technologies for urban and rural pollution sources, including agricultural areas. Alternatively, treated wastewater can be reused directly in agriculture through fertigation, potentially bypassing complex recovery processes. However, this approach presents challenges, including possible contamination with pathogens or heavy metals, nutrient imbalances, soil salinity issues, and the need for careful regulation and public acceptance (Mainardis et al., 2022).

Various single-method recovery techniques have been explored and broadly categorized into four main groups: biological, chemical, physical, and electrochemical. Indeed, biological methods offer a promising approach for P recovery from wastewater, using microorganisms and

---

* Corresponding author.
E-mail address: malgorzata.szlachta@tuni.fi (M. Szlachta).

https://doi.org/10.1016/j.jenvman.2025.125786
Received 22 January 2025; Received in revised form 27 April 2025; Accepted 10 May 2025

plants to capture and recycle P. Enhanced biological P removal systems utilize phosphate-accumulating organisms to store and remove P (Yuan et al., 2012). However, to close the phosphorus loop, the P stored in the biomass must be further processed and recovered in a readily reusable form. This typically requires coupling enhanced biological phosphorus removal (EBPR) with downstream recovery techniques, such as chemical precipitation or side-stream recovery processes (Daneshgar et al., 2022; Tomei et al., 2020). Algal pond systems recover phosphorus by incorporating it into algal biomass during growth, which can then be harvested and processed for reuse (Peng et al., 2018). Researchers also explore various bio-origin materials and organisms, such as agricultural by-products and microbial-derived nanoparticles, for efficient P recovery (Günther et al., 2018; Vučić and Müller, 2021; Witek-Krowiak et al., 2022).

Chemical techniques, most commonly chemical precipitation, are the most widespread form of phosphate recovery due to their reliable performance at the plant scale (Chrispim et al., 2019; Deng and Dhar, 2023). Multiple different forms of chemical phosphate recovery exist, including chemical precipitation, struvite precipitation, crystallization, wet-chemical processes, and thermochemical processes (Enyemadze et al., 2021; Jaffer et al., 2002; Krishnamoorthy et al., 2021; Lei et al., 2018; Li et al., 2022; Nadagouda et al., 2024; Ye et al., 2017; Zheng et al., 2022; Zhi et al., 2024). Phosphate recovery through chemical processes from wastewater and sewage sludge is prevalent, being extensively implemented on a large scale with encouraging outcomes attributed to the chemical method's high reliability and stability (Lei et al., 2018; Yi and Lo, 2003).

Moreover, researchers are extensively exploring physical treatment methods such as filtration (Bashar et al., 2018), membrane technologies (Zheng et al., 2022), and adsorption (Bacelo et al., 2020). Adsorption involves capturing phosphorus molecules onto solid adsorbent materials, providing high removal efficiency and rapid kinetics (Oliveira et al., 2015; Wang et al., 2024).

There has been growing interest in electrochemical phosphate recovery methods due to their potential to address the alkali dosing issue associated with chemical phosphate recovery techniques (Du et al., 2023a). Electrochemical phosphate recovery also offers a promising solution to the limitations of other conventional methods (Liu et al., 2021). Utilizing water electrolysis to induce the required high pH for phosphate precipitation eliminates the need for costly alkali dosing (Witek-Krowiak et al., 2022). Although current energy costs are significant, affordable renewable energy could potentially render these processes economically viable and environmentally sustainable (Neset and Cordell, 2012). Moreover, modular electrochemical units can be seamlessly integrated into existing large wastewater treatment plants or employed in decentralized networks for on-site phosphate recovery from wastewater (Cid et al., 2018).

While each technique offers specific advantages, they also present notable limitations when applied individually. Biological systems, for instance, necessitate stringent conditions and are operationally complex due to the involvement of microbial adaptation (Aida et al., 2016; Vučić et al., 2024; Yang et al., 2017; Yuan et al., 2012). These plants effectively recycle nutrients, such as P, into valuable biomass, which can be utilized for various applications such as animal feed, fuel, and fertilizer production (Molitor et al., 2024; Roy, 2017). Moreover, while biological approaches can effectively reduce eutrophication by removing phosphorus from water, they typically accumulate it in biomass rather than recovering it as reusable phosphate salts. This leads to the generation of substantial secondary waste, such as sludge, which requires further treatment or disposal (Kappel et al., 2013). Due to these drawbacks, biological phosphate recovery has been underutilized, with chemical techniques being favored instead. Chemical phosphate recovery techniques, particularly precipitation, are favored for their reliability and large-scale feasibility. Nevertheless, they are not without drawbacks. These methods often require substantial alkali dosing to adjust pH. However, the cost contribution can vary significantly depending on the targeted precipitate and buffering conditions, contributing up to 97 % of total operating costs in some cases (Daneshgar et al., 2019; Jeon and Yeom, 2009; Lei et al., 2017), and producing significant volumes of waste sludge (Yesigat et al., 2022).

Physical methods such as filtration and membrane technologies have also gained traction. Filtration using various media is effective but often suffers from low removal efficiency and frequent maintenance demands (Bashar et al., 2018; Kholoma et al., 2016; Kõiv et al., 2010; Vohla et al., 2011). Similarly, membrane technologies offer high phosphorus removal rates but are limited by membrane fouling and high operational costs (Leo et al., 2011; Robles et al., 2020; Xie et al., 2016; Zheng et al., 2022). While efficient and rapid, adsorption also faces challenges related to adsorbent saturation and regeneration requirements, limiting its long-term sustainability (Hussain et al., 2011; Li et al., 2013; Wang et al., 2024; Z. Zhang et al., 2021).

Electrochemical methods have emerged as a promising alternative by eliminating the need for chemical dosing through water electrolysis to induce high pH. However, the high energy demand associated with these systems remains a significant barrier to scale-up and widespread implementation (Witek-Krowiak et al., 2022).

Collectively, limitations, such as high operational costs, generation of secondary waste, and technical complexities, constrain the scalability, economic feasibility, and environmental sustainability of single-method phosphorus recovery strategies. Consequently, synergistic approaches have gained attention as a promising pathway to overcome these challenges and improve overall recovery efficiency. These approaches combine two or more complementary recovery methods to improve efficiency, reduce resource consumption, and achieve better sustainability compared to using a single process. By integrating different techniques, synergistic strategies can lower costs, enhance phosphorus removal and recovery, and reduce environmental impact (Ambat et al., 2019; Ardiyanti et al., 2024). This combined approach not only improves P recovery outcomes but also supports broader sustainability goals related to resource conservation and environmental protection (Neset and Cordell, 2012).

This review offers a novel and critical examination of synergistic approaches to P recovery from aqueous wastewater streams. It stands out by critically addressing and comparing all synergistic processes in a single document, which has not been done before, as per the author's knowledge. By exploring existing knowledge and recent advancements, it aims to deepen the understanding of these innovative technologies and their potential applications in wastewater treatment. Additionally, the review delves into the economic and sustainability benefits of synergistic approaches, evaluating their feasibility for large-scale implementation. This approach provides valuable insights and guidance for future research and practical applications in the field.

2. Understanding phosphorus dynamics

2.1. Sources, characteristics, and environmental impacts

Phosphorus in wastewater mainly comes from point sources (e.g., sewage treatment plants) and non-point sources (e.g., agricultural runoff). Point sources are consistent and easier to manage, with human urine contributing significant nutrient loads (Renfrew et al., 2024; Yesigat et al., 2022). Non-point sources are variable and harder to control (Zhang, 2017). Phosphorus exists primarily as organic, condensed, and orthophosphates. Orthophosphates, common in fertilizers, can runoff into water bodies, contributing to eutrophication—harmful algal blooms and oxygen-depleted zones (Karunanithi et al., 2015; Nolan and Stoner, 2000). pH affects P solubility, influencing its bioavailability and removal during treatment. Condensed phosphates, which include salts and metals like calcium and potassium, have distinct structures (Lei et al., 2018). Despite control efforts, legacy P in sediments remains a challenge. The EU's goal to reduce fertilizer use by 20 % by 2030 underscores the need for improved data, regulations, and treatment technologies to manage P pollution and protect aquatic ecosystems (European Commission, 2020, 2023; Walsh et al., 2023).

2.2. Global efforts and the regulatory framework for phosphorus recovery from wastewater

In recent years, there has been an increased global effort to address P recovery in wastewater treatment plants. The number of large-scale P recovery facilities has significantly increased, with Europe leading in this regard, having 50 units compared to the rest of the world's 29 units in 2018 (Carrillo et al., 2024). Over the past two decades, Germany and the Netherlands have notably emerged as major participants in implementing P treatment and recovery programs. Following suit are the United States and Canada, both with 15 units. Asia, led by Japan, has also progressed, with 13 plants installed. Additionally, Australia has invested in P recovery with its facilities. This trend highlights a common recognition of the necessity for P control in protecting water resources (Carrillo et al., 2024). Council Directive 86/278/EEC and the Waste Framework Directive specify standards for P usage in agriculture and waste management. Germany and the Netherlands have stringent rules that require municipal wastewater treatment plants to recycle P from sewage sludge (Krishnamoorthy et al., 2021). Switzerland, Denmark, and Austria prioritize sustainable waste management, with explicit targets for P recovery. Japan leads in research and large-scale operations in Asia, while initiatives are emerging in other countries such as China. These activities demonstrate a global trend toward sustainable P management, which is critical for environmental protection and resource conservation (Carrillo et al., 2024). In addition to individual countries, the European Union has established a regulatory framework comprising a set of directives and policies to address P pollution. This comprehensive framework safeguards water quality and fosters sustainable development across Europe (Garske et al., 2020). Key European directives such as the Water Framework Directive and the Urban Wastewater Treatment Directive set targets for P levels in surface waters and require wastewater treatment to mitigate pollution. Sustainability concerns of the European Union have driven efforts towards resource efficiency, circular economy principles, and climate resilience. Initiatives such as the Circular Economy Action Plan and the European Green Deal prioritize transitioning to circular economy models, promoting P recycling to minimize environmental impact and reduce reliance on finite resources (European Commission, 2020). Through collaboration and innovation, Europe aims for environmentally sound and economically viable P management practices to ensure the health and sustainability of its water bodies and ecosystems. The report on the current status of Nutrient Recovery Technologies (as of 19/10/22) across European Union Member States highlights the progress in recovering phosphorus (P) and nitrogen (N) from wastewater and other bio-based input streams. It emphasizes new additions to the publicly accessible technologies for nutrient recovery (ESPP, 2019). Tracking industries engaged in material and resource recovery from waste and wastewater at national and regional levels, particularly those registered in the Industrial Reporting Database, helps map the status of these technologies in the EU. Notable projects and full-scale plants include ICL's operations in the Netherlands and Germany, which began in March 2019, recovering P from sewage sludge and incineration ash (WalnutPlatform EU, 2022). The PAKU plant in Rovaniemi, Finland, has been operating since early 2021, focusing on sludge incineration with nutrient recovery (ESPP, 2019). PHOS4Green, located in Haldensleben, Germany, launched its full-scale plant in June 2021, using sewage sludge incineration ash to create phosphate-based fertilizers (ESPP, 2019). Renewable Nutrients' QuickWash process, used for recovering phosphorus from various waste streams, has been piloted in several locations with plans for large-scale installations in the UK and USA. Other key initiatives include the TetraPhos plant in Hamburg, Germany, the AshDec pilot plant in Leoben, Austria, and CarboREM's industrial-scale continuous plant in Mezzocorona, Italy. These projects highlight the dynamic and growing landscape of nutrient recovery technologies worldwide, as summarized in Table 1.

3. Synergetic approaches to phosphorus recovery

Synergetic approaches in wastewater treatment and P recovery combine various methods or technologies to maximize efficiency and reduce environmental impact. This approach involves integrating biological processes with chemical or physical treatments as well as incorporating advanced technologies or innovative solutions, enhancing P removal rates, improving water quality, and reducing the environmental impact of wastewater discharge (Xing et al., 2022). By considering interactions and synergies, synergetic strategies optimize performance and sustainability. This section explores the concept of synergetic approaches and discusses various strategies employed, including coupling methods, sequential integration, and hybrid systems.

3.1. Coupling methods

Coupling methods integrate complementary treatment processes to address the limitations of standalone systems, such as low selectivity, incomplete recovery, or high energy/chemical demands. By synergizing technologies (e.g., electrochemical precipitation with filtration or biological removal with crystallization), these methods enhance efficiency, reduce costs, and enable targeted resource recovery. Below are detailed key coupling protocols, emphasizing their design motivations, challenges addressed, and process synergies.

3.1.1. Electrochemical coupling approaches

Phosphorus recovery via chemical precipitation often relies on external pH adjusters (e.g., alkali/acid), increasing operational costs and sludge production. Electrochemical coupling minimizes reagent use while improving selectivity and energy efficiency. Electrochemical systems generate localized pH changes via water electrolysis, enabling in-situ precipitation of phosphate salts (e.g., struvite, Ca-P). Coupling with filtration (e.g., microfiltration) captures precipitates efficiently, avoiding redissolution. Du et al. (2023b) investigated electrochemical coupling approaches for P recovery as struvite. The applied voltage eliminated the need for external alkalis, reducing sludge by 30 % and improving energy efficiency by 25 % compared to the chemical precipitation method. It was shown that electrochemical coupling can enhance the recovery efficiency, energy efficiency, and P recovery compared to chemical precipitation methods. A recent investigation developed an undivided electrolytic cell combined with a microfiltration system for P recovery, utilizing the electrolytic unit to create an alkaline environment for calcium phosphate precipitation and the microfilter to capture precipitates (J. Chen et al., 2024). The cell's anode extracted H^+ ions, creating an alkaline cathode environment for Ca-P precipitation, while the microfilter retained crystals and achieved a P recovery efficiency of 81 %, with a recovery rate of 18.3 g P $(m^2\ h)^{-1}$ and energy consumption of 8.75 kWh $(kg\ P)^{-1}$. Overall, this study offers a promising electrochemical design for mitigating P shortages and reducing P concentrations in wastewater. Zhang et al. (2024) investigated an electrochemical system to recover P as iron(III) phosphate ($FePO_4$) from hypophosphite-laden wastewater, as illustrated in Fig. 1, which commonly contains chloride ions (Cl^-). The system achieved a hypophosphite removal ratio of approximately 100 % and completed P recovery within 30 min at 5.0 V and an initial solution pH of 3.0. With a maximum Faradaic efficiency of ~94 % and a minimum energy consumption of ~16 kWh/kg P, the system improves phosphorus selectivity in chloride-rich wastewater, where standalone methods struggle due to interference from Cl^- ions. It also enables simultaneous treatment and recovery by oxidizing hypophosphite to phosphate and precipitating it as $FePO_4$ in one process. This synergy overcomes the inefficiencies of single-method approaches, making it a more effective solution for treating Cl^--rich wastewater.

Table 1
Global efforts in phosphorus recovery.

Region/ country	Estimated number of large-scale units	Key technologies used	Estimated P recovery	Key initiatives/features	Regulatory frameworks	Notable projects/ technologies
Germany	>10	Struvite, AshDec, RecoPhos, TetraPhos	~6000–10,000 t P/year	Leading in regulatory-driven P recovery	National P recycling mandate (2017 Sewage Sludge Ordinance)	PHOS4Green, ICL, TetraPhos
Netherlands	>5	Struvite crystallization, manure treatment	~2000 t P/year	Early technology adopter, manure-rich agriculture	National legislation on nutrient reuse	ICL Amsterdam, NuReSys
Switzerland	3–5	AshDec, Slag-based recovery	~1000 t P/year	Sustainable sludge treatment, aligned with EU directives	National P recovery law (2016)	ZAB plant (Zürich), VUNA
Austria, Denmark	2–4	AshDec, struvite, P-RoC	~1000–1500 t P/year	Recycling from mono-incineration ashes	National goals aligned with EU circular economy	AshDec (Austria), Biofos (DK)
Finland	1	Ash treatment, mono-incineration	~200–400 t P/year	Focus on sludge-to-energy with nutrient recovery	National nutrient strategy	PAKU plant (Rovaniemi)
Italy	1	CarboREM (thermochemical recovery)	Pilot scale	Industrial-scale continuous processing	Local-level initiatives	CarboREM (Mezzocorona)
United States	~15	Quick Wash, Crystalactor, NuReSys, Ostara	~5000–6000 t P/year (est.)	Expanding in wastewater utilities and agriculture	Varies by state	Ostara (Chicago, Portland), QuickWash
Canada	~5–10	Ostara, research pilot plants	~500–1000 t P/year (est.)	Collaborative efforts with the U.S and academia	Local policies	EPCOR (Edmonton), UBC Projects
Japan	~13	Thermal recovery, MAP precipitation	~5000–7000 t P/year	Advanced technology implementation and R&D investment	Municipal guidelines	Multiple regional plants
China	Emerging (~5+)	Pilot studies: struvite, biochar, precipitation	Pilot scale	National policies driving pilot-scale demonstration	Nutrient recycling in rural revitalization plans	Nanjing University pilot programs
Australia	3–5	Adsorption, struvite, fertigation	Small scale	Interest in circular economy and water reuse	National sustainability roadmap	Western water projects
European Union (Total)	~50	Wide range: struvite, AshDec, RecoPhos, NuReSys	>20,000 t P/year (est.)	Driving force in the global P sustainability agenda	Circular Economy Action Plan, EU Green Deal	ESPP database, Horizon EU projects

Information in the table retrieved from: ESPP, 2019; WalnutPlatform EU, 2022; European Commission (2020).

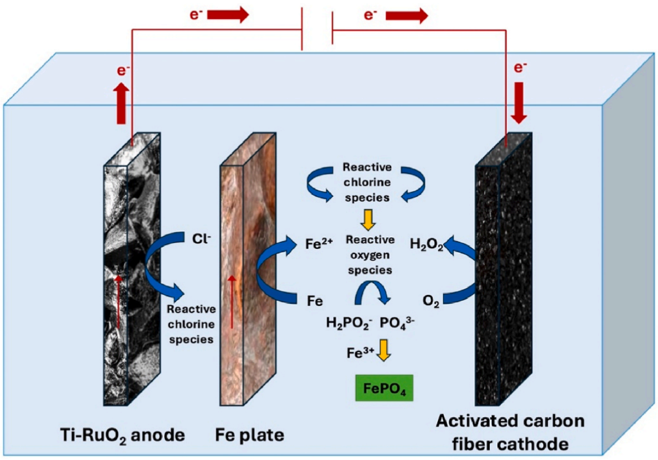

Fig. 1. Schematic diagram of electrochemical treatment of hypophosphite and simultaneous recovery of P via field-induced electro-Fenton coupled with an anodic oxidation system; adapted from (Zhang et al., 2024).

3.1.2. Biological coupling approaches

Biological P removal (e.g., EBPR) often struggles with low recovery rates, as P remains trapped in biomass. Coupling with crystallization enables direct P extraction from wastewater. Biological coupling systems (e.g., PAOs—polyphosphate-accumulating organisms) concentrate P intracellularly, while in-situ crystallization (e.g., hydroxyapatite) immobilizes dissolved P into recoverable minerals. Xin et al. (2024) explored induced crystallization (IC) coupled biological P removal (IC-BPR) for simultaneous P removal and recovery from wastewater. Optimal conditions were determined by varying the side stream ratio (SSR), with an SSR of 40 % yielding the highest efficiencies. At this ratio, P removal efficiency reached 94 %, with 75 % attributed to IC, and total P recovery efficiency was 67 %. These findings highlight the efficacy of IC in enhancing P removal and recovery, providing valuable insights for wastewater treatment with P resource recovery technologies. Zou and Wang (2016) investigated the combination of enhanced biological P removal with crystallization recovery of P to assess its feasibility in nutrient removal and P recovery from domestic wastewater. The results demonstrated high nutrient removal performance, with average COD, PO_4^{3-}, and NO^{3-} removal efficiencies of 83 %, 88 %, and 92 %, respectively. Additionally, 60 % of P was recovered as hydroxyapatite. Furthermore, the incorporation of a P recovery column significantly enhanced the biological P removal efficiency, leading to a notable decrease in the effluent P concentration. This study presented a promising alternative for P removal and recovery from wastewater, with potential benefits for environmental sustainability. Liao et al. (2024) investigated the efficacy of enhanced biological P removal coupled with in-situ fermentation (EBPR-F) for improving P removal from digested swine wastewater. By using fermentable substrates as external carbon sources to promote in-situ fermentation, P removal was enhanced compared to conventional enhanced biological P removal (EBPR) dominated by *Candidatus Accumulibacter*. EBPR-F exhibited over 95 % total P removal, with concentrations in the effluent consistently below 1.0 mg L^{-1}, meeting discharge standards. Enrichment of polyphosphate-accumulating organisms such as Tetrasphaera through enhanced in-situ fermentation contributed to the improved P removal efficiency of EBPR-F.

3.1.3. Other coupling approaches

Single-stage systems often fail to simultaneously remove N and P efficiently. Coupling processes combine physicochemical P recovery with autotrophic N removal (e.g., anammox). Hydroxyapatite (HAP) precipitation coexists with anaerobic ammonium oxidation (anammox), enabling synergistic N-P removal without competing carbon demands.

Guo et al. (2024) evaluated a one-stage hydroxyapatite-based partial nitritation/anaerobic ammonium oxidation (anammox) process (HAP-PNA) to treat the nutrient-rich permeate from a high-solid anaerobic membrane bioreactor (AnMBR). The HAP-PNA process combined hydroxyapatite precipitation to remove P with nitritation and anammox bacteria to remove nitrogen in a single stage. The process achieved 82 % nitrogen removal and up to 73 % P removal from the AnMBR permeate. C. Zhang et al. (2021) proposed a process that involves preconcentrating P using flow-electrode capacitive deionization (FCDI) and immobilizing it as vivianite crystals in a fluidized bed crystallization (FBC) column. Optimal operational parameters were identified through experimentation, achieving a remarkable 63 % P removal and concentration in the FCDI device with reasonable energy consumption. Subsequent immobilization in the FBC system resulted in the formation of high-purity vivianite crystals, with approximately 80 % of P successfully converted. Chen and coworkers introduced an innovative approach for P removal and recovery from wastewater using undivided electrolytic cells (F. Chen et al., 2024). These cells feature H^+ or OH^- extraction from corresponding electrode surfaces, enabling efficient P recovery. Operating under specific conditions, the system achieved a high 81 % P recovery efficiency with an alkaline effluent pH of 10.5. The calculated P recovery rate, treatment capacity, and energy consumption surpassed those of cutting-edge divided electrolytic systems and conventional undivided electrolytic systems. Overall, this established undivided electrolytic cell coupled with microfiltration offers promising prospects for P recovery from wastewater without the need for acid-base reagents.

Coupling different treatment processes for P recovery from wastewater offers several advantages. This approach leverages synergistic effects, where multiple treatment techniques complement each other, resulting in better overall performance and selectivity. Moreover, coupling methods provide flexibility in wastewater treatment design, allowing tailored solutions to meet specific treatment objectives and accommodate varying wastewater compositions. Additionally, coupling methods enable resource recovery, such as energy, nutrients, and water, contributing to resource sustainability (Sengupta et al., 2015). However, there are also disadvantages to consider. Coupling methods can increase the complexity of wastewater treatment systems, requiring sophisticated design, operation, and maintenance (Bunce et al., 2018). Furthermore, they may incur higher capital and operational costs compared to single-process treatment systems, particularly for advanced technologies. Additionally, the need for additional space and operational challenges in coordinating and optimizing multiple treatment components can be significant drawbacks. Challenges remain in addressing limitations in recovery rates and energy consumption, but these technologies hold promise for sustainable nutrient recovery as part of the circular economy (Du et al., 2023b). Continued development aims to enable their implementation in real wastewater streams, with specific techniques such as calcium-to-P ratio optimization and hydroxyapatite formation showing potential for improving nutrient removal efficiency.

3.2. Sequential methods

Sequential methods involve the sequential application of different treatment steps or processes, where wastewater undergoes treatment in a step-by-step manner, moving from one treatment stage to the next. Sequential methods typically involve a predetermined treatment sequence, with each step addressing specific pollutants or treatment objectives. Lou et al. (2024) investigated the efficient recovery and valorization of multiple anions from phosphogypsum (PG) leachate by employing stepwise precipitation, electrodialysis, and crystallization methods, as illustrated in Fig. 2. This demonstrated high recovery rates for fluoride, phosphate, and sulfate anions, ensuring effluent compliance with discharge standards. Fluoride and phosphate anions are precipitated as calcium fluoride and magnesium ammonium phosphate, respectively, while sulfate anions are recovered through electrodialysis and crystallization. Additionally, the concentrated sulfate-rich solution is utilized for the electrochemical production of persulfate, further enhancing the environmental and economic benefits of the integrated approach. Vasenko et al. (2020) present a novel two-step sequential approach for P recovery from municipal wastewater. It involves two distinct steps: first, ozonation is applied to degrade natural organic matter in the digester supernatant, which enhances the subsequent crystallization step where calcium phosphates are recovered. Throughout the investigation, low-crystallinity hydroxyapatite/amorphous calcium phosphate products were consistently formed, demonstrating the feasibility of this approach for high-purity P recovery from digester supernatants.

There is very limited research on sequential methods for P recovery, which reflects several challenges inherent in the complexity and integration of such approaches. Sequential methods involve a series of interconnected processes, each with its own set of challenges and limitations, requiring careful coordination and optimization. Researchers are prioritizing simpler single-step technologies over sequential methods due to their perceived complexity (Sartorius et al., 2012). Additionally, the lack of well-documented case studies demonstrating the effectiveness of sequential methods may contribute to a reluctance among researchers to invest time and resources in exploring this approach further. Despite these challenges, there is recognition of the potential benefits of sequential methods for improving P recovery efficiency, highlighting the need for further research and innovation in this area to address the growing demand for sustainable P management solutions.

3.3. Hybrid methods

Hybrid methods combine different treatment processes within a single treatment unit to achieve synergistic effects and maximize P removal and recovery efficiencies. In the context of P recovery, hybrid methods combine different approaches such as chemical precipitation, membrane filtration, ion exchange, biological treatment, and/or

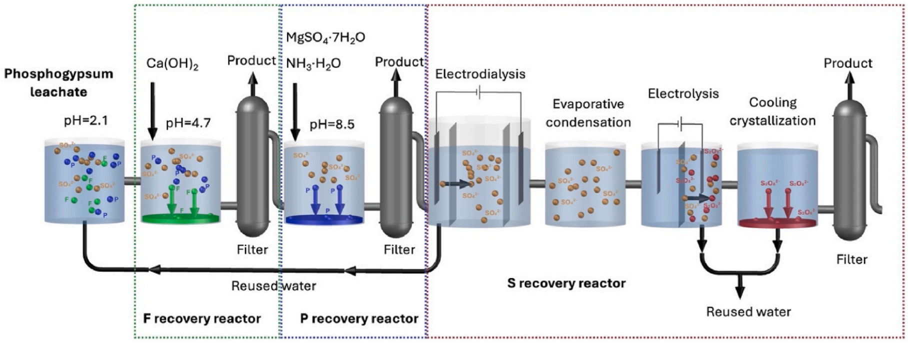

Fig. 2. Concept of closed-loop recovery and valorization of multiple anions from phosphogypsum leachate; adopted from (Lou et al., 2024).

technologies such as electrochemical systems or nanotechnology. These integrated approaches leverage the strengths of each method to enhance overall efficiency, effectiveness, and sustainability in P extraction and recovery from various sources such as wastewater, agricultural runoff, or industrial effluents.

3.3.1. *Electrodialysis-based hybrid method*

Zhang et al. (2013) proposed an innovative hybrid system incorporating an ED process and a struvite reactor for phosphate recovery. Their research showcased the efficiency of dosing the P-rich effluent from the ED process into the struvite reactor, achieving a high recovery rate of 93 % for phosphate. Furthermore, Shi et al. (2018) developed a lab-scale bipolar membrane electrodialysis system for nutrient recovery. Their findings revealed that the bipolar membrane electrodialysis system could recover 78 % of ammonium and 75 % of phosphate ions, attributing its success to the reduction of nutrient loss and enhancement of nutrient enrichment. Li et al. (2024) demonstrated the successful integration of bipolar membrane electrodialysis (BMED) and resin adsorption (RA) techniques for treating triethylammonium phosphate wastewater, as illustrated in Fig. 3. The hybrid BMED and RA process achieved high recovery rates for triethylammonium phosphate wastewater and phosphoric acid, exceeding 99 % and 96 %, respectively, while also minimizing waste generation and environmental impacts. These studies collectively underscore the potential of ED-based hybrid approaches in nutrient recovery.

3.3.2. *Bio-electro-chemical hybrid system*

Microbial fuel cells (MFCs) and microbial electrolysis cells (MECs) are extensively researched bio-electro-chemical hybrid systems (BESs), with MFCs showing significant potential for advancing nutrient recovery by generating electricity and creating high pH conditions conducive to chemical precipitation (Yaqoob et al., 2021). In MFCs, microorganisms anaerobically oxidize organic substances in an anode chamber, generating electrons that are released to the anode concurrently with the production of protons and biogas (Logan et al., 2006). These electrons flow through an external circuit to the cathode, where they facilitate electricity generation. Simultaneously, protons migrate across a cation-exchange membrane from the anolyte to the catholyte while biogas is collected. Transitioning to MECs involves applying an external voltage (>0.25 V), wherein the cathode reaction diverges, allowing for hydrogen production (Wang and Ren, 2013).

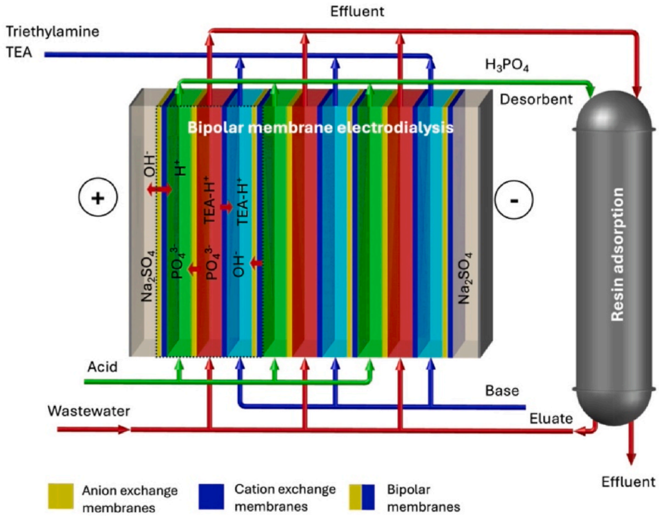

Fig. 3. Schematic illustration of the BMED and RA hybrid system (TEA: triethylamine; BPM: bipolar membranes; AEM: anion exchange membranes; CEM: cation exchange membranes; BMED: bipolar membrane electrodialysis; RA: resin adsorption); adopted from (Li et al., 2024).

However, while MFCs are not capable of concentrating phosphorus (P) on their own, integrating them with membrane systems such as forward osmosis (FO), membrane distillation (MD), and electrodialysis (ED) can enhance nutrient recovery from wastewater. This integration promises to improve the quality and quantity of recovered P, highlighting a promising direction for future development (Al-Juboori et al., 2024).

3.3.3. *Hybrid membrane bioreactor technology*

The integration of membrane bioreactor (MBR) technology into hybrid systems offers a promising approach for organics removal and subsequent nutrient recovery, minimizing the membrane fouling potential and enhancing overall efficiency (Huang et al., 2015).

One such advancement is the osmotic membrane bioreactor (OMBR). Qiu and Ting (2014) demonstrated the efficacy of an OMBR-based hybrid system in direct nutrient recovery from municipal wastewater, achieving over 90 % nutrient recovery via struvite precipitation. Further enhancements to the OMBR hybrid system include incorporating membranes for phosphate recovery (Qiu et al., 2015). This addition enables the extraction of phosphate and mineral salts rejected by the membrane, leading to efficient phosphate recovery through calcium phosphate precipitates without the need for added Ca^{2+} ions. Additionally, the introduction of fixed bed biofilms into OMBR hybrid systems offers alternative approaches to nutrient recovery, reducing energy consumption and the membrane fouling potential (Luo et al., 2016; Yan et al., 2018). The integration of microbial electrochemical units into anaerobic OMBRs, as demonstrated by (Hou et al., 2017), further enhances nutrient recovery efficiency while maintaining high organic removal rates. Hence, further investigation into P recovery via anaerobic osmotic membrane bioreactor-based hybrid systems is warranted in future studies. However, the significance of feed solutions in osmotic membrane bioreactor systems has been inadequately addressed in the existing literature, underscoring the need for future research to comprehensively explore this aspect.

3.3.4. *Other hybrid methods*

Hybrid ion exchange nanotechnology for P removal and recovery holds significant promise for advancing wastewater treatment. Ownby et al. (2021) demonstrated the potential of hybrid ion exchange nanotechnology by characterizing resin, adsorption, and desorption behaviors. Among the regeneration chemistries evaluated, those utilizing recovered NH_4OH and tap water showed promise for efficient P recovery, offering sustainable and cost-effective solutions. However, further research is needed to explore their economic feasibility in real-world settings and optimize operational parameters for maximum efficiency.

The broader concept of hybrid approaches, which combine multiple technologies or methodologies, enhances performance through synergistic interactions, improved resource efficiency, and resilience to varying conditions (Zheng et al., 2022). Despite their advantages, hybrid systems face challenges, including design complexity, higher upfront capital, and operational costs, difficulties in scaling up from laboratory to commercial scales, and integration issues arising from the need to coordinate disparate technologies and ensure compatibility between components and scaling difficulties (Egle et al., 2016). Overcoming these hurdles requires interdisciplinary collaboration and innovation to unlock their full potential.

Fig. 4 compares eight synergetic approaches for P recovery across four metrics: phosphorus recovery efficiency, energy efficiency, selectivity, and cost, all scored out of 100. It focuses on performance for sustainability and efficiency, emphasizing how effectively phosphorus can be recovered while considering energy use, selectivity for targeting phosphorus, and economic factors. A detailed discussion of these trends, including the implications for practical applications and the specific advantages of coupling methods in various waste streams, is provided in the next section.

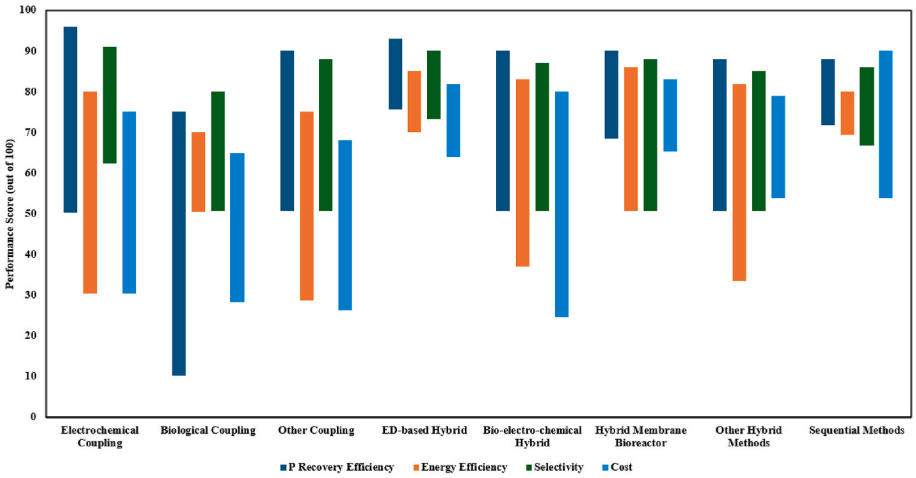

Fig. 4. Comparative performance analysis of phosphorus recovery methods.

4. Performance evaluation, efficiency metrics, and selectivity of synergetic approaches

In P recovery processes, the concepts of performance and efficiency play an important role in evaluating their effectiveness and sustainability. Performance metrics provide information about a method's ability to meet its intended goals, focusing on selective P removal rates and compliance with regulatory standards. A high-performing P recovery process demonstrates robustness in achieving desired outcomes while effectively treating wastewater streams. Conversely, efficiency measures the economic utilization of resources in the recovery process, encompassing factors such as energy consumption, chemicals usage, and overall operational costs. An efficient P recovery process optimizes resource utilization, minimizing input requirements while maximizing P recovery output. Striking a balance between performance and efficiency is essential for developing cost-effective and environmentally sustainable P recovery solutions. A detailed comparison between synergistic approaches and single methods is crucial to assess their relative strengths, limitations, and applicability in phosphorus recovery (Table S1). Single methods focus on either dissolved or particulate

Table 2
Overview of synergistic methods employed in various processes to recover phosphorus from wastewater.

Process	Phosphorus recovery	Feed stream	Product	References
Hybrid methods				
Hybrid system incorporating an ED process and a struvite reactor	93 %	Syntetic wastwater	Struvite	Zhang et al. (2013)
Bipolar membrane electrodialysis system	75 % 77 %	Synthetic wastwater Real wastwater	NH_4^+, PO_4^{3-} and volatile fatty acids	Shi et al. (2018)
Bipolar membrane electrodialysis coupled resin adsorption techniques	96 %	Real wastewater	Triethylamine and phosphoric acid	Li et al. (2024)
Hybrid anion exchange resin	>90 %	Real wastwater	Struvite	O'Neal and Boyer (2013)
Hybrid microfiltration-forward osmosis membrane bioreactor process	>90 %	Real wastwater	phosphate phosphorus (PO_4^{3-}-P)	Qiu et al. (2015)
Coupled methods				
Flow-electrode capacitive deionization coupled with a fluidized bed crystallization column	80 %	Synthetic wastwater	Vivianite	(C. Zhang et al., 2021)
Undivided electrolytic cell combined with a microfiltration system	90 % 65 %	Synthetic wastewater Real wastwater	Calcium phosphate	(J. Chen et al., 2024)
Field-induced electro-Fenton coupled with an anodic oxidation electrochemical system	100 %	Real wastewater	Iron(III) phosphate ($FePO_4$)	Zhang et al. (2024)
Induced crystallization coupled with biological P removal	67 %	Synthetic wastewater	Crystallized phosphorus	Xin et al. (2024)
Enhanced biological P removal combined with crystallization	59 %	Real wastewater	Hydroxyapatite	Zou and Wang (2016)
Enhanced biological P removal coupled with *in situ* fermentation	95 %	Real wastewater	polyphosphate	Liao et al. (2024)
One-stage hydroxyapatite-based partial nitritation/anammox	73 %	Real wastewater	Hydroxyapatite	Guo et al. (2024)
Sequential methods				
Stepwise precipitation, electrodialysis, and crystallization methods	>99 %	Real wastewater	Precipitates ($MgNH_4PO_4 \cdot H_2O$)	Lou et al. (2024)
A multi-stage precipitation approach	99 %	Real wastewater	$BaSO_4$, $CaHPO_4 \cdot 2H_2O$, and $Ca_5(PO_4)_3OH$	Zhou et al. (2023)
Ozonation and crystallization sequential process	73–86 %	Real wastewater	Low-crystallinity hydroxyapatite (HAp)/amorphous calcium phosphate (ACP)	Vasenko et al. (2020)

phosphorus, while synergistic approaches often achieve higher phosphorus recovery rates (>90 %) and produce high-value by-products. They also demonstrate better robustness to influent variability, meeting stricter discharge limits (<0.1 mg L^{-1}), and better handling of variable wastewater compositions. However, they come with trade-offs, including higher capital and operational costs, and require skilled operators for optimal performance. By systematically comparing these methods across key parameters like efficiency, cost, scalability, and environmental impact, researchers can identify the most practical and sustainable solutions tailored to different wastewater treatment scenarios.

A review of the literature on synergistic approaches for phosphorus recovery from wastewater (Table 2) highlights that selective P recovery is still relatively rare in research. However, there has been a notable shift in recent studies towards prioritizing coupling methods to achieve selective P recovery from wastewater. Field-induced electro-Fenton coupled with an anodic oxidation system and enhanced biological P removal coupled with *in situ* fermentation have shown promising results, with P recovery rates exceeding 90 % (Liao et al., 2024; Zhang et al., 2024). Coupling processes demonstrate high efficiency by integrating two or more treatment technologies with a major focus on selectivity. This approach optimizes operational parameters, reduces energy consumption, and enhances overall performance. By harnessing the complementary strengths of combined treatments, coupling methods offer improved efficiency and effectiveness in managing complex wastewater compositions. Moreover, by optimizing each technology's role within a contiguous system, coupling processes achieve higher selectivity and performance, making them a promising solution for effective and sustainable phosphorus recovery.

Hybrid methods prioritize the selective recovery of P, adapting to various wastewater compositions and treatment goals. Systems like electrodialysis (ED) combined with struvite reactors or bipolar membrane electrodialysis achieve P recovery rates of 75–96 % (Li et al., 2024). While their efficiency may not always surpass specialized methods, hybrid processes integrate diverse technologies, leveraging the strengths of each to enhance overall performance (Zheng et al., 2022).

These systems strike a balance between efficiency and selectivity, making them suitable for complex environmental challenges. Their adaptability allows for tailored solutions that meet a wide range of operational and environmental requirements.

However, challenges remain, including design complexity, high capital and operational costs, scaling difficulties, and integration issues when coordinating different technologies (Egle et al., 2016). Addressing these challenges demands interdisciplinary collaboration and innovative solutions to fully realize the potential of hybrid systems.

In contrast, sequential methods prioritize maximizing overall product recovery from wastewater through a sequential arrangement of multiple process units. While not specifically targeting single metal recovery like P, they contribute to P recovery as part of a broader strategy for resource utilization. Sequential methods such as stepwise precipitation, electrodialysis, and multi-stage precipitation have demonstrated high P recovery rates of nearly 100 % (Lou et al., 2024). Advancements suggest the potential for selective P recovery within these methods. Sequential processes employ a systematic treatment cascade, addressing diverse wastewater compositions and treatment objectives. This strategic design allows for optimization throughout the treatment cascade, balancing selectivity and holistic recovery. Although they may not achieve the peak efficiency of coupling methods, sequential methods' structured framework enables tailored treatment strategies adaptable to various wastewater complexities, leveraging synergistic interactions between stages to optimize overall performance.

Phosphorus recovery technologies vary in their maturity levels, as evaluated by technology readiness levels (TRLs). Struvite and chemical precipitation methods (TRLs 7–8) and enhanced biological phosphorus removal (EBPR) methods (TRLs 6–8) are among the most developed (Kaljunen et al., 2022; Murujew, 2019). Conversely, adsorption technologies and electrodialysis are at intermediate stages (TRLs 4–6), while phytoremediation and membrane bioreactors are still evolving (TRLs 4–7) (Al-Juboori et al., 2024; Scotti et al., 2021). Advancing these synergetic technologies requires addressing their scalability, cost-effectiveness, and selectivity, particularly for complex wastewater streams.

Comprehensive techno-economic assessments are essential to evaluate the feasibility of technologies, considering capital investment, operational costs, and environmental impacts. As these technologies progress along the TRL scale, they hold the potential to transform wastewater treatment into a more efficient, sustainable, and cost-effective process (Table S2).

Synergistic approaches to recovering P from wastewater represent a promising intersection of advanced technologies and sustainable practices. Emerging research directions emphasize optimizing the integration of biological, electrochemical, and membrane-based systems to enhance phosphorus recovery efficiency while reducing energy consumption and operational costs (Table 3). These synergistic approaches demand targeted research into system integration, process optimization, and material innovation to unlock their full potential for sustainable phosphorus recovery.

5. Economic and environmental considerations

The evaluation of methods for P recovery from wastewater, both economically and environmentally, is a relatively underexplored area. Despite the importance of P as a finite and essential resource, the focus on its recovery from wastewater streams has been limited. This lack of attention may stem from various factors, including technical complexities, regulatory frameworks, and market dynamics. Therefore, the commercialization of recovered P from wastewater treatment systems remains limited, resulting in a need for precise market values for these products. However, some estimated data are available, indicating varying market values for specific methods for P recovery (Table 4). The market value of P recovered from struvite's methods has been reported to be between US$245 and US$ 345 per ton. At the same time, calcium phosphate precipitates could potentially be utilized in the production of triple superphosphate or as a raw material for phosphate rock replacement, having a market value of approximately US $554 per ton. Despite these values, phosphate rock-based fertilizers in 2020 maintained a more favorable market price, ranging from approximately US$2.1 to US $3.7 per kg of P (Ye et al., 2020). However, research suggests that the production of struvite in recovery systems consumes significantly less energy compared to conventional phosphate fertilizers such as triple superphosphate, offering potential advantages in sustainability and production costs (Molinos-Senante et al., 2011). Nevertheless, the process typically requires the addition of magnesium, which can be a significant cost factor. Exploring alternative, low-cost sources of magnesium, such as seawater, bittern, or industrial by-products, may help enhance the overall economic viability of struvite recovery (Desmidt et al., 2015).

Nevertheless, in the synergetic approach, anaerobic digestion is essential in increasing soluble phosphate availability for struvite precipitation, which could generate revenue from struvite sales. For instance, a case study by Morrissey et al. (2022) estimated annual gross revenues from struvite fertilizer sales ranging from $163,627 to $295,438, based on a medium-sized wastewater treatment plant treating approximately 20,000 m^3/day, with phosphate capture rates of 45 % and 90 %, respectively. This corresponds to an estimated revenue of $0.02–$0.04 per m^3 of treated wastewater, highlighting the potential economic viability of struvite recovery under favorable conditions. Moreover, hydrogen capture offers additional annual revenues. Although there is potential for revenue generation, the income generated is inadequate to cover the rising capital and operational expenses. Break-even analysis indicates that struvite fertilizers would need to be sold at $6.0/kg to offset costs, while hydrogen compression and storage

Table 3
Possible synergistic approaches for phosphorus recovery and required key innovations for enhancing efficiency and commercial viability.

Synergistic approach	Processes components	Benefits	Challenges	Innovations needed for commercial viability	References
Electrochemical coupling	Electrochemical cell, microfiltration, ion-exchange systems	High recovery efficiency, reduced energy consumption, phosphate recovery from low-concentration wastewater	High initial costs, energy consumption, complex system design	Optimization of electrode materials, improved process scalability, development of energy-efficient electrochemical cells, and cost reduction of ion-exchange systems	(J. Chen et al., 2024; Du et al., 2023a, 2023b)
Biological coupling	Induced crystallization (IC), biological phosphorus removal (BPR)	High phosphorus removal and recovery efficiency, reduced sludge generation	Limited scalability, slow response time, operational complexity	Development of more energy-efficient electrocoagulation systems, cheaper adsorbents, and enhanced process control systems	(Dai et al., 2017; Li et al., 2023)
Bio-electro-chemical systems	Microbial fuel cells (MFC), microbial electrolysis cells (MEC)	Simultaneous phosphorus removal and energy generation, sustainable process, low operational cost	Low phosphorus concentration recovery, complexity in integration of bio-electrochemical systems	Enhancement of bio-electrochemical systems efficiency, improvement in microbial activity, development of hybrid systems for higher phosphorus recovery, scaling-up challenges	(El Messaoudi et al., 2024; Lei et al., 2019; Srivastava et al., 2022)
Hybrid membrane bioreactor	Membrane bioreactor (MBR), osmotic membranes, microbial systems	High efficiency in organics removal and nutrient recovery, reduces membrane fouling, improves nutrient recovery from effluents	Membrane fouling, complexity in process integration, high operational costs	Development of fouling-resistant membranes, optimization of microbial systems integration, reduction of operational and maintenance costs	(Carrillo et al., 2020; Cordell et al., 2011; Gourevitch et al., 2021; Prabhakar and Isloor, 2024)
Electrodialysis hybrid systems	Electrodialysis (ED), struvite precipitation reactor	Efficient phosphate and ammonium recovery, reduced nutrient loss, simultaneous phosphorus recovery and nutrient enrichment	High energy consumption, complexity of managing two technologies simultaneously	Development of energy-efficient ED systems, improved struvite precipitation efficiency, process optimization for energy consumption reduction, integration of dual systems for ease of operation	(Meng et al., 2024; Tran et al., 2024)
Ion-exchange nanotechnology	Ion-exchange resins, adsorption/desorption systems	High phosphorus recovery, low chemical requirements, sustainable regeneration and reuse of resins	Resin lifespan, slow desorption rates, cost of resin regeneration	Development of more durable resins, faster desorption rates, cost-effective resin regeneration methods, and enhancement of adsorption capacity through nanotechnology	(Foster et al., 2025; Ruiz-Cosgaya et al., 2024)
Electrochemical struvite recovery	Electrochemical reactors, struvite precipitation reactors	High recovery rates, low energy consumption, no need for external chemicals (such as magnesium) to form struvite	Requires precise control of pH and electrolyte conditions, high setup and operational costs	Development of more robust electrochemical reactors, improved pH and electrolyte control, reduction in setup and operational costs, scalability of systems	Carrillo et al. (2020)
Membrane distillation hybrid system	Membrane distillation (MD), struvite precipitation, reverse osmosis (RO)	Effective phosphorus recovery from brine and wastewater, low energy consumption compared to traditional distillation processes, integration with other treatment systems	Scaling up the MD process, fouling of membranes, and operational instability during extended use	Development of more durable MD membranes, optimization of membrane fouling control, improving scalability, and improving process stability for long-term operation	(Afsari et al., 2024; Liu et al., 2024)
Integrated RO and chemical precipitation	RO, chemical precipitation (e.g., calcium phosphate)	High phosphorus removal efficiency, reduces the chemical consumption, recovery of valuable byproducts (e.g., calcium phosphate)	High energy consumption, large space requirement, and high operational costs	Development of low-energy RO membranes, optimization of chemical precipitation, reduction of space and operational requirements, and cost-effective scaling	Li et al. (2021)
Thermophilic biological Phosphorus removal	Thermophilic microorganisms, biofilm reactors, crystallization	High-temperature operation, enhanced phosphorus removal due to thermophilic organisms' activity, reduced sludge generation	Difficulty in controlling operational temperature, long-term sustainability of thermophilic organisms	Development of more robust thermophilic microorganisms, optimization of temperature control for consistent operation, enhancing the long-term sustainability and efficiency of the system	Jiao et al. (2023)
Phyto-chemical coupling for phosphorus recovery	Aquatic plants, chemical precipitation, filtration systems	Sustainable, low-cost phosphorus removal using plant-based systems, natural nutrient uptake, and recovery from aquatic environments	Difficulty in maintaining plant growth, seasonal variations, and high land area requirements	Development of more efficient aquatic plant systems, seasonal growth optimization, enhanced filtration methods, and integration with other nutrient recovery systems for land-efficient solutions	Goggin et al. (2022)

would require a selling price of \$15.6/kg, as shown in Fig. 5.

The capital and input costs associated with electrochemical struvite recovery indicate a need for more than a 400 % increase in commercial fertilizer prices to achieve economic viability. Alternatively, a monetary value of \$10.4/kg P_2O_5 would be required to justify the avoidance of phosphates going to landfills, aligning with previous estimations of environmental benefits from P recovery (Morrissey et al., 2022). The economic viability of P recovery methods faces challenges due to the ongoing affordability of rock phosphate and industrial ammonium for fertilizer production. Operating costs associated with these recovery processes often surpass the market price of recovered P, such as struvite, with reported costs of approximately US\$1.8 per kg. Consequently, the lack of adequate economic returns to cover operational expenses poses a significant obstacle to the commercial viability of P recovery efforts.

Even though the high operation costs limit the economic feasibility of P recovery, the system could generate a wide range of other benefits. P recovery from wastewater could improve the dewaterability of the treated sludge and decrease the scaling speed rate, both of which would result in improved wastewater management (Shaddel et al., 2021). Moreover, P recovery from wastewater treatment processes, such as struvite and calcium phosphate precipitate, offers a promising avenue for sustainable fertilizer production. Struvite, enriched with ammonium

Table 4
Comparative economic analysis of phosphorus recovery end-products.

Parameter	Struvite	Calcium phosphate	Vivianite
Purity (%)	85–95	70–90	60–75
Energy cost (kWh/kg P)	5.2–7.8	8.5–12.3	10.1–14.5
Chemical cost (USD/kg P)	1.2–1.8	2.0–3.5	1.5–2.2
Market price (USD/kg P)	2.1–3.7	~5.5	1.5–2.5 (est.)
Production cost (USD/kg P)	1.8–2.5	3.0–4.2	2.5–3.8
Environmental benefit	Low energy use reduces scaling in WWTPs	Replaces phosphate rock, high soil solubility	Reduces sludge volume, moderate nutrient release
References	(Morrissey et al., 2022; Ye et al., 2020)	Ye et al. (2020)	Shaddel et al. (2021)

and phosphate, and calcium phosphate precipitates are notable products due to their soil solubility and high plant nutrient uptake potential, typically exceeding 76 %. Thermochemical treatments and metal-biochar adsorbents also offer avenues for phosphate recovery. For instance, products obtained with $MgCl_2$ in thermochemical treatment show fertilization efficiency reaching 88 % in acidic soil, compared to 71 % in neutral soil and 4 % in alkaline soil (Ye et al., 2020). Thermochemical treatments are suited to centralized facilities with high sludge volumes, potentially benefiting from energy cogeneration, while metal-biochar adsorbents offer flexibility for various scales of operation. Further research into process optimization, energy balance, and long-term environmental impacts is essential to capitalize on their potential in sustainable fertilizer production fully. The environmental benefits of P recovery highlight these methods' crucial role in mitigating environmental degradation caused by nutrient pollution.

Additionally, phosphorus recovery promotes the reuse of this valuable nutrient in agricultural and industrial applications, decreasing reliance on finite phosphate rock reserves and reducing the environmental impact associated with traditional fertilizer production. Life cycle assessment (LCA) is crucial for evaluating the environmental impacts of phosphorus recovery technologies. It provides a comprehensive framework to examine each stage of these processes, from resource extraction to end-use, identifying environmental hotspots and trade-offs. This approach aids in designing and optimizing recovery systems, ensuring they align with sustainability goals by measuring impacts such as greenhouse gas emissions, resource consumption, and eutrophication potential (Behjat et al., 2024). By integrating LCA into the evaluation of phosphorus recovery methods, decision-makers can make informed choices that balance economic and environmental objectives, thereby supporting the sustainable management of phosphorus resources.

6. Summary

This review underscores the potential of synergetic technologies to emerge as economically viable solutions for the future in the field of P recovery, emphasizing their capability to integrate diverse approaches to maximize efficiency while minimizing environmental impact. Despite the economic challenges associated with P recovery, its environmental benefits, including mitigating P pollution and reducing reliance on finite phosphate rock reserves, underscore the importance of ongoing research and investment in sustainable P management technologies. Recent studies have yielded promising results with coupling methods, achieving selective P recovery rates exceeding 90 %. Meanwhile, hybrid methods offer a balanced approach by combining various treatment strategies to optimize results, although with moderate efficiency. Sequential methods prioritize overall product recovery, demonstrating high P recovery rates through systematic, multi-step processes tailored to specific wastewater compositions and treatment goals. Coupling methods stand out for their high efficiency, broader applicability, and optimized resource utilization. This approach offers greater flexibility and scalability, making it suitable for small-scale and large industrial operations. While significant progress has been made in developing synergetic methods for P recovery, much work remains to be done.

Several crucial areas require attention and further exploration in P recovery from wastewater (Table 5). Firstly, ongoing research and development efforts are essential to enhance the economic feasibility of synergetic technologies for P recovery. This includes exploring innovative synergetic technologies and process optimizations to reduce operational costs and increase the competitiveness of recovered P products in

Table 5
Comparison of synergetic methods for phosphorus recovery with challenges for future research.

Method/ Parameter	Coupling	Hybrid	Sequential
Efficiency	High (>90 %)	Moderate (80 %)	High (95 %)
Cost	Moderate	High	High
Environmental impact	Low	Moderate	Moderate
Key advantages	High selectivity, energy efficiency	Balanced approach, multi-nutrient	Tailored processes, high purity
Key challenges	System complexity, optimization	Integration issues, higher costs	Time-consuming, resource-intensive
Challenges for future research	Develop simplified designs; create standardized protocols for compatibility; conduct pilot studies for scalability	Design modular systems for easy integration; investigate cost-effective materials; use machine learning for optimization	Research catalysts to speed up processes; explore energy-efficient technologies; develop flexible frameworks for different wastewaters

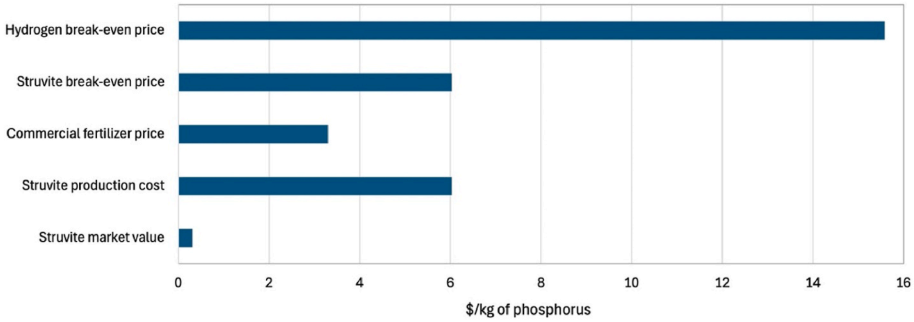

Fig. 5. Detailed economic analysis of the struvite precipitation method for P recovery (data used from the references cited in section 5).

the market. Comprehensive techno-economic assessments are necessary to assess the feasibility and sustainability of synergetic P recovery approaches on a broader scale. It is imperative to bridge the gap between technological advancements and practical implementation by incorporating TRL analysis into future research frameworks. This will provide insights into the readiness of P recovery technologies for practical deployment and help identify key challenges and opportunities for further development. However, most of the synergetic technologies for P recovery are currently in the embryonic stage. Moreover, collaboration between academia, industry, and regulatory bodies is essential to facilitate knowledge exchange, regulatory support, and investment in P recovery initiatives.

Future research should focus on minimizing the environmental footprint of P recovery processes, such as reducing energy consumption and waste generation. This includes exploring renewable energy sources and adopting green chemistry principles to design more environmentally friendly synergetic technologies. Additionally, applying machine learning and process automation can provide real-time optimization, enabling better control over the complex interplay of biological, chemical, and electrochemical mechanisms in these systems. Moreover, research should aim at multi-nutrient recovery strategies—recovering phosphorus alongside nitrogen and potassium—to produce tailored fertilizers that cater to diverse agricultural demands, thereby boosting the market value of the recovered products. Insights into process upscaling and modular design are also critical for transitioning laboratory-scale technologies to industrial wastewater treatment systems, with an emphasis on minimizing environmental footprints. A promising direction lies in valorizing by-products, transforming sludge and recovered struvite into high-value commodities like bio-fertilizers or soil amendments, aligning with circular economy principles. Finally, partnerships between academia, industry, and policymakers could drive the development of pilot projects and policy frameworks, ensuring that these synergistic technologies achieve large-scale adoption and address global phosphorus sustainability challenges effectively.

CRediT authorship contribution statement

Parminder Kaur: Writing – original draft, Investigation, Methodology, Visualization. **Małgorzata Szlachta:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Junhua Xu:** Writing – review & editing, Investigation, Methodology. **Jouko Vepsäläinen:** Writing – review & editing. **Reijo Lappalainen:** Writing – review & editing. **Farihahusnah Hussin:** Writing – review & editing, Methodology. **Mohamed Kheireddine Aroua:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was financially supported by the Research Council of Finland - project MinPhos. Funding was provided through grant numbers 354497 (Tampere University, Małgorzata Szlachta), 354496 (University of Eastern Finland, Jouko Vepsäläinen), and 354498 (University of Eastern Finland, Reijo Lappalainen). We thank Mikko Auriola from Savonia University of Applied Sciences for his assistance with the visualization component of this paper. We also thank the anonymous reviewers and editor for their valuable comments, which helped us considerably improve this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.125786.

Data availability

Data will be made available on request.

References

Afsari, by M., Tijing, L., Shon, H., 2024. Modification of Membranes for Treatment of Challenging Water and Nutrient Recovery Using Membrane Distillation.

Aida, T.M., Nonaka, T., Fukuda, S., Kujiraoka, H., Kumagai, Y., Maruta, R., Ota, M., Suzuki, I., Watanabe, M.M., Inomata, H., Smith, R.L., 2016. Nutrient recovery from municipal sludge for microalgae cultivation with two-step hydrothermal liquefaction. Algal Res. 18, 61–68. https://doi.org/10.1016/j.algal.2016.06.009.

Al-Juboori, R.A., Ahmed, F.E., Khanzada, N.K., Khatri, M., Al-shaeli, M., Ibrahim, Y., Hilal, N., 2024. Burgeoning innovation and scalability activities for phosphorus recovery from wastewater treatment facilities. Sustain. Mater. Technol. 40, e00907. https://doi.org/10.1016/j.susmat.2024.e00907.

Ambat, I., Bec, S., Peltomaa, E., Srivastava, V., Ojala, A., Sillanpää, M., 2019. A synergic approach for nutrient recovery and biodiesel production by the cultivation of microalga species in the fertilizer plant wastewater. Sci. Rep. 9. https://doi.org/10.1038/s41598-019-55748-w, 19073–19073.

Ardiyanti, R., Azrague, K., Medema, G., Hallé, C., 2024. Navigating quality, health and environmental risk: a novel framework for wastewater resource recovery products. J. Clean. Prod. 434. https://doi.org/10.1016/j.jclepro.2023.140260, 140260–140260.

Bacelo, H., Pintor, A.M.A., Santos, S.C.R., Boaventura, R.A.R., Botelho, C.M.S., 2020. Performance and prospects of different adsorbents for phosphorus uptake and recovery from water. Chem. Eng. J. 381. https://doi.org/10.1016/j.cej.2019.122566, 122566–122566.

Bashar, R., Gungor, K., Karthikeyan, K.G., Barak, P., 2018. Cost effectiveness of phosphorus removal processes in municipal wastewater treatment. Chemosphere 197, 280–290. https://doi.org/10.1016/j.chemosphere.2017.12.169.

Behjat, M., Svanström, M., Peters, G., 2024. Environmental assessment of phosphorus recovery from dairy sludge: a comparative LCA study. Waste Manag. 187, 50–60. https://doi.org/10.1016/J.WASMAN.2024.06.011.

Blengini, G.A., Nuss, P., Dewulf, J., Nita, V., Talens Peiró, L., Vidal-Legaz, B., Latunussa, C., Mancini, L., Blagoeva, D., Pennington, D., Pellegrini, M., Van Maercke, A., Solar, S., Grohol, M., Ciupagea, C., 2017. EU methodology for critical raw materials assessment: policy needs and proposed solutions for incremental improvements. Resour. Policy 53, 12–19. https://doi.org/10.1016/j.resourpol.2017.05.008.

Bunce, J.T., Ndam, E., Ofiteru, I.D., Moore, A., Graham, D.W., 2018. A review of phosphorus removal technologies and their applicability to small-scale domestic wastewater treatment systems. Front. Environ. Sci. 6. https://doi.org/10.3389/fenvs.2018.00008, 8–8.

Carrillo, V., Castillo, R., Magrí, A., Holzapfel, E., Vidal, G., 2024. Phosphorus recovery from domestic wastewater: a review of the institutional framework. J. Environ. Manag. 351. https://doi.org/10.1016/j.jenvman.2023.119812, 119812–119812.

Carrillo, V., Fuentes, B., Gómez, G., Vidal, G., 2020. Characterization and recovery of phosphorus from wastewater by combined technologies. Rev. Environ. Sci. Biotechnol. 19, 389–418. https://doi.org/10.1007/s11157-020-09533-1.

Chen, F., Zhang, Y.S., Bai, C.W., Huang, X.T., Sun, Y.J., Chen, X.J., 2024. Ozone meets peroxides: a symphony of hybrid techniques in wastewater treatment. Chem. Eng. J. 483. https://doi.org/10.1016/j.cej.2024.149129, 149129–149129.

Chen, J., Cheng, Z., Yuan, W., Song, W., Zhou, Y., Lei, Y., Jiang, B., 2024. High-flux electrochemical phosphorus recovery in an undivided electrolytic cell coupled with microfiltration with low energy consumption. Chem. Eng. J. 484, 149801. https://doi.org/10.1016/j.cej.2024.149801.

Chrispim, M.C., Scholz, M., Nolasco, M.A., 2019. Phosphorus recovery from municipal wastewater treatment: critical review of challenges and opportunities for developing countries. J. Environ. Manag. 248. https://doi.org/10.1016/j.jenvman.2019.109268, 109268–109268.

Cid, C.A., Jasper, J.T., Hoffmann, M.R., 2018. Phosphate recovery from human waste via the formation of hydroxyapatite during electrochemical wastewater treatment. ACS Sustain. Chem. Eng. 6, 3135–3142. https://doi.org/10.1021/acssuschemeng.7b03155.

Cordell, D., Rosemarin, A., Schröder, J.J., Smit, A.L., 2011. Towards global phosphorus security: a systems framework for phosphorus recovery and reuse options. Chemosphere 84, 747–758. https://doi.org/10.1016/j.chemosphere.2011.02.032.

Cordell, D., Turner, A., Chong, J., 2015. The hidden cost of phosphate fertilizers: mapping multi-stakeholder supply chain risks and impacts from mine to fork. In: Global Change, Peace and Security. Routledge, pp. 323–343. https://doi.org/10.1080/14781158.2015.1083540.

Dai, H., Lu, X., Peng, Y., Yang, Z., Zhsssu, H., 2017. Effects of supersaturation control strategies on hydroxyapatite (HAP) crystallization for phosphorus recovery from wastewater. Environ. Sci. Pollut. Res. 24, 5791–5799. https://doi.org/10.1007/s11356-016-8236-2.

Daneshgar, S., Buttafava, A., Callegari, A., Capodaglio, A.G., 2019. Economic and energetic assessment of different phosphorus recovery options from aerobic sludge. J. Clean. Prod. 223, 729–738. https://doi.org/10.1016/j.jclepro.2019.03.195.

Daneshgar, S., Cecconet, D., Capsoni, D., Capodaglio, A.G., 2022. Side-stream phosphorus recovery in activated sludge processes. Water 14, 1861. https://doi.org/10.3390/w14121861.

Deng, L., Dhar, B.R., 2023. Phosphorus recovery from wastewater via calcium phosphate precipitation: a critical review of methods, progress, and insights. Chemosphere 330. https://doi.org/10.1016/j.chemosphere.2023.138685, 138685–138685.

Desmidt, E., Ghyselbrecht, Karel, Zhang, Yang, Pinoy, Luc, Van der Bruggen, Bart, Verstraete, Willy, Rabaey, Korneel, Meesschaert, B., 2015. Global phosphorus scarcity and full-scale P-recovery techniques: a review. Crit. Rev. Environ. Sci. Technol. 45, 336–384. https://doi.org/10.1080/10643389.2013.866531.

Du, J., Waite, T.D., Biesheuvel, P.M., Tang, W., 2023a. Recent advances and prospects in electrochemical coupling technologies for metal recovery from water. J. Hazard. Mater. 442, 130023. https://doi.org/10.1016/j.jhazmat.2022.130023.

Du, J., Waite, T.D., Feng, J., Lei, Y., Tang, W., 2023b. Coupled electrochemical methods for nitrogen and phosphorus recovery from wastewater: a review. Environ. Chem. Lett. 21, 885–909. https://doi.org/10.1007/s10311-023-01561-x.

Egle, L., Rechberger, H., Krampe, J., Zessner, M., 2016. Phosphorus recovery from municipal wastewater: an integrated comparative technological, environmental and economic assessment of P recovery technologies. Sci. Total Environ. 571, 522–542. https://doi.org/10.1016/j.scitotenv.2016.07.019.

El Messaoudi, N., Miyah, Y., Georgin, J., Huerta-Angeles, G., Ansari, K., Said, H.A., Algethami, F.K., Kaur, P., Meili, L., 2024. Future trends and innovations in the treatment of industrial effluent. In: Advances in Chemical Pollution, Environmental Management and Protection. Elsevier. https://doi.org/10.1016/bs.apmp.2024.10.008.

Enyemadze, I., Momade, F.W.Y., Oduro-Kwarteng, S., Essandoh, H., 2021. Phosphorus recovery by struvite precipitation: a review of the impact of calcium on struvite quality. J. Water, Sanit. Hyg. Dev. 11, 706–718. https://doi.org/10.2166/washdev.2021.078.

ESPP [WWW Document], 2019. ESPP-DPP-NNP phosphorus recovery technol. Cat. URL. https://www.phosphorusplatform.eu/activities/p-recovery-technology-inventory, 1.22.25.

European Commission, 2023. Fertilisers. Publications Office of the European Union.

European Commission, 2020. A new circular economy action plan COM 2020/98. Off. J. Eur. Union, 20–20.

Foster, X., Tarpeh, W.A., Dong, H., Vaneeckhaute, C., 2025. Enhancing the regeneration efficiency of a hybrid anion exchange resin for removal of phosphorus from wastewater with a lower environmental impact. J. Water Process Eng. 69, 106851. https://doi.org/10.1016/j.jwpe.2024.106851.

Garske, B., Stubenrauch, J., Ekardt, F., 2020. Sustainable phosphorus management in European agricultural and environmental law. Rev. Eur. Community Int. Environ. Law 29, 107–117. https://doi.org/10.1111/reel.12318.

Goggin, B.J., Chopin, T., Houlahan, J., Frego, K., Gray, C., Junge, R., 2022. Freshwater Integrated Multi-Trophic Aquaculture (FIMTA): Applying Criteria for Plant Selection and the Effect of Plant Species on the Bioremediation of Aquaculture.

Gourevitch, J.D., Koliba, C., Rizzo, D.M., Zia, A., Ricketts, T.H., 2021. Quantifying the social benefits and costs of reducing phosphorus pollution under climate change. J. Environ. Manag. 293. https://doi.org/10.1016/j.jenvman.2021.112838, 112838–112838.

Günther, S., Grunert, M., Müller, S., 2018. Overview of recent advances in phosphorus recovery for fertilizer production. Eng. Life Sci. 18, 434–439. https://doi.org/10.1002/elsc.201700171.

Guo, G., Zhou, S., Chen, Y., Li, Y.Y., 2024. Phosphorus recovery coupling with one-stage partial nitritation/anammox process for the treatment of high-nutrient permeate from anaerobic membrane bioreactor treating concentrated organic sludge. Chem. Eng. J. 484. https://doi.org/10.1016/j.cej.2024.149474, 149474–149474.

Hou, D., Lu, L., Sun, D., Ge, Z., Huang, X., Cath, T.Y., Ren, Z.J., 2017. Microbial electrochemical nutrient recovery in anaerobic osmotic membrane bioreactors. Water Res. 114, 181–188. https://doi.org/10.1016/j.watres.2017.02.034.

Huang, L., Lee, D.-J., Lai, J.-Y., 2015. Forward osmosis membrane bioreactor for wastewater treatment with phosphorus recovery. Bioresour. Technol. 198, 418–423. https://doi.org/10.1016/j.biortech.2015.09.045.

Hussain, S., Aziz, H.A., Isa, M.H., Ahmad, A., Van Leeuwen, J., Zou, L., Beecham, S., Umar, M., 2011. Orthophosphate removal from domestic wastewater using limestone and granular activated carbon. Desalination 271, 265–272. https://doi.org/10.1016/j.desal.2010.12.046.

Jaffer, Y., Clark, T.A., Pearce, P., Parsons, S.A., 2002. Potential phosphorus recovery by struvite formation. Water Res. 36, 1834–1842. https://doi.org/10.1016/S0043-1354(01)00391-8.

Jeon, D.J., Yeom, S.H., 2009. Recycling wasted biomaterial, crab shells, as an adsorbent for the removal of high concentration of phosphate. Bioresour. Technol. 100, 2646–2649. https://doi.org/10.1016/j.biortech.2008.11.035.

Jiao, P., Tian, Q., Wolfgang, S., Dong, X., Wu, Y., 2023. Cold-resistant performance and the promoted development of functional community with flexible metabolic patterns in a Biofilm Bio-Nutrient Removal (BBNR) system amended with supplementary carbon source for phosphorus recovery. Environ. Res. 227, 115807. https://doi.org/10.1016/j.envres.2023.115807.

Kaljunen, J.U., Yazdani, R., Al-Juboori, R.A., Zborowski, C., Meinander, K., Mikola, A., 2022. Adsorptive behavior of phosphorus onto recycled waste biosolids after being acid leached from wastewater sludge. Chem. Eng. J. Adv. 11, 100329. https://doi.org/10.1016/j.ceja.2022.100329.

Kappel, C., Yasadi, K., Temmink, H., Metz, S.J., Kemperman, A.J.B., Nijmeijer, K., Zwijnenburg, A., Witkamp, G.J., Rijnaarts, H.H.M., 2013. Electrochemical phosphate recovery from nanofiltration concentrates. Sep. Purif. Technol. 120, 437–444. https://doi.org/10.1016/j.seppur.2013.10.022.

Karunanithi, R., Szogi, A.A., Bolan, N., Naidu, R., Loganathan, P., Hunt, P.G., Vanotti, M. B., Saint, C.P., Ok, Y.S., Krishnamoorthy, S., 2015. Phosphorus recovery and reuse from waste streams. Adv. Agron. 131, 173–250. https://doi.org/10.1016/bs.agron.2014.12.005.

Kholoma, E., Renman, G., Renman, A., 2016. Phosphorus removal from wastewater by field-scale fortified filter beds during a one-year study. Environ. Technol. U. K. 37, 2953–2963. https://doi.org/10.1080/09593330.2016.1170888.

Kõiv, M., Liira, M., Mander, Ü., Mõtlep, R., Vohla, C., Kirsimäe, K., 2010. Phosphorus removal using Ca-rich hydrated oil shale ash as filter material - the effect of different phosphorus loadings and wastewater compositions. Water Res. 44, 5232–5239. https://doi.org/10.1016/j.watres.2010.06.044.

Krishnamoorthy, N., Dey, B., Unpaprom, Y., Ramaraj, R., Maniam, G.P., Govindan, N., Jayaraman, S., Arunachalam, T., Paramasivan, B., 2021. Engineering principles and process designs for phosphorus recovery as struvite: a comprehensive review. J. Environ. Chem. Eng. 9. https://doi.org/10.1016/j.jece.2021.105579, 105579–105579.

Lei, Y., Du, M., Kuntke, P., Saakes, M., Van Der Weijden, R., Buisman, C.J.N., 2019. Energy efficient phosphorus recovery by microbial electrolysis cell induced calcium phosphate precipitation. ACS Sustain. Chem. Eng. 7, 8860–8867. https://doi.org/10.1021/acssuschemeng.9b00867.

Lei, Y., Song, B., Saakes, M., van der Weijden, R.D., Buisman, C.J.N., 2018. Interaction of calcium, phosphorus and natural organic matter in electrochemical recovery of phosphate. Water Res. 142, 10–17. https://doi.org/10.1016/j.watres.2018.05.035.

Lei, Y., Song, B., Van Der Weijden, R.D., Saakes, M., Buisman, C.J.N., 2017. Electrochemical induced calcium phosphate precipitation: importance of local pH. Environ. Sci. Technol. 51, 11156–11164. https://doi.org/10.1021/acs.est.7b03909.

Leo, C.P., Chai, W.K., Mohammad, A.W., Qi, Y., Hoedley, A.F.A., Chai, S.P., 2011. Phosphorus removal using nanofiltration membranes. Water Sci. Technol. 64, 199–205. https://doi.org/10.2166/wst.2011.598.

Li, M., Zhang, H., Sun, H., Mohammed, A., Liu, Y., Lu, Q., 2022. Effect of phosphate and ammonium concentrations, total suspended solids and alkalinity on lignin-induced struvite precipitation. Sci. Rep. 12, 2901. https://doi.org/10.1038/s41598-022-06930-0.

Li, R., Kelly, C., Keegan, R., Xiao, L., Morrison, L., Zhan, X., 2013. Phosphorus removal from wastewater using natural pyrrhotite. Colloids Surf. A Physicochem. Eng. Asp. 427, 13–18. https://doi.org/10.1016/j.colsurfa.2013.02.066.

Li, X., Shen, S., Xu, Y., Guo, T., Dai, H., Lu, X., 2023. Mining phosphorus from waste streams at wastewater treatment plants: a review of enrichment, extraction, and crystallization methods. Environ. Sci. Pollut. Res. Int. 30, 28407–28421. https://doi.org/10.1007/s11356-023-25388-9.

Li, X., Shen, S., Xu, Y., Guo, T., Dai, H., Lu, X., 2021. Application of membrane separation processes in phosphorus recovery: a review. Sci. Total Environ. 767, 144346. https://doi.org/10.1016/j.scitotenv.2020.144346.

Li, Y., Peng, Z., Sun, Y., Yao, J., Liu, Y., 2024. Recovery of triethylamine and phosphoric acid from wastewater using a novel hybrid process of bipolar membrane electrodialysis and resin adsorption. Desalination 576. https://doi.org/10.1016/j.desal.2024.117363, 117363–117363.

Liao, Y., Zhang, C., Li, P., Feng, T., Wu, J., 2024. Coupled in-situ fermentation for enhanced biological phosphorus removal from digested swine wastewater. Water Switz 16. https://doi.org/10.3390/w16010080.

Liu, Q., Sun, W., Zeng, Q., Zhang, H., Wu, C., Lichtfouse, E., Liu, H., 2024. Integrated processes for simultaneous nitrogen, phosphorus, and potassium recovery from urine: a review. J. Water Process Eng. 59, 104975. https://doi.org/10.1016/j.jwpe.2024.104975.

Liu, Y., Deng, Y.Y., Zhang, Q., Liu, H., 2021. Overview of recent developments of resource recovery from wastewater via electrochemistry-based technologies. Sci. Total Environ. 757, 143901. https://doi.org/10.1016/j.scitotenv.2020.143901.

Logan, B.E., Hamelers, B., Rozendal, R., Schröder, U., Keller, J., Freguia, S., Aelterman, P., Verstraete, W., Rabaey, K., 2006. Microbial fuel cells: methodology and technology. Environ. Sci. Technol. 40, 5181–5192. https://doi.org/10.1021/es0605016.

Lou, X.Y., Wang, J., Liang, J., Liu, S., Wang, R., Deng, L., Li, D., Hu, X., Chen, H., 2024. Sequence closed-loop recovery of fluoride, phosphate, and sulfate anions from phosphogypsum leachate via precipitation-electrodialysis-crystallization approaches. Sep. Purif. Technol. 342. https://doi.org/10.1016/j.seppur.2024.127014, 127014–127014.

Luo, W., Hai, F.I., Price, W.E., Guo, W., Ngo, H.H., Yamamoto, K., Nghiem, L.D., 2016. Phosphorus and water recovery by a novel osmotic membrane bioreactor-reverse osmosis system. Bioresour. Technol. 200, 297–304. https://doi.org/10.1016/j.biortech.2015.10.029.

Mainardis, M., Cecconet, D., Moretti, A., Callegari, A., Goi, D., Freguia, S., Capodaglio, A. G., 2022. Wastewater fertigation in agriculture: issues and opportunities for improved water management and circular economy. Environ. Pollut. 296, 118755. https://doi.org/10.1016/j.envpol.2021.118755.

Mekonnen, M.M., Hoekstra, A.Y., 2018. Global anthropogenic phosphorus loads to freshwater and associated grey water footprints and water pollution levels: a high-resolution global study. Water Resour. Res. 54, 345–358. https://doi.org/10.1002/2017WR020448.

Meng, J., Shi, X., Wang, S., Hu, Z., Koseoglu-Imer, D.Y., Lens, P.N.L., Zhan, X., 2024. Application of electrodialysis technology in nutrient recovery from wastewater: a review. J. Water Process Eng. 65, 105855. https://doi.org/10.1016/j.jwpe.2024.105855.

Molinos-Senante, M., Hernández-Sancho, F., Sala-Garrido, R., 2011. Cost–benefit analysis of water-reuse projects for environmental purposes: a case study for Spanish wastewater treatment plants. J. Environ. Manag. 92, 3091–3097. https://doi.org/10.1016/j.jenvman.2011.07.023.

Molitor, H., Kim, G.-Y., Hartnett, E., Gincley, B., Alam, M.M., Feng, J., Avila, N., Fisher, A., Hodaei, M., Li, Y., 2024. Intensive Microalgal Cultivation and Tertiary Phosphorus Recovery from Wastewaters via the EcoRecover Process.

Morrissey, K.G., English, L., Thoma, G., Popp, J., 2022. Prospective life cycle assessment and cost analysis of novel electrochemical struvite recovery in a U.S. Wastewater treatment plant. Sustain. Switz. 14. https://doi.org/10.3390/su142013657.

Muntwyler, A., Panagos, P., Pfister, S., Lugato, E., 2024. Assessing the phosphorus cycle in European agricultural soils: looking beyond current national phosphorus budgets. Sci. Total Environ. 906. https://doi.org/10.1016/j.scitotenv.2023.167143, 167143–167143.

Murujew, O., 2019. Tertiary Phosphorus Removal from Wastewater. (Doctoral Thesis). Cranfield University.

Nadagouda, M.N., Varshney, G., Varshney, V., Hejase, C.A., 2024. Recent advances in technologies for phosphate removal and recovery: a review. ACS Environ. Au 4, 271–291. https://doi.org/10.1021/acsenvironau.3c00069.

Neset, T.S.S., Cordell, D., 2012. Global phosphorus scarcity: identifying synergies for a sustainable future. J. Sci. Food Agric. 92, 2–6. https://doi.org/10.1002/jsfa.4650.

Nolan, B.T., Stoner, J.D., 2000. Nutrients in groundwaters of the conterminous United States, 1992-1995. Environ. Sci. Technol. 34, 1156–1165. https://doi.org/10.1021/es9907663.

Oliveira, M., Araújo, A., Azevedo, G., Pereira, M.F.R., Neves, I.C., Machado, A.V., 2015. Kinetic and equilibrium studies of phosphorous adsorption: effect of physical and chemical properties of adsorption agent. Ecol. Eng. 82, 527–530. https://doi.org/10.1016/j.ecoleng.2015.05.020.

O'Neal, J.A., Boyer, T.H., 2013. Phosphate recovery using hybrid anion exchange: applications to source-separated urine and combined wastewater streams. Water Res. 47, 5003–5017. https://doi.org/10.1016/j.watres.2013.05.037.

Ownby, M., Desrosiers, D.A., Vaneeckhaute, C., 2021. Author Correction: phosphorus removal and recovery from wastewater via hybrid ion exchange nanotechnology: a study on sustainable regeneration chemistries, 2021 npj Clean Water 4 (1), 6. https://doi.org/10.1038/s41545-021-00104-7, 10.1038/s41545-020-00097-9). Npj Clean Water 4, 6–6.

Peng, L., Dai, H., Wu, Y., Peng, Y., Lu, X., 2018. A comprehensive review of the available media and approaches for phosphorus recovery from wastewater. Water Air Soil Pollut. 229. https://doi.org/10.1007/s11270-018-3706-4.

Prabhakar, N., Isloor, A.M., 2024. Recovery/recycling process of pollutant material in bio/membrane reactor. In: Curr. Trends Future Dev. Bio-Membr. Recent Achiev. Chem. Process. Membr. React., pp. 249–276. https://doi.org/10.1016/B978-0-443-13876-8.00004-5.

Qiu, G., Law, Y.M., Das, S., Ting, Y.P., 2015. Direct and complete phosphorus recovery from municipal wastewater using a hybrid microfiltration-forward osmosis membrane bioreactor process with seawater brine as draw solution. Environ. Sci. Technol. 49, 6156–6163. https://doi.org/10.1021/es504554f.

Qiu, G., Ting, Y.P., 2014. Direct phosphorus recovery from municipal wastewater via osmotic membrane bioreactor (OMBR) for wastewater treatment. Bioresour. Technol. 170, 221–229. https://doi.org/10.1016/j.biortech.2014.07.103.

Renfrew, D., Vasilaki, V., Nika, E., Harris, E., Katsou, E., 2024. Tracing wastewater resources: unravelling the circularity of waste using source, destination, and quality analysis. Water Res. 250. https://doi.org/10.1016/j.watres.2023.120901, 120901–120901.

Robles, Á., Aguado, D., Barat, R., Borrás, L., Bouzas, A., Giménez, J.B., Martí, N., Ribes, J., Ruano, M.V., Serralta, J., Ferrer, J., Seco, A., 2020. New frontiers from removal to recycling of nitrogen and phosphorus from wastewater in the Circular Economy. Bioresour. Technol. 300. https://doi.org/10.1016/j.biortech.2019.122673, 122673–122673.

Roy, E.D., 2017. Phosphorus recovery and recycling with ecological engineering: a review. Ecol. Eng. 98, 213–227. https://doi.org/10.1016/j.ecoleng.2016.10.076.

Ruiz-Cosgaya, L., Izquierdo, W.A., Martínez-Guijarro, R., Serralta, J., Rabat, R., 2024. Ion exchange columns. A promising technology for nitrogen and phosphorus recovery in the main line of a Wastewater Treatment Plant. J. Environ. Manage. To be publ, 122719. https://doi.org/10.1016/J.JENVMAN.2024.122719.

Sartorius, C., von Horn, J., Tettenborn, F., 2012. Phosphorus recovery from wastewater – state-of-the-art and future potential. Proc. Water Environ. Fed. 2011, 299–316. https://doi.org/10.2175/193864711802867676.

Schoumans, O.F., Bouraoui, F., Kabbe, C., Oenema, O., van Dijk, K.C., 2015. Phosphorus management in Europe in a changing world. Ambio 44, 180–192. https://doi.org/10.1007/s13280-014-0613-9.

Scotti, A., Silvani, V., Milia, S., Cappai, G., Ubaldini, S., Ortega, V., Colombo, R., Godeas, A., Gómez, M., 2021. Scale-up of Mycorrhizal-Assisted Phytoremediation system from Technology Readiness Level 6 (relevant environment) to 7 (operational environment): cost-benefits within a circular economy context. In: Soil Science-Emerging Technologies, Global Perspectives and Applications. IntechOpen.

Sengupta, S., Nawaz, T., Beaudry, J., 2015. Nitrogen and phosphorus recovery from wastewater. Curr. Pollut. Rep. 1, 155–166. https://doi.org/10.1007/s40726-015-0013-1.

Shaddel, S., Shaddel, R., Østerhus, S.W., 2021. Phosphorus recovery from nutrient-rich streams at wastewater treatment plants. In: Integrated and Hybrid Process Technology for Water and Wastewater Treatment. Elsevier, pp. 463–486. https://doi.org/10.1016/B978-0-12-823031-2.00014-8.

Shi, L., Hu, Y., Xie, S., Wu, G., Hu, Z., Zhan, X., 2018. Recovery of nutrients and volatile fatty acids from pig manure hydrolysate using two-stage bipolar membrane electrodialysis. Chem. Eng. J. 334, 134–142. https://doi.org/10.1016/j.cej.2017.10.010.

Snyder, N.A., Morales-Guio, C.G., 2024. Perspective on the electrochemical recovery of phosphate from wastewater streams. Electrochem. Sci. Adv. 4, e2200010. https://doi.org/10.1002/elsa.202200010.

Srivastava, R.K., Sarangi, P.K., Vivekanand, V., Pareek, N., Shaik, K.B., Subudhi, S., 2022. Microbial fuel cells for waste nutrients minimization: recent process technologies and inputs of electrochemical active microbial system. Microbiol. Res. 265, 127216. https://doi.org/10.1016/j.micres.2022.127216.

Stamm, C., Binder, C.R., Frossard, E., Haygarth, P.M., Oberson, A., Richardson, A.E., Schaum, C., Schoumans, O., Udert, K.M., 2022. Towards circular phosphorus: the need of inter- and transdisciplinary research to close the broken cycle. Ambio 51, 611–622. https://doi.org/10.1007/s13280-021-01562-6.

Tomei, M.C., Stazi, V., Daneshgar, S., Capodaglio, A.G., 2020. Holistic approach to phosphorus recovery from urban wastewater: enhanced biological removal combined with precipitation. Sustainability 12, 575. https://doi.org/10.3390/su12020575.

Tran, Q., Garcia-Jaramillo, M., Schindler, J., Eness, A., Bryla, D.R., Patel, H., Navab-Daneshmand, T., Jin, X., 2024. Sustainable nutrient water recovery by a hybrid electrodialysis (ED) - forward osmosis (FO) process for agricultural application. J. Environ. Chem. Eng. 12, 112091. https://doi.org/10.1016/j.jece.2024.112091.

Vasenko, L., Bonnemain-Fernandes, A., Malwade, C., Qu, H., 2020. Phosphorus recovery from municipal wastewater via a two-step process of ozonation and crystallization: process development, optimization and upscaling. Environ. Sci. Water Res. Technol. 6, 817–828. https://doi.org/10.1039/C9EW00994A.

Vohla, C., Kõiv, M., Bavor, H.J., Chazarenc, F., Mander, Ü., 2011. Filter materials for phosphorus removal from wastewater in treatment wetlands-A review. Ecol. Eng. 37, 70–89. https://doi.org/10.1016/j.ecoleng.2009.08.003.

Vučić, V., Harms, H., Müller, S., 2024. Biological recovery of phosphorus (BioP-Rec) from wastewater streams using brewer's yeast on pilot-scale. Eng. Life Sci. 24, e2300208. https://doi.org/10.1002/elsc.202300208.

Vučić, V., Müller, S., 2021. New developments in biological phosphorus accessibility and recovery approaches from soil and waste streams. Eng. Life Sci. 21, 77–86. https://doi.org/10.1002/elsc.202000076.

WalnutPlatform EU [WWW Document], 2022. Exist. Nutr. Recovery facil. URL. https://walnutplatform.eu/portal/index.php/existing-nutrient-recovery-facilities, 1.22.25.

Walsh, M., Schenk, G., Schmidt, S., 2023. Realising the circular phosphorus economy delivers for sustainable development goals. Npj Sustain. Agric. 1, 1–15. https://doi.org/10.1038/s44264-023-00002-0.

Wang, H., Ren, Z.J., 2013. A comprehensive review of microbial electrochemical systems as a platform technology. Biotechnol. Adv. 31, 1796–1807. https://doi.org/10.1016/j.biotechadv.2013.10.001.

Wang, L., Zhang, Y., Li, X., He, C., Szlachta, M., Chen, Y., Xu, J., 2024. Structural transformation investigations of δ to α manganese dioxides: phosphate sorption and its mechanism. Sep. Purif. Technol. 346. https://doi.org/10.1016/j.seppur.2024.127497, 127497–127497.

Witek-Krowiak, A., Gorazda, K., Szopa, D., Trzaska, K., Moustakas, K., Chojnacka, K., 2022. Phosphorus recovery from wastewater and bio-based waste: an overview. Bioengineered 13, 13474–13506. https://doi.org/10.1080/21655979.2022.2077894.

Xie, M., Shon, H.K., Gray, S.R., Elimelech, M., 2016. Membrane-based processes for wastewater nutrient recovery: technology, challenges, and future direction. Water Res. 89, 210–221. https://doi.org/10.1016/j.watres.2015.11.045.

Xin, G., Zhou, X., Zuo, P., Ma, W., Liu, C., Zhao, Y., 2024. Enhanced the simultaneous removal and recovery of phosphorus in induced crystallization coupled biological phosphorus removal process. Green Technol. Sustain 2. https://doi.org/10.1016/j.grets.2024.100088, 100088–100088.

Xing, D., Li, X., Jin, C., Zhao, Y., Yang, X., Gao, M., Ji, J., Xu, X., She, Z., Guo, L., 2022. Coupling of wastewater treatment and microalgae products recovery: effect of phosphorus components on the biochemical composition and phosphorus absorption of Chlorella pyrenoidosa. J. Water Process Eng. 49. https://doi.org/10.1016/j.jwpe.2022.102968, 102968–102968.

Yan, T., Ye, Y., Ma, H., Zhang, Y., Guo, W., Du, B., Wei, Q., Wei, D., Ngo, H.H., 2018. A critical review on membrane hybrid system for nutrient recovery from wastewater. Chem. Eng. J. 348, 143–156. https://doi.org/10.1016/j.cej.2018.04.166.

Yang, Y., Shi, X., Ballent, W., Mayer, B.K., 2017. Biological phosphorus recovery: review of current progress and future needs. Water Environ. Res. 89, 2122–2135. https://doi.org/10.2175/106143017x15054988926424.

Yaqoob, A.A., Ibrahim, M.N.M., Guerrero-Barajas, C., 2021. Modern trend of anodes in microbial fuel cells (MFCs): an overview. Environ. Technol. Innov. 23. https://doi.org/10.1016/j.eti.2021.101579, 101579–101579.

Ye, Y., Ngo, H.H., Guo, W., Chang, S.W., Nguyen, D.D., Zhang, X., Zhang, J., Liang, S., 2020. Nutrient recovery from wastewater: from technology to economy. Bioresour. Technol. Rep. 11. https://doi.org/10.1016/j.biteb.2020.100425, 100425–100425.

Ye, Y., Ngo, H.H., Guo, W., Liu, Yiwen, Li, J., Liu, Yi, Zhang, X., Jia, H., 2017. Insight into chemical phosphate recovery from municipal wastewater. Sci. Total Environ. 576, 159–171. https://doi.org/10.1016/j.scitotenv.2016.10.078.

Yesigat, A., Worku, A., Mekonnen, A., Bae, W., Feyisa, G.L., Gatew, S., Han, J.L., Liu, W., Wang, A., Guadie, A., 2022. Phosphorus recovery as K-struvite from a waste stream: a review of influencing factors, advantages, disadvantages and challenges. Environ. Res. 214. https://doi.org/10.1016/j.envres.2022.114086, 114086–114086.

Yi, W.G., Lo, K.V., 2003. Phosphate recovery from greenhouse wastewater. J. Environ. Sci. Health Part B Pestic. Food Contam. Agric. Wastes 38, 501–509. https://doi.org/10.1081/PFC-120021669.

Yuan, Z., Pratt, S., Batstone, D.J., 2012. Phosphorus recovery from wastewater through microbial processes. Curr. Opin. Biotechnol. 23, 878–883. https://doi.org/10.1016/j.copbio.2012.08.001.

Zhang, C., Cheng, X., Wang, M., Ma, J., Collins, R., Kinsela, A., Zhang, Y., Waite, T.D., 2021. Phosphate recovery as vivianite using a flow-electrode capacitive desalination (FCDI) and fluidized bed crystallization (FBC) coupled system. Water Res. 194. https://doi.org/10.1016/j.watres.2021.116939, 116939–116939.

Zhang, H., 2017. Phosphorus and Water Quality Oklahoma Cooperative Extension Service. Oklahoma State University.

Zhang, J., Liu, Y., Li, J., Wang, K., Zhao, X., Liu, X., 2024. Enhanced recovery of phosphorus from hypophosphite-laden wastewater via field-induced electro-Fenton coupled with anodic oxidation. J. Hazard. Mater. 464. https://doi.org/10.1016/j.jhazmat.2023.132750, 132750–132750.

Zhang, Y., Desmidt, E., Van Looveren, A., Pinoy, L., Meesschaert, B., Van Der Bruggen, B., 2013. Phosphate separation and recovery from wastewater by novel electrodialysis. Environ. Sci. Technol. 47, 5888–5895. https://doi.org/10.1021/es4004476.

Zhang, Z., Du, X., Wang, Q., Gao, F., Jin, T., Hao, X., Ma, P., Li, J., Guan, G., 2021. A scalable three-dimensional porous λ-MnO2/rGO/Ca-alginate composite electroactive film with potential-responsive ion-pumping effect for selective recovery of lithium ions. Sep. Purif. Technol. 259, 118111. https://doi.org/10.1016/j.seppur.2020.118111.

Zheng, Y., Wan, Y., Zhang, Y., Huang, J., Yang, Y., Tsang, D.C.W., Wang, H., Chen, H., Gao, B., 2022. Recovery of phosphorus from wastewater: a review based on current phosphorous removal technologies. Crit. Rev. Environ. Sci. Technol. 53, 1148–1172. https://doi.org/10.1080/10643389.2022.2128194.

Zhi, Y., Wang, Y., Xu, D., Jiang, G., Leng, L., Kapusta, K., 2024. Phosphorus recovery from hydrothermal conversion products of sewage sludge through wet-chemical methods. Process Saf. Environ. Prot. 182, 1024–1034. https://doi.org/10.1016/j.psep.2023.12.053.

Zhou, Y., Zheng, G., Liu, Z., Liu, R., Tao, C., 2023. Multi-stage precipitation for the eco-friendly treatment of phosphogypsum leachates using hybrid alkaline reagents. J. Water Process Eng. 53. https://doi.org/10.1016/j.jwpe.2023.103626, 103626–103626.

Zou, H., Wang, Y., 2016. Phosphorus removal and recovery from domestic wastewater in a novel process of enhanced biological phosphorus removal coupled with crystallization. Bioresour. Technol. 211, 87–92. https://doi.org/10.1016/j.biortech.2016.03.073.