PAN POLSKA AKADEMIA NAUK

JOURNAL OF WATER AND LAND DEVELOPMENT

e-ISSN 2083-4535

ITP-PIB

Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2026.157837
2026, No. 68 (I–III): 214–223

Technological potential for nutrient recovery in the context of the circular economy

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RECEIVED 18.09.2025 ACCEPTED 05.01.2026 AVAILABLE ONLINE 31.03.2026

Abstract: The depletion of natural nutrient resources, rising fertiliser production costs, and increasing environmental pressures have intensified interest in the recovery of nitrogen (N) and phosphorus (P) from waste streams. This review critically examines nutrient-rich waste streams and systematically evaluates key nutrient recovery technologies according to their technology readiness levels (TRL). The analysis distinguishes between well-established biological processes and emerging innovative methods. It also addresses a persistent research and implementation gap between rapid technological development and limited political, municipal, and infrastructural readiness for large-scale deployment, particularly within existing wastewater treatment systems. Particular attention is given to regulatory drivers, including EU Directive 2024/3019, which introduces stricter effluent limits of 10 mg N·dm^{-3} and 0.7 mg P·dm^{-3} for agglomerations with a population equivalent between 10,000 and 150,000. These requirements necessitate costly infrastructure modernisation and process adaptation. The review identifies infrastructural constraints as the main barrier to implementation. At the same time, it highlights opportunities for integrating multi-stage approaches to ensure both environmental safety and resource efficiency. Social and legal aspects are also evaluated, with particular emphasis on psychological resistance and the necessity of compliance with Regulation EU No. 2019/1009 as critical factors influencing market acceptance. By synthesising technological, regulatory, and economic perspectives, this review contributes to closing knowledge gaps in nutrient cycling and supports stakeholders in advancing circular economy (CE) principles within waste management systems.

Keywords: circular economy, nitrogen and phosphorus recycling, nutrient recovery, waste management, wastewater management

INTRODUCTION

The recovery of nutrients – primarily nitrogen (N) and phosphorus (P) – can be achieved from various waste streams, such as wastewater, sludge, and ash (Rey-Martínez *et al.*, 2024). Most research in this field focuses on sewage sludge, animal manure, and digestate due to their large-scale production volumes and the necessity for effective management (Aragón-Briceño *et al.*, 2021). Globally, approximately 380 bln m^3 of wastewater is generated every year. This wastewater contains significant quantities of key nutrients: 16.6 mln Mg of N, 3.0 mln Mg of P, and 6.3 mln Mg of potassium (K) (Qadir *et al.*, 2020). Recovering N and P from municipal wastewater could reduce the demand for mineral fertilisers by 20 and 15%, respectively (Wang, Skerlos and Novak, 2024). This recovery could potentially meet approximately 13.4% of agricultural nutrient requirements (Qadir *et al.*, 2020).

Nutrient recovery from waste-derived sources plays a pivotal role in shaping nutrient management strategies. Modern technologies must integrate effective separation with the recovery of valuable elements (Szopa *et al.*, 2024). The characteristics of waste streams – including volume, the presence of chemical and biological contaminants, and the form and concentration of nutrients – are critical for selecting an appropriate recovery method (Carey *et al.*, 2016; Wang, Skerlos and Novak, 2024). For recycling to be economically viable, nutrients should be present in plant-available forms. For nitrogen, these include ammonium (NH_4^+) and nitrate (NO_3^-) ions. For phosphorus, suitable forms include soluble orthophosphate ions ($H_2PO_4^-$, HPO_4^{2-}) and PO_4^{3-} compounds with magnesium, iron, aluminium, ammonium, or calcium. It is important to note that nutrient concentrations in waste streams are relatively low (1–200 mg·dm^{-3}), which significantly affects the economic feasibility of their recovery (Mehta *et al.*, 2015). Nevertheless, implementing nutrient recovery systems provides measurable environmental and economic benefits. These include reduced eutrophication of surface waters, decreased dependence on mineral fertilisers, enhanced food security, and the promotion of sustainable agricultural practices (Szopa *et al.*, 2024). Such approaches are fully consistent with the principles of the circular economy (CE). While P recovery technologies are well-developed and continue to improve (Egle, Rechberger and Zessner, 2015), nitrogen (N) recovery still faces significant research gaps. These limitations are primarily related to low capture and recovery efficiency (Śniatała *et al.*, 2024).

This review discusses selected methods for managing waste-derived nutrients, focusing particularly on N and P recycling within the CE framework. The study evaluates the potential of existing and emerging recovery technologies (Fig. 1), while considering social, legal, and economic aspects. Special attention is given to implementation barriers and development pathways in the light of current European Union regulations. By addressing the existing research gaps, this paper provides a comprehensive perspective on nutrient recycling in the context of evolving legislation and supports both scientific institutions and stakeholders implementing CE principles.

MATERIALS AND METHODS

The methodology was based on a systematic search and analysis of scientific literature and legal reports published between 2009 and 2025. The starting year was selected to align with the adoption of key European fertiliser and waste-related frameworks, such as Regulation (2009). The sources were retrieved from international databases such as Scopus, Web of Science, ScienceDirect, and Google Scholar. Legal acts were sourced from EUR-Lex. The literature search employed Boolean operators combining keywords related to nutrient recovery, circular economy, and wastewater treatment. Identified technologies were classified according to their technology readiness level (TRL), distinguishing between well-established processes (TRL ≥ 8) and emerging methods (TRL < 8).

RESULTS AND DISCUSSION

NUTRIENT RECOVERY TECHNOLOGIES AT A HIGH TECHNOLOGY READINESS LEVEL (TRL ≥ 8)

Conventional nutrient recovery methods with proven reliability are primarily biological processes mediated by microorganisms. These include (i) composting, (ii) anaerobic digestion (AD), and (iii) biological treatment processes. However, other biological waste management approaches, such as aerobic biostabilisation (Wolny-Koładka *et al.*, 2016) and biodrying (Malinowski and Wolny-Koładka, 2017), primarily aim at stabilisation, hygienisation, and decomposition of the biodegradable fraction of waste. Such pretreatment improves the safety and quality of the resulting material, allowing for its subsequent utilisation in wastewater treatment plants or as a feedstock for nutrient recovery.

Composting is an aerobic biodegradation process, resulting in the formation of mineral compounds. These compounds enhance soil microbial activity, improve soil structure, and increase water retention capacity (Dereszewska and Cytawa, 2023). The quality of the final compost depends heavily on feedstock composition, which determines its potential use as a fertiliser and soil amendment (O'Callaghan, 2016). During composting, partial N losses occur through the volatilisation of gaseous compounds, while P is largely retained, except for soluble

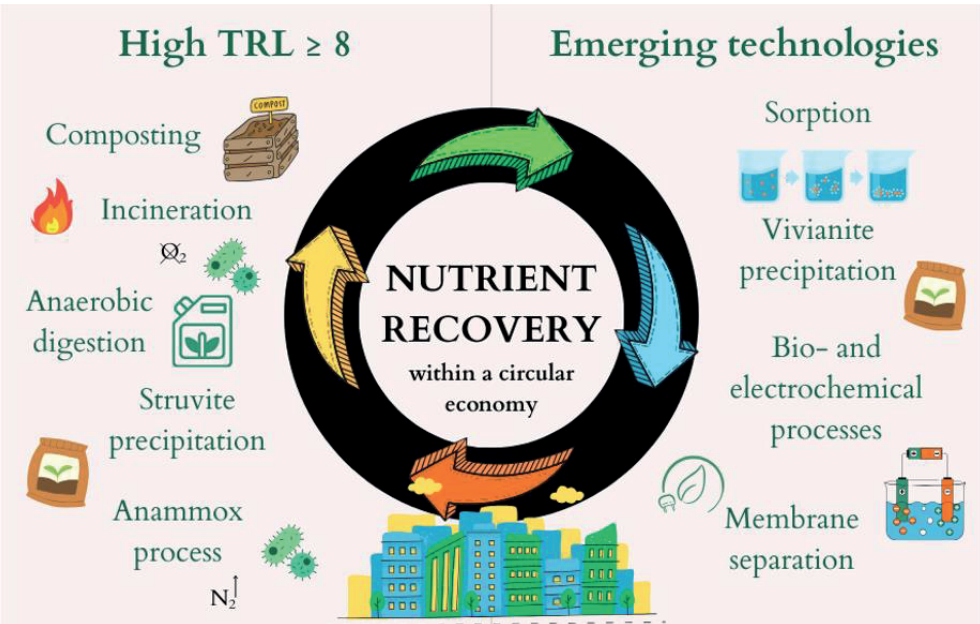

Fig. 1. Overview of selected nutrient recovery technologies within a circular economy (CE) framework; source: own elaboration

fractions in leachates (Carey *et al.*, 2016). An emerging approach involves the use of sewage sludge as a composting feedstock, which may also contribute to carbon sequestration in soil (Dereszewska and Cytawa, 2023). Rapid composting technologies have been recently developed, allowing for the production of P-rich biofertilisers (e.g., 3.90% N; 2.42% P; 0.65% K) (Guerra *et al.*, 2019). The effectiveness of composting as a nutrient recycling method should be verified through a comprehensive analysis. Key parameters include pH, microbial activity, macro- and micronutrient content, and the presence of contaminants, including heavy metals and pathogens (Carey *et al.*, 2016).

Anaerobic digestion (AD) is a microbial decomposition process of organic matter under anaerobic conditions that produces biogas – mainly methane (CH_4) – and digestate. The composition of these products depends on process parameters and feedstock type, which may include plant or animal biomass, wastewater, or sewage sludge (Puyol *et al.*, 2017). Due to its high content of organic and mineral compounds, digestate can be applied as a fertiliser to improve soil physicochemical properties, particularly in grassland management (Kowalczyk-Juśko and Szymańska, 2015). According to Regulation (2009), "digestion residues from the transformation of biogas or composting may be placed on the market and used as organic fertilisers or soil improvers". The application of digestate contributes to improved soil structure and the stabilisation of ammonium nitrogen content without negatively impacting aquatic ecosystems (Kowalczyk-Juśko, 2013). Digestate composition varies significantly depending on the feedstock. Sewage sludge-based digestate is typically rich in P, while that produced from slaughterhouse waste contains more N (Romero-Güiza *et al.*, 2016). Although N and K can be relatively easily recovered from the liquid stream, P recovery remains challenging due to the formation of insoluble phosphate (PO_4^{3-}) precipitates (Carey *et al.*, 2016). Importantly, the AD process couples nutrient recycling with the production of renewable energy in the form of biogas, which can be utilised in cogeneration systems (O'Callaghan, 2016). A notable example of integrated nutrient recovery was demonstrated in the Run4Life and SMART–Plant projects, where domestic wastewater was treated through thermophilic digestion and membrane bioreactors to produce a spectrum of valuable fertilisers, including NPK products, struvite, ammonium nitrate/sulphate, and P-based compounds (Rey-Martínez *et al.*, 2024).

Biological treatment processes rely on specialised microorganisms capable of metabolising N and P compounds and are widely applied in municipal wastewater treatment. Nitrogen removal is well-understood and highly efficient, typically achieved through nitrification and denitrification (Derco *et al.*, 2024). Enhanced biological P removal (EBPR) utilises polyphosphate-accumulating organisms (PAOs), which can store over 5% of P by dry mass (Egle, Rechberger and Zessner, 2015). Conducted under alternating aerobic and anaerobic conditions, EBPR can remove 80–90% of soluble P at C:P ratios exceeding 5 (Mehta *et al.*, 2015). The resulting sludge may contain 5–7% P, compared to only 1–2% in conventional activated sludge (Romero-Güiza *et al.*, 2016).

Thermochemical processes represent another group of high-TRL nutrient recovery technologies and include gasification and pyrolysis. These methods aim to produce materials with enhanced energetic and chemical value (O'Callaghan, 2016) and require carbon-rich feedstocks. Gasification is performed at temperatures above 800°C with a controlled oxidising agent, yielding syngas (a mixture of carbon monoxide and hydrogen) and ash containing inorganic components such as metals, P, and K. When the ash meets regulatory limits for heavy metals and contains sufficient P, it can be used as a soil amendment (Carey *et al.*, 2016). Pyrolysis is an anaerobic process conducted at temperatures up to 1000°C, producing three main fractions: solid (biochar), gaseous (pyrolytic gas), and liquid (bio-oil). Biochar is the principal product and is used as a sorbent, soil conditioner, and remediation agent (Carey *et al.*, 2016). Its unique properties, such as carbon sequestration potential, ion exchange capacity, nutrient retention, and contaminant immobilisation, make it a promising subject of ongoing research (Kehrein *et al.*, 2020). Bridle and Pritchard (2004) reported that sewage sludge pyrolysis allows for the recovery of 100% of P and K, and 55% of N from the feedstock, while pyrolysis of swine manure yields P-enriched biochar (Ehmann and Lewandowski, 2015).

INNOVATIVE NUTRIENT RECOVERY TECHNOLOGIES (TRL < 8)

Membrane technologies

Membrane filtration is a versatile and widely applied method in industrial processes. It functions as an integrated system for concentrating and separating components from mixed streams, without requiring phase transitions. In nutrient recycling systems, this technology is distinguished by its high efficiency and selectivity. It is particularly effective for recovering nutrients from wastewater and liquid waste. This performance results from the uniform pore size distribution characteristic of modern membranes (Derco *et al.*, 2024).

Membrane separation techniques have proven particularly effective in the recovery of N, P, and K from agricultural effluents, especially during manure processing (Mehta *et al.*, 2015). Research confirms the high efficiency of these methods in recovering various forms of P (Derco *et al.*, 2024). For nitrogen, membrane systems exhibit stable performance, largely independent of fluctuations in flow rate or ammonium concentration (Derco *et al.*, 2024). The retention efficiency of ammonium and nitrate ions in reverse osmosis and nanofiltration processes often exceeds 80%, with N recovery increasing under mildly acidic conditions as pH decreases (Mehta *et al.*, 2015). Optimal operating conditions, typically within a pH range of 6–8, help minimise membrane fouling, which is the primary limitation of these systems (Mehta *et al.*, 2015). Fouling, caused by the accumulation of organic matter, colloids, and microorganisms on membrane surfaces, leads to pore blockage, reduced selectivity, and decreased permeate flux (Śniatała *et al.*, 2023).

Electrochemical processes

Contemporary electrochemical technologies offer a promising approach to nutrient recovery. They utilise electric current and electrodes to initiate chemical reactions. The main approaches include electrodialysis and electrocoagulation. Electrodialysis, based on the migration of ions under an applied electric field through ion-exchange membranes, enables the selective separation of anions and cations (Kehrein *et al.*, 2020). A promising application of electrodialysis involves the regeneration of solutions containing magnesium or calcium ions, which could support P recovery (Soo, Kim and Shon, 2024). However, significant practical limitations remain. These are primarily related to high energy requirements and the need for periodic membrane regeneration (Śniatała *et al.*, 2023).

Electrocoagulation involves the release of metal ions from electrodes into the solution and is widely used in the treatment of wastewater containing various pollutants (Soo, Kim and Shon, 2024). In nutrient recovery systems, N can be captured through electrochemical reduction or oxidation, while P can be recovered via electrochemical precipitation or a combination of electrocoagulation and flocculation (Ammar *et al.*, 2024). A comprehensive review of N and P recovery through electrochemical processes, with particular emphasis on capacitive deionisation, was presented by Askari *et al.* (2024).

Precipitation and coagulation

The phosphate (PO_4^{3-}) precipitation process involves the application of coagulants, primarily multivalent metal ions such as calcium, aluminium, or iron. These ions form insoluble salts with PO_4^{3-} ions (Śniatała *et al.*, 2023). The innovative aspect of this classic method lies in the process leading to the precipitation of hydroxyapatite, dicalcium phosphate, or vivianite (Egle, Rechberger and Zessner, 2015). Vivianite ($Fe_3(PO_4)_2 \cdot 8H_2O$) is particularly interesting due to its slow-release properties and beneficial effects on plant chlorosis. Its fertiliser value may be up to six times greater than that of calcium phosphate (Robles *et al.*, 2020). However, vivianite typically occurs as difficult-to-separate crystals and is susceptible to oxidation (Robles *et al.*, 2020).

An example of a commercial implementation of the P precipitation process is the Quick Wash® technology (Fig. 2), developed by Renewable Nutrients, which is an innovative two-stage process that combines solubilisation with controlled P precipitation, enabling the recovery of over 95% of the total P from solid waste streams (Renewable Nutrients, no date).

Synergistic precipitation of N and P can be achieved by adding a magnesium (Mg) reagent in an alkaline environment. This leads to the formation of struvite ($MgNH_4PO_4 \cdot 6H_2O$, magnesium ammonium phosphate, MAP), a white crystalline compound of relatively high purity. This process is considered environmentally favourable because it requires minimal chemical input (Siciliano *et al.*, 2020). The economic feasibility of struvite production depends on the P concentration in the wastewater. Reported profitability thresholds range from 50 to 200 mg P·dm^{-3} (Mehta *et al.*, 2015; Śniatała *et al.*, 2023). Struvite has been officially recognised as a fertiliser, but its application necessitates the consideration of several important factors (Regulation, 2019). Due to its low N content, additional N supplementation is often required (Ehmann and Lewandowski, 2015). Moreover, the alkaline nature of struvite can elevate soil pH, reducing nutrient bioavailability (Ehmann and Lewandowski, 2015). Robles-Aguilar *et al.* (2019) demonstrated that struvite can act as an effective fertiliser amendment, particularly for plants exhibiting adaptive morphological and physiological mechanisms. Their study found that struvite application resulted in the highest P uptake per unit root surface area under both acidic and alkaline conditions. Current struvite production in Europe is estimated at approximately 15,000 Mg per year (Siciliano *et al.*, 2020). Among the commercial implementations, the Ostara Pearl® process is one of the most recognised technologies enabling the controlled precipitation of high-purity struvite granules (Crystal Green®). These slow-release fertilisers exhibit high plant availability under both acidic and alkaline soil conditions and reduce nutrient losses (Ostara, no date).

However, potential risks associated with waste-derived fertilisers must be carefully considered (Regulation, 2019). Wastewater may contain contaminants, including heavy metals and organic pollutants, which may adversely affect the quality and safety of the final product. For example, arsenic concentrations may reach up to 570 mg·kg^{-1} (Kowalczyk-Juśko, 2013).

Sorption

Sorption processes are well-established methods in wastewater treatment and environmental remediation. They are valued for their high operational effectiveness and versatility. These processes enable the selective capture of both nutrients and contaminants through two mechanisms: absorption, which involves penetration of a substance into the sorbent structure, and adsorption, which refers to accumulation of a substance on the sorbent surface. Effective sorbents should exhibit biocompatibility and biodegradability, and contain functional groups, such

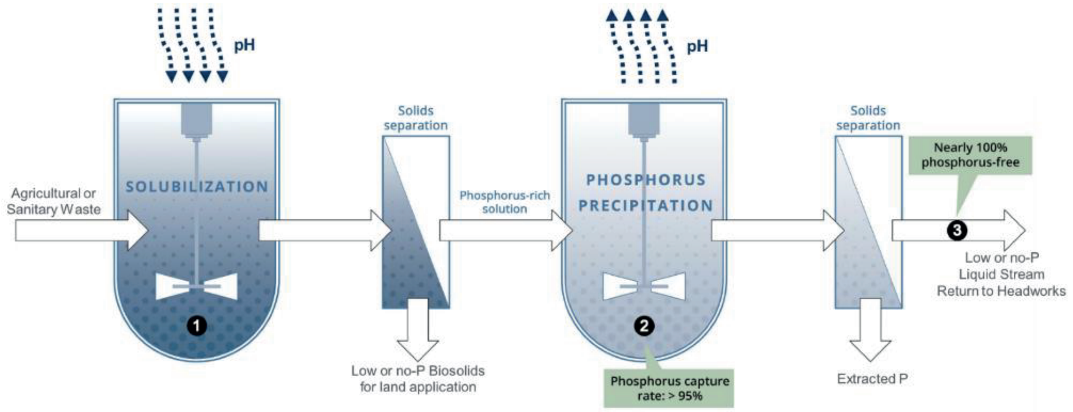

Fig. 2. Schematic diagram of the two-stage Quick Wash® P recovery process developed by Renewable Nutrients; source: Renewable Nutrients

as hydroxyl –OH and carboxyl –COOH, that facilitate ion exchange. Low toxicity and high mechanical strength are also essential properties. Adsorption mechanisms involve various physicochemical interactions, including ion exchange, electrostatic interactions, physisorption, hydrogen bonding, and complex formation (Wang *et al.*, 2023). Sorption technologies are applicable across a wide range of nutrient concentrations (1–2,000 $mg\cdot dm^{-3}$) (Mehta *et al.*, 2015). However, their practical use has certain limitations. One challenge is the co-adsorption of valuable nutrient ions and unwanted contaminants, which may restrict the recycling potential of the sorbent. Furthermore, effective desorption and material durability under variable environmental conditions, such as pH, temperature, and presence of pathogens, continue to pose technical challenges.

The innovative potential of this method lies in the ongoing development of advanced sorbent materials, as summarised in Table 1. In addition to high sorption capacity, effective sorbents must exhibit a porous structure that enables controlled nutrient release. They should also exhibit high water retention capacity and selectivity toward specific ions (Szopa *et al.*, 2024).

Composite and modified sorbents with enhanced simultaneous adsorption capacity for N and P ions show significant potential (Ahmed, Mekonnen and Mekonnen, 2023). However, P speciation and binding behaviour depend strongly on the sorbent type (Carey *et al.*, 2016). Despite their potential, sorption technologies face several limitations. These include high production and modification costs associated with sorbent production, challenges in material regeneration, dependence on non-renewable resources, and limited long-term durability.

CHALLENGES AND PERSPECTIVES OF NUTRIENT RECOVERY

The analysis by Kehrein *et al.* (2020) reveals a complex set of challenges concerning the effective recycling of resources. The authors identify eight fundamental barriers: (i) operational costs, (ii) quantity of recoverable raw material, (iii) market competitiveness, (iv) disposal and management, (v) transportation, (vi) emissions, (vii) social acceptance, and (viii) policy.

TECHNOLOGICAL AND INFRASTRUCTURAL CHALLENGES

Wastewater treatment plants offer enormous potential for nutrient recovery (Fig. 3). Sewage sludge contains significant amounts of N (10–15%) and P (1.0–2.5%). However, the efficient utilisation of these nutrients requires complex processing (Rey-Martínez *et al.*, 2024). Wastewater can be subjected to multi-stage treatment and concentration processes, such as membrane filtration, adsorption, ion exchange, or electrochemical methods, to increase nutrient concentrations (Carey *et al.*, 2016). However, the implementation of advanced technologies encounters substantial obstacles. One of the most critical challenges is the disparity between laboratory and industrial scales of application.

Table 1. Selected innovative adsorbents in nutrient recovery

Selected adsorbents	Sorbate	Adsorption capacity ($mg\cdot g^{-1}$)	pH	References
Alginate/Fe capsules	PO_4^{3-}	49.50	4.0–10.0	Siwek *et al.* (2016)
Biosolids-derived biochar	NH_4^+	1.80	–	Halder *et al.* (2023)
Chitosan-montmorillonite-Fe nanocomposite hydrogel	PO_4^{3-}	86.70	5.4	Dou and Xie (2023)
Gel-type polymer sorbent	PO_4^{3-}	137.20	–	Pacchione *et al.* (2024)
K-zeolite	PO_4^{3-}	250.00	6.0–9.0	Hermassi *et al.* (2020)
Magnetite-biochar nanocomposite of jackfruit peel	PO_4^{3-} NO_3^-	7.94 5.26	4.0–6.0	Nayak *et al.* (2021)
MgAl-layered double hydroxides / sodium alginate beads	NO_3^-	22.36	4.0–10.0	Vu and Wu (2022)
Mg-doped *Sargassum horneri* biochar	PO_4^{3-} NH_4^+	>120.00 22.80–28.20	8.0–10.0	Lee *et al.* (2021)
Mg-Fe bimetallic oxide nanocomposite	PO_4^{3-} NH_4^+	318.60 138.20	2.0–9.0	Yu *et al.* (2024)
Mg-loaded chitosan carbonised microspheres	PO_4^{3-} NH_4^+	131.02 67.21	8.5	Li *et al.* (2023)
Mg-modified starch cryogels	PO_4^{3-} NH_4^+	70.07 25.52	2.5–9.5	Zhao *et al.* (2024)
Modified rice husk	PO_4^{3-} NO_3^-	6.94 2.46	3.0–9.0	Sooksawat *et al.* (2021)
Mordenite-chitosan	NH_4^+	17.70	7.0	Safie and Yaser (2024)
Soda-modified biochar of sorghum straw	PO_4^{3-} NH_4^+	114.96 3.87	2.0–11.0	Liu and Zhang (2023)
Zr-modified acid-leaching residue adsorbent	PO_4^{3-}	53.10	10.0	Hu *et al.* (2023)

Source: own elaboration.

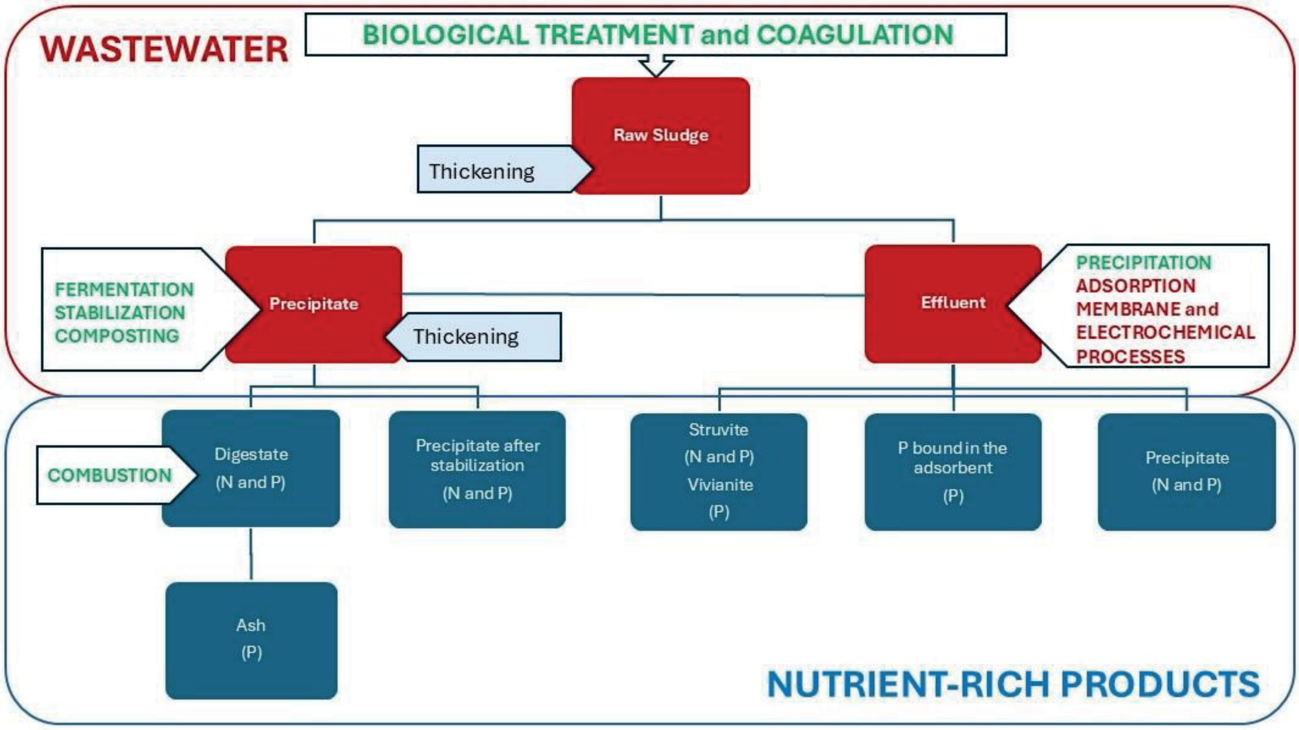

Fig. 3. Schematic diagram of nutrient recovery methods in wastewater treatment plants (conventional methods are shown in green, while methods not implemented on an industrial scale are in red); source: own elaboration

Many promising technologies have demonstrated effectiveness under controlled conditions but have not been deployed in full-scale facilities due to the lack of operational reference data and the difficulty of adapting existing infrastructure (Derco *et al.*, 2024).

Examples of successful process integration, such as those demonstrated in the SYSTEMIC project (2017–2021), show that the synergy between biogas production and nutrient recovery from digestate can deliver tangible environmental and economic benefits. Nevertheless, scaling these achievements to the industrial level remains challenging and requires not only technological innovation but also systemic transformation (Kehrein *et al.*, 2020). Although the initial investment cost of modern installations may seem acceptable, ongoing technological advancements necessitate frequent upgrades and costly maintenance. These cumulative expenses gradually limit the large-scale industrialisation of nutrient recycling (Kehrein *et al.*, 2020). The economic performance of the processes depends on the type of technology employed, the need for waste stream pretreatment, and plant capacity. These factors also influence the payback period and long-term scalability (Śniatała *et al.*, 2023).

The relatively low nutrient concentrations in wastewater, combined with the presence of diverse contaminants, significantly reduce the profitability of recovery processes. One potential solution is the strategic combination of multiple waste streams to achieve a more favourable nutrient balance. Alternatively, the integration of advanced separation systems may enhance recovery efficiency; however, this necessitates comprehensive optimisation of both process parameters and plant design, ultimately increasing operational costs and energy demand. Moreover, integrating new installations into existing infrastructure involves complex engineering and administrative challenges, often requiring compliance with additional legal and environmental standards.

SOCIAL AND LEGAL ASPECTS

The growing environmental awareness in society and the increasing emphasis on the CE have accelerated the adoption of nutrient recycling solutions. However, a paradox of the modern ecological market lies in the simultaneous rise of genuine interest in zero-waste initiatives and greenwashing practices. In this context, fertiliser products, such as struvite, should not only carry "eco-friendly" labels but also be supported by verifiable information on certification, agronomic validation, and regulatory compliance. Including such information on product labels can significantly enhance consumer confidence and improve market acceptance (Mehta *et al.*, 2015). From a legal perspective, the European Union actively supports the development of nutrient recovery technologies. Regulation (2019) establishes standards for the quality and certification of fertiliser products placed on the EU market, including those derived from recycling processes. Scientific research confirms that recycled fertilisers can achieve effectiveness comparable to conventional products (Śniatała *et al.*, 2024). Nonetheless, public acceptance remains limited, partly due to psychological resistance to products derived from wastewater treatment (Śniatała *et al.*, 2024). Overcoming this barrier will require sustained educational efforts and transparent certification systems.

The newly adopted Directive (2024) introduces additional obligations for the water and wastewater sectors by setting more stringent standards for nutrient removal. The directive mandates expanded municipal wastewater management and imposes effluent limits of 10.0 mg $N{\cdot}dm^{-3}$ and 0.7 mg $P{\cdot}dm^{-3}$ for agglomerations with a population equivalent (PE) between 10,000 and 150,000. Even stricter thresholds of 8.0 mg $N{\cdot}dm^{-3}$ and 0.5 mg $P{\cdot}dm^{-3}$ apply to agglomerations exceeding 150,000 PE. Although these regulatory measures pose significant organisational and financial challenges for wastewater treatment operators, they also stimulate technological innovation and represent a major step toward sustainable resource management.

FUTURE DEVELOPMENT DIRECTIONS

The rapid development of nutrient recovery technologies requires a stronger focus in future research on process optimisation, aiming to reduce operational costs while enhancing efficiency, regardless of the initial nutrient load. Three key strategic directions can be identified: (i) capturing nutrients from low-concentration streams; (ii) releasing nutrients bound in complex structures; and (iii) extracting nutrients from sources such as sewage sludge (Mehta *et al.*, 2015).

An important research area involves identifying environmentally sustainable substitutes for conventional reagents. For instance, waste-derived materials may serve as magnesium sources in the struvite precipitation process. Instead of traditional chemical reagents, alternatives such as waste nigari (seawater bittern – a by-product of seawater desalination) or other locally available magnesium-rich residues can be used, reducing both process costs and environmental impact (Campos *et al.*, 2019).

The implementation of nature-based solutions (NbS), defined as technologies inspired and supported by natural processes, represents a strategic pathway to advancing nutrient recycling (Wirth *et al.*, 2021). NbS approaches enhance biodiversity and natural capital, reduce chemical and energy inputs, and effectively remove contaminants, thereby aligning environmental restoration with resource recovery goals.

Another promising direction is the development of *in-situ* recycling systems, particularly in rural areas where farms act simultaneously as fertiliser consumers, nutrient emitters, and producers of nutrient-rich waste (e.g., slurry containing 4–33 g $P \cdot kg^{-1}$) (Rey-Martínez *et al.*, 2024). An example of such innovative *in-situ* technology is the SyreN system developed by BioCover, which acidifies slurry during field application to reduce ammonia volatilisation (approximately 49%) (BioCover, 2018). SyreN significantly enhances N retention in the ammonium form and improves overall nutrient use efficiency, making it highly complementary to circular nutrient management strategies. Localised nutrient recovery systems can substantially reduce transport costs, alleviate environmental pressures, and foster new circular business models (Śniatała *et al.*, 2024).

The advancement of the sector will also depend on the integration of advanced monitoring systems and transparent data sharing concerning nutrient concentrations, thereby fostering public acceptance and supporting process optimisation. Life cycle assessment (LCA) remains an essential analytical tool, enabling a comprehensive evaluation of the environmental impact of recycling technologies (Robles *et al.*, 2020). Notable examples of LCA-based nutrient recovery studies include those by Fang *et al.* (2016) and Lam, Zlatanović and Hoek van der (2020).

Progress in this field is further reinforced by collaborative initiatives and stakeholder networks such as NUTRIMAN (Nutrient Management and Nutrient Recovery Thematic Network) and ESPP (European Sustainable Phosphorus Platform) (Hofmann *et al.*, 2024). NUTRIMAN compiles a catalogue of ready-to-implement (TRL > 6) technologies tested under real operating conditions, while ESPP promotes legal and policy advancements, focusing primarily on P recovery but also encompassing N-related processes. Cross-sectoral collaboration facilitates knowledge exchange, accelerates innovation uptake, and strengthens the link between research and policy.

A major future breakthrough is likely to arise from the deployment of artificial intelligence-based systems integrating sensor networks, automation, and advanced mathematical modelling (Śniatała *et al.*, 2024; Robles *et al.*, 2020). Such digital tools can improve predictive capabilities in nutrient recovery systems.

CONCLUSIONS

A contemporary approach to nutrient management requires a critical assessment of current practices. The modernisation of existing infrastructure, combined with the implementation of advanced technologies aligned with CE principles, will demand substantial investment and coordinated action among multiple stakeholders.

Developing comprehensive decision-making frameworks, integrating environmental and economic assessments with advanced AI tools and LCA methodologies, is essential for selecting optimal technologies. The choice of technological pathways must account not only for economic feasibility but also nutrient concentration efficiency, the degree of circularity, and compatibility with existing systems.

The implementation of these technologies is a gradual, long-term process, the effects of which will be evident through reduced dependence on synthetic fertilisers, conservation of natural resources through the use of alternative nutrient sources, and lower costs associated with aquatic ecosystem remediation. The foundation of this transformation lies in the consistent application of the 3R principle (reduce – reuse – recycle), alongside a paradigm shift in the perception of waste – from a disposal challenge to a valuable resource. Such a shift will enable the transformation of treatment plants into centres for secondary raw material production.

Despite existing obstacles, nutrient recycling should be regarded as a strategic opportunity to develop a sustainable nutrient management system (Kehrein *et al.*, 2020). The combination of technological innovation, new business models, and cross-sectoral collaboration provides a basis for developing efficient and economically viable solutions in the coming years.

In the context of the escalating climate and resource crisis (EC, 2020), sustainable nutrient management is no longer optional but imperative. The key challenge lies in creating a coherent system that combines innovation, social acceptance, economic viability, and regulatory alignment. Although the challenges are substantial at every level, a holistic and coordinated approach remains crucial. Only through such integrated efforts can society address the challenges of the coming decades and achieve a truly circular nutrient management system.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

REFERENCES

Ahmed, A.M., Mekonnen, M.L. and Mekonnen, K.N. (2023) "Polymer-based nanocomposite adsorbents for resource recovery from wastewater," *RSC Advances*, 13(45), pp. 31687–31703. Available at: https://doi.org/10.1039/D3RA05453E.

Ammar, M. *et al.* (2024) "Removal of inorganic pollutants and recovery of nutrients from wastewater using electrocoagulation: A review," *Separations*, 11(11), 320. Available at: https://doi.org/10.3390/separations11110320.

Aragón-Briceño, C.I. *et al.* (2021) "Hydrothermal carbonization of wet biomass from nitrogen and phosphorus approach: A review," *Renewable Energy*, 171, pp. 401–415. Available at: https://doi.org/10.1016/j.renene.2021.02.109.

Askari, M. *et al.* (2024) "Advances in capacitive deionization (CDI) systems for nutrient recovery from wastewater: Paving the path towards a circular economy," *Desalination*, 583, 117695. Available at: https://doi.org/10.1016/j.desal.2024.117695.

BioCover (2018) *SyreN brochure*. Available at: https://www.biocover.dk/CustomerData/Files/Folders/1017-pdf-uk/4145_syren-brochure-2018-eng.pdf (Accessed: November 16, 2025).

Bridle, T.R. and Pritchard, D. (2004) "Energy and nutrient recovery from sewage sludge via pyrolysis," *Water Science & Technology*, 50(9), pp. 169–175. Available at: https://doi.org/10.2166/wst.2004.0562.

Campos, J.L. *et al.* (2019) "Nitrogen and phosphorus recovery from anaerobically pretreated agro-food wastes: A review," *Frontiers in Sustainable Food Systems*, 2, 91. Available at: https://doi.org/10.3389/fsufs.2018.00091.

Carey, D.E. *et al.* (2016) "Recovery of agricultural nutrients from biorefineries," *Bioresource Technology*, 215, pp. 186–198. Available at: https://doi.org/10.1016/j.biortech.2016.02.093.

Derco, J. *et al.* (2024) "Nutrient removal and recovery from municipal wastewater," *Processes*, 12(5), 894. Available at: https://doi.org/10.3390/pr12050894.

Dereszewska, A. and Cytawa, S. (2023) "Circular economy in wastewater treatment plants–potential opportunities for biogenic elements recovery," *Water*, 15(21), 3857. Available at: https://doi.org/10.3390/w15213857.

Directive (2024) "Directive (EU) 2024/3019 of the European Parliament and of the Council of 27 November 2024 concerning urban wastewater treatment," *Official Journal*, L 2024/3019. Available at: https://eur-lex.europa.eu/eli/dir/2024/3019/oj/eng (Accessed: March 18, 2025).

Dou, Z. and Xie, X. (2023) "Chitosan–Montmorillonite–Fe Nanocomposite hydrogel for phosphate recovery and reuse," *ACS ES&T Engineering*, 3(5), pp. 682–689. Available at: https://doi.org/10.1021/acsestengg.2c00390.

EC (2020) *Critical raw materials resilience: Charting a path towards greater security and sustainability*. Brussels: European Commission. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0474 (Accessed: March 10, 2025).

Egle, L., Rechberger, H. and Zessner, M. (2015) "Overview and description of technologies for recovering phosphorus from municipal wastewater," *Resources, Conservation and Recycling*, 105, pp. 325–346. Available at: https://doi.org/10.1016/j.resconrec.2015.09.016.

Ehmann, A. and Lewandowski, I. (2015) "Effect of manure-based ammonium sulfate and biochar on biomass yield and soil properties," in *23rd European Biomass Conference and Exhibition*. [Poster]. Vienna, Austria, 01–04 June, 2015.

Fang, L.L. *et al.* (2016) "Life cycle assessment as development and decision support tool for wastewater resource recovery technology," *Water Research*, 88, pp. 538–549. Available at: https://doi.org/10.1016/j.watres.2015.10.016.

Guerra, N. *et al.* (2019) "Advanced composting and bio-drying as an opportunity to recover material and energetic resources from sludges," in *3rd IWA Resource Recovery Conference*, pp. 365–367. Venice, Italy, September 8–12, 2019. Available at: https://www.smart-plant.eu/images/publications/resource-recovery-products/73_IWARR2019_Book-of-Abstracts-2.jpg.pdf (Accessed: March 18, 2025).

Halder, P. *et al.* (2023) "Ammonium nitrogen (NH^{4+}-N) recovery from synthetic wastewater using biosolids-derived biochar," *Bioresource Technology Reports*, 23, 101592. Available at: https://doi.org/10.1016/j.biteb.2023.101592.

Hermassi, M. *et al.* (2020) "Phosphate recovery from aqueous solution by K-zeolite synthesized from fly ash for subsequent valorisation as slow release fertilizer," *Science of The Total Environment*, 731, 139002. Available at: https://doi.org/10.1016/j.scitotenv.2020.139002.

Hofmann, A.H. *et al.* (2024) "Nutrient recovery from wastewater for hydroponic systems: A comparative analysis of fertilizer demand, recovery products, and supply potential of WWTPs," *Journal of Environmental Management*, 352, 119960. Available at: https://doi.org/10.1016/j.jenvman.2023.119960.

Hu, S. *et al.* (2023) "Selective recovery of phosphorus from the leachate of incinerated sewage sludge ash using the Zr-modified acid-leaching residue as adsorbent for two-fold resource utilization," *Chemical Engineering Journal*, 477, 147174. Available at: https://doi.org/10.1016/j.cej.2023.147174.

Kehrein, P. *et al.* (2020) "A critical review of resource recovery from municipal wastewater treatment plants – market supply potentials, technologies and bottlenecks," *Environmental Science: Water Research & Technology*, 6(4), pp. 877–910. Available at: https://doi.org/10.1039/C9EW00905A.

Kowalczyk-Juśko, A. (2013) *Biogazownie szansą dla rolnictwa i środowiska [Biogas plants an opportunity for agriculture and the environment]*. Warszawa: Wydaw. FDPA.

Kowalczyk-Juśko, A. and Szymańska, M. (2015) *Poferment nawozem dla rolnictwa [Digestate as a fertilizer for agriculture]*. Warszawa: Wydaw. FDPA.

Lam, K.L., Zlatanović, L. and Hoek van der, J.P. (2020) "Life cycle assessment of nutrient recycling from wastewater: A critical review," *Water Research*, 173, 115519. Available at: https://doi.org/10.1016/j.watres.2020.115519.

Lee, Y.E. *et al.* (2021) "Fabrication of Mg-doped sargassum biochar for phosphate and ammonium recovery," *Sustainability*, 13(22), 12752. Available at: https://doi.org/10.3390/su132212752.

Li, L. *et al.* (2023) "Simultaneous ammonium and phosphate removal with Mg-loaded chitosan carbonized microsphere: Influencing factors and removal mechanism," *Environmental Research*, 228, 115850. Available at: https://doi.org/10.1016/j.envres.2023.115850.

Liu, L. and Zhang, M. (2023) "Soda residue as a novel modifier for straw biochar enhanced recovery of phosphate and ammonium from water," *International Journal of Environmental Science and Technology*, 20(12), pp. 13783–13798. Available at: https://doi.org/10.1007/s13762-023-04935-4.

Malinowski, M. and Wolny-Kołladka, K. (2017) "Microbiological and energetic assessment of the effects of the biodrying of fuel produced from waste," *Ecological Chemistry and Engineering S*, 24(4), pp. 551–564. Available at: https://doi.org/10.1515/eces-2017-0036.

Mehta, C. *et al.* (2015) "Technologies to recover nutrients from waste streams: A critical review," *Critical Reviews in Environmental Science and Technology*, 45(4), pp. 385–427. Available at: https://doi.org/10.1080/10643389.2013.866621.

Nayak, A. *et al.* (2021) "Fabrication of microwave assisted biogenic magnetite-biochar nanocomposite: A green adsorbent from jackfruit peel for removal and recovery of nutrients in water sample," *Journal of Industrial and Engineering Chemistry*, 100, pp. 134–148. Available at: https://doi.org/10.1016/j.jiec.2021.05.028.

O'Callaghan, K. (2016) "Technologies for the utilisation of biogenic waste in the bioeconomy," *Food Chemistry*, 198, pp. 2–11. Available at: https://doi.org/10.1016/j.foodchem.2015.11.030.

Ostara (no date) *Crystal Green Pearl® Fertilizer*. Available at: https://www.ostara.com/nutrient-recovery/crystal-green-pearl/ (Accessed: November 10, 2025).

Pacchione, M. *et al.* (2024) "Evaluation of performance and stability of a gel-type polymer sorbent for recovery of phosphate from waste streams," *ACS Applied Polymer Materials*, 6(24), pp. 15304–15312. Available at: https://doi.org/10.1021/acsapm.4c03237.

Project SYSTEMIC (2017–2021) *Project funded under the EU Framework Programme (Horizon 2020, No. 730400)*. Available at: https://systemicproject.eu/ (Accessed: March 18, 2025).

Puyol, D. *et al.* (2017) "Resource recovery from wastewater by biological technologies: Opportunities, challenges, and prospects," *Frontiers in Microbiology*, 7, 2106. Available at: https://doi.org/10.3389/fmicb.2016.02106.

Qadir, M. *et al.* (2020) "Global and regional potential of wastewater as a water, nutrient and energy source," *Natural Resources Forum*, 44(1), pp. 40–51. Available at: https://doi.org/10.1111/1477-8947.12187.

Regulation (2009) *Regulation (EC) No. 1069/2009 of the European Parliament and of the Council of 21 October 2009 laying down health rules as regards animal by-products and derived products not intended for human consumption and repealing Regulation (EC) No. 1774/2002 (Animal by-products Regulation)*. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009R1069 (Accessed: April 10, 2025).

Regulation (2019) *Regulation (EU) No. 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No. 1069/2009 and (EC) No. 1107/2009 and repealing Regulation (EC) No. 2003/2003 (Text with EEA relevance)*. Available at: https://eur-lex.europa.eu/eli/reg/2019/1009/oj/eng (Accessed: March 17, 2025).

Renewable Nutrients (no date) *Quick Wash® Phosphorus Extraction & Recovery*. Available at: https://www.renewablenutrients.com/quickwash (Accessed: November 10, 2025).

Rey-Martínez, N. *et al.* (2024) "Combination of technologies for nutrient recovery from wastewater: A review," *Cleaner Waste Systems*, 7, 100139. Available at: https://doi.org/10.1016/j.clwas.2024.100139.

Robles, Á. *et al.* (2020) "New frontiers from removal to recycling of nitrogen and phosphorus from wastewater in the Circular Economy," *Bioresource Technology*, 300, 122673. Available at: https://doi.org/10.1016/j.biortech.2019.122673.

Robles-Aguilar, A.A. *et al.* (2019) "The effect of pH on morphological and physiological root traits of *Lupinus angustifolius* treated with struvite as a recycled phosphorus source," *Plant and Soil*, 434, pp. 65–78. Available at: https://doi.org/10.1007/s11104-018-3787-2.

Romero-Güiza, M.S. *et al.* (2016) "Nutrient recovery technologies for anaerobic digestion systems: An overview," *Revista ION*, 29(1), pp. 7–26. Available at: https://doi.org/10.18273/revion.v29n1-2016001.

Safie, N.N. and Yaser, A.Z. (2024) "Adsorption of ammonium ion (NH_4^+) using mordenite-chitosan from synthetic and actual sewage: Batch and fixed-bed studies," *Process Safety and Environmental Protection*, 185, pp. 670–683. Available at: https://doi.org/10.1016/j.psep.2024.03.048.

Siciliano, A. *et al.* (2020) "Advances in struvite precipitation technologies for nutrients removal and recovery from aqueous waste and wastewater," *Sustainability*, 12(18) , 7538. Available at: https://doi.org/10.3390/su12187538.

Siwek, H. *et al.* (2016) "Removal of phosphate from aqueous solution using alginate/iron(III) chloride capsules: A laboratory study," *Water, Air, & Soil Pollution*, 227, 427. Available at: https://doi.org/10.1007/s11270-016-3128-0.

Śniatała, B. *et al.* (2023) "Macro-nutrients recovery from liquid waste as a sustainable resource for production of recovered mineral fertilizer: Uncovering alternative options to sustain global food security cost-effectively," *Science of The Total Environment*, 856, 159283. Available at: https://doi.org/10.1016/j.scitotenv.2022.159283.

Śniatała, B. *et al.* (2024) "Advancing sustainable wastewater management: A comprehensive review of nutrient recovery products and their applications," *Science of The Total Environment*, 937, 173446. Available at: https://doi.org/10.1016/j.scitotenv.2024.173446.

Soo, A., Kim, J. and Shon, H.K. (2024) "Technologies for the wastewater circular economy – A review," *Desalination and Water Treatment*, 317, 100205. Available at: https://doi.org/10.1016/j.dwt.2024.100205.

Sooksawat, N. *et al.* (2021) "Recycling rice husk for removal of phosphate and nitrate from synthetic and swine wastewater: Adsorption study and nutrient analysis of modified rice husk," *Journal of Environmental Science and Health Part A*, 56, pp. 1080-1092. Available at: https://doi.org/10.1080/10934529.2021. 1962165.

Szopa, D. *et al.* (2024) "Hydrogel applications in nitrogen and phosphorus compounds recovery from water and wastewater: An overview," *Sustainability*, 16(15), 6321. Available at: https://doi.org/10.3390/su16156321.

Vu, C.T. and Wu, T. (2022) "MgAl-layered double hydroxides/sodium alginate beads for nitrate adsorption from groundwater and potential use as a slow-release fertilizer," *Journal of Cleaner Production*, 379, 134508. Available at: https://doi.org/10.1016/j.jclepro.2022.134508.

Wang, X. *et al.* (2023) "Nutrient recovery technologies for management of blackwater: A review," *Frontiers in Environmental Science*, 10, 1080536. Available at: https://doi.org/10.3389/fenvs.2022.1080536.

Wang, Z., Skerlos, S.J. and Novak, P.J. (2024) "Nitrogen and Phosphorus Recovery from Anthropogenic Liquid Waste Streams," *Annual Review of Environment and Resources*, 49(1), pp. 281–307. Available at: https://doi.org/10.1146/annurev-environ-112320-082121.

Wirth, M. *et al.* (2021) "Potential Nutrient Conversion Using Nature-Based Solutions in Cities and Utilization Concepts to Create Circular Urban Food Systems," *Circular Economy and Sustainability*, 1(3), pp. 1147–1164. Available at: https://doi.org/10.1007/s43615-021-00081-6.

Wolny-Koładka, K. *et al.* (2016) "Effect of the intensive aerobic biostabilization phase on selected microbiological and physicochemical parameters of wastes," *Infrastructure and Ecology of Rural Areas*, 4(1), pp. 1099–1115. Available at: https://doi.org/10.14597/infraeco.2016.4.1.080.

Yu, S.H. *et al.* (2024) "Mg-Fe bimetallic oxide nanocomposite for superior phosphate removal and recovery from aquatic environment: Synergistic effects of sorption and struvite crystallization," *Journal of Environmental Chemical Engineering*, 12(2), 112132. Available at: https://doi.org/10.1016/j.jece.2024.112132.

Zhao, C. *et al.* (2024) "Magnesium-modified starch cryogels for the recovery of nitrogen and phosphorus from wastewater and its potential as a fertilizer substitute: A novel nutrient recovery approach," *Journal of Environmental Chemical Engineering*, 12(5), 114044. Available at: https://doi.org/10.1016/j.jece.2024.114044.