From Tradition to Innovation: The Evolution and Future Prospects of Phosphorus Removal Technologies in Wastewater Treatment

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Abstract. Phosphorus removal from wastewater is a critical environmental issue due to its role in eutrophication and negative impacts on aquatic ecosystems. This paper systematically reviews the evolution and prospects of phosphorus removal technologies, from traditional methods to innovative advancements. Traditional methods such as chemical precipitation and biological treatment have demonstrated high removal efficiencies but suffer from issues related to sludge generation, high operational costs, and secondary pollution risks. Innovative technologies, including the use of modified biochar, electro-flocculation, and micro electrolysis, have shown significant improvements in efficiency and cost-effectiveness. The paper also examines emerging composite processes that integrate multiple methods to maximize phosphorus removal while minimizing drawbacks. Additionally, the study highlights the importance of phosphorus resource recovery and circular economy approaches, alongside the potential for intelligent and automated wastewater management systems. This review further examines international phosphorus discharge standards to identify global regulatory trends, thus providing practical guidance and strategic insights for policymakers and practitioners implementing future-oriented phosphorus removal solutions.

1 Introduction

As a non-renewable resource in the environment, phosphorus discharged from agricultural and food industry wastewater into confined or semi-confined water bodies can trigger the overgrowth of specific algal blooms, leading to eutrophication. It could reduce water quality and increase water supply costs. Eutrophic waters have limited ability to self-regulate and often rely on artificial intervention. Phosphorus mainly exists as phosphate in phosphate ores. Still, during production and consumption in the food industry, large amounts of phosphorus are lost as runoff or manure into aquatic systems or soil. In global animal husbandry, only about 50% of phosphorus can be recycled [1], therefore, increasing phosphorus recycling has significant environmental and economic benefits.

Due to the lack of systematic operation and regulation for wastewater phosphorus, small-scale wastewater treatment plants are often less effective than large-scale treatment plants [2]. Large amounts of sludge generation commonly accompany conventional phosphorus removal processes, but only part of the sludge can be converted into fertilizer after subsequent treatment. In practical applications, existing processes mainly focus on the removal of phosphorus from wastewater. The research on recycling is relatively insufficient. How to strike a balance between environmental protection and economic benefits is still an urgent topic to be explored. Molinos-Senante et al. [3] proposed an evaluation method to assess the economic feasibility of phosphorus recycling from wastewater.

Currently, the removal methods of sewage phosphorus mainly include chemical precipitation, adsorption, and biological treatment. A combination of methods is often used in practical applications. The traditional physical and chemical methods have advantages of a wide range of applications and high removal efficiency, but the phosphorus products generated by them are more difficult to separate, and their effect on sewage treatment with a low concentration of phosphorus is weaker. In contrast, biological treatment is more sensitive to low concentrations of phosphorus and is suitable for trace treatment. However, the stability and efficiency of its microbial treatment are low, and more sludge will be produced. In recent years, ion exchange, membrane treatment, and other emerging methods have been gradually maturing. Although these methods have certain advantages in technology, there are generally high costs and strict requirements for the quality of influent water and other issues. In addition, the efficient tandem application of physical-chemical and biological treatments has significantly improved the efficiency of wastewater phosphorus recovery [4]. In this paper, the author reviewed the traditional effluent phosphorus removal technologies and their advantages and drawbacks, organized and evaluated the novel technologies, and provided a theoretical and practical basis for achieving more efficient effluent phosphorus removal in the future.

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2 Characterization and removal mechanism of phosphorus in wastewater

2.1 Forms and sources of phosphorus in sewage

Phosphorus in wastewater can be categorized based on its physical form, namely particulate phosphate and dissolved total phosphate. The focus of wastewater monitoring is typically on the detection of dissolved phosphorus due to the relative ease with which particulate phosphates can be separated. Dissolved phosphorus is predominantly composed of inorganic phosphorus. Its main forms include aluminium-bound phosphorus (Al-P) and iron-bound phosphorus (Fe-P). Organic phosphorus shows diversified forms, and its main sources are feces and agricultural wastewater. Differences in dissolved oxygen (DO) conditions in the water column have a significant effect on the distribution characteristics of phosphorus. Under different dissolved oxygen environments, the major forms of inorganic phosphorus were relatively stable, while organic phosphorus was prone to transformation. This transformation process has been shown to further affect the adsorption and release behavior of phosphorus.[5]

2.2 Chemical and physical mechanisms of phosphorus removal

The process of chemical precipitation entails the introduction of metal cations into the effluent, which undergoes a reaction with phosphate ions, resulting in the formation of a precipitate that is insoluble in water. The most employed metal cations in this context include Fe^{2+}, Fe^{3+}, and Al^{3+}. The precipitate that is formed assumes the form of chemical sludge, and the separation of phosphorus-containing sludge from water is accomplished through processes such as sedimentation or filtration. The adsorption method utilizes adsorption materials with high adsorption capacity, a rapid adsorption rate, and excellent selectivity and harmlessness to adsorb phosphorus in the water body. The adsorption process can be categorized into physical adsorption and chemical adsorption. Physical adsorption relies on the formation of multilayer adsorption by electrostatic gravitational force and the deposition of solid surfaces. Chemical adsorption realizes monolayer adsorption by ligand complexation and ion exchange mechanisms.

Biological phosphate removal technology is predicated on the metabolic process of microorganisms, and its methods can be divided into polyphosphate bacteria phosphate removal and denitrifying phosphorus removal. In the process of phosphorus removal by polyphosphate bacteria, polyphosphate is first decomposed by polyphosphate bacteria in anaerobic conditions. Phosphate is then taken up by the bacteria in the water under aerobic conditions and converted to polyphosphate. This results in the formation of phosphorus-rich sludge. The process of phosphorus enrichment of wastewater involves alternating between anaerobic and aerobic conditions to achieve the desired phosphorus removal. Conversely, denitrifying phosphate removal bacteria function in an anaerobic environment, where they facilitate the decomposition of body polyphosphate to generate poly β-hydroxybutyric acid (PHB), which serves as an energy storage mechanism. In anoxic conditions, these bacteria utilize PHB as an energy source, thereby contributing to the transfer of nitrate ions, the absorption of phosphorus-containing substances in the water, and, ultimately, the generation of activated sludge.

3 Traditional Phosphorus Removal Technology and Application Status

3.1 Physical and chemical method

Physicochemical methods offer flexibility and high efficiency in wastewater phosphorus removal, and their main methods include chemical precipitation and adsorption. Chemical precipitation achieves phosphorus removal by adding precipitants such as iron, aluminum, or calcium salts, which cause metal ions to react with phosphate ions to produce insoluble precipitates. Depending on the timing of the addition, the metal sludge produced by precipitation can be separated at different stages of wastewater treatment: the addition of precipitant before precipitation causes the metal to precipitate into the primary sludge; the addition of metal salts to the aeration tank of the activated sludge process causes the precipitation to enter into the secondary sludge; and the addition of precipitant after the secondary treatment generates an additional tertiary sludge, which is a way of obtaining relatively pure effluent, but correspondingly increases the cost.[6] Furthermore, the excellent phosphorus removal capacity, low heavy metal content, and environmental friendliness of the struvite (MAP) method make it promise. The precipitate produced can be used as a slow-release fertilizer.[7] The adsorption method is mainly based on low cost and often uses industrial by-products as adsorbents, reflecting the concept of 'waste for waste.' Relevant studies have demonstrated the feasibility of calcined alkaline residues as adsorbents for phosphate adsorption, and the corresponding process parameters have been determined;[8] Meanwhile, the maximum adsorption capacity of construction waste bricks containing iron, silicon, and aluminum oxides can reach up to 5.35 mg/g as an adsorbent.[9] Despite the simplicity of operation and high phosphorus removal efficiency of the traditional physicochemical method, the products generated are of low bioavailability and usually require further treatment for resource utilization. Moreover, in practice, due to the complexity of the influent water composition, other substances may react competitively with the precipitant or adsorbent, thus affecting the stability and removal effect of the process.

3.2 Biological treatment technology

The Sequencing Batch Reactor Activated Sludge Process (SBR) includes five stages: influent, reaction, sedimentation, discharge, and idling [10], and its research shows that after a certain operation cycle, the formation of a dominant bacterial colony in the reactor can improve the phosphorus removal efficiency, and at the same time, the nitrogen and phosphorus removal effect can be further enhanced by regulating the parameters of the airflow rate and aeration time. However, the SBR reactor has limitations such as large aeration volume, low volume utilization, and discontinuous reaction. On the other hand, the core of the anaerobic-aerobic process lies in the polyphosphate-aggregating organisms (PAOs), such as Tetrasphaera and Accumulibacter, which usually exhibit synergistic effects in wastewater treatment plants [11]. Biological treatment technologies operate without the need for additional chemicals, but they rely on large amounts of oxygen and energy, resulting in a large footprint and high infrastructure, operation, and maintenance costs. Although common biological phosphorus removal processes can achieve phosphorus removal rates of about 90 percent, the time required for phosphorus removal is usually longer than that of physico-chemical methods due to microbial characteristics and complex backflow systems.

3.3 Bottlenecks in traditional methods

Traditional physico-chemical methods and biological methods can both achieve removal efficiencies of about 80 percent in wastewater phosphorus removal, but they suffer from phosphorus enrichment in sludge, limited subsequent use, and the possibility of secondary pollution. Although the reprocessing of sludge through wet chemical or thermal chemical methods can achieve phosphorus recovery, the agricultural utilization of phosphorus in sludge produced by some chemical precipitation methods is low, making it difficult to be converted into fertilizer; at the same time, inappropriate sludge disposal methods may cause secondary pollution. In addition, high salt ions such as chloride ions and sulfate ions are often enriched in wastewater during chemical treatment, and additional treatment is required to meet the effluent standards.[12]

On the other hand, the challenges of treatment scale and economic viability cannot be ignored. Biological treatment methods are difficult to build a large-scale supporting system for small-scale wastewater treatment plants due to the high demand for space; while in the application of chemical precipitation method, the chemical inputs required to achieve the desired effluent phosphorus concentration often far exceed the stoichiometric ratio. Currently, the technical bottleneck of the physical-chemical method is mainly focused on how to reduce the amount of pharmaceutical input and improve the utilization rate of sludge resources, while the biological treatment method urgently needs to solve the problems of how to enhance the stability of microorganisms, improve the efficiency of phosphorus removal, and simplify the process.

4 Progress and evaluation of innovative phosphorus removal technologies

4.1 New Materials and Processes

In recent years, researchers have explored a great deal in phosphorus removal technologies, developing a variety of innovative solutions based on new materials and processes (Table 1). In terms of new materials, modified biochar can be loaded with minerals on its surface to improve the selectivity to phosphate. The modified biochar has high adsorption capacity and high adsorption rate. Its adsorption product can be directly used as a slow-release fertilizer. Modified fly ash, on the other hand, has been physically or chemically treated to show the advantages of lightweight, low cost, and high adsorption efficiency after aluminum modification. In terms of new technologies, Fenton oxidation technology makes use of ·OH radicals generated by Fe^{2+} and H_2O_2 under acidic conditions to remove organic phosphorus efficiently; electro-flocculation technology generates multiple hydroxides at the anode by applying DC voltage, thus flocculating and adsorbing phosphorus in the wastewater rapidly; and micro electrolysis technology relies on the formation of a micro primary battery of iron filings and carbon in the acidic environment. Organic matter in the water is converted into easily degradable substances under the action of the cell, and spontaneous adsorption is achieved. These technologies have shown significant advantages in improving phosphorus removal efficiency, simplifying operations, and reducing operating costs.

Table 1. Innovative phosphorus removal technologies and their key features

Type of technology	Technology	Principle of technology	Advantages
New Materials	Modified Biochar	Loading minerals on biochar to improve its phosphate selectivity	High adsorption capacity, high adsorption rate, fertilization properties of the product [13-15]
	Modified Fly Ash	Improved performance through physical or chemical modification	Light weight, low cost, high adsorption efficiency after aluminum modification [16]
New technologies	Fenton Oxidation Technology	·OH produced by Fe2+ and H2O2 under acidic conditions as an oxidant to remove organic phosphorus	High level of phosphorus aggregation in the supernatant of effluent, effective in removing organic phosphorus [17]

	Electro-flocculation Technology	Applying a DC voltage produces poly hydroxide flocculation of effluent phosphorus at the anode	High adsorption efficiency, short effluent residence time, compact module [18]
	Micro Electrolysis Technology	Iron and carbon in iron filings form a micro primary cell under acidic conditions, which converts organic matter in water to readily degradable organic matter and adsorbs spontaneously	Simple operation, low feeding, high removal efficiency [19,20]

4.2 Compound process

Traditional processes have their limitations in phosphorus removal; therefore, the phosphorus removal effect of combining traditional processes with innovative technologies is usually superior to the application of a single technology [21]. For example, a team applied modified red mud (RM) adsorbents in combination with photocatalytic reduction technology. A phosphorus adsorption rate of up to 99.96% was achieved under optimal operating conditions, which significantly exceeded the effect of adsorption alone. Meanwhile, the microalgae composite membrane treatment technology utilized the photosynthesis of microalgae to induce phosphatase secretion, and thereby promote external organic phosphorus uptake. When microalgae are integrated into a fixed membrane-activated sludge (IFAS) system, the metabolic function of the bacterial population can be altered to improve phosphorus removal efficiency. This composite technology demonstrates potential as a green solution for water treatment and pollutant recovery [22]. In addition, composite bacterial colonization is also a novel phosphorus removal strategy with development potential. The phosphorus removal effects of different functional bacteria can be verified and rationally proportioned to build a synergistic microbial agent. The corresponding bacterial agents can be customized for wastewater with different pollutant characteristics, which can further enhance the relevance and overall efficiency of the phosphorus removal process.

5 Evaluation and Comparison of Wastewater Phosphorus Removal Technologies

The control of phosphorus levels in wastewater is becoming increasingly stringent globally, and countries are taking measures to prevent phosphorus-induced eutrophication of water bodies. There are significant differences between countries in evaluating the performance of effluent phosphorus removal technologies and in setting effluent standards for wastewater treatment plants. This reflects both the policy orientation of their respective environmental management and the differences in economic, technological, and regulatory conditions. For this reason, a variety of technical standards and management approaches have emerged internationally to regulate and promote efficient phosphorus removal from wastewater. Table 2 summarizes the requirements and regulations for phosphorus control in wastewater in some countries, providing a reference for cross - border experience exchange. It is worth noting that with the continuous development of new technologies, these requirements may undergo new changes.

Table 2. Requirements and regulations for effluent phosphorus control in selected countries

Country / Area	Effluent Standard	Special Requirement	Technical and Management Measures	Standard Number
China	A standard: 0.5mg/L B standard: 1.0mg/L	According to population density and the need for water protection	Combining traditional and innovative technologies, enhancing phosphorus recovery from sludge and promoting resource recycling	GB 18918-2002
EU	Main standard: 1.0mg/L	Wastewater treatment plants serving a population greater than 100,000 need to be equipped with phosphorus treatment facilities	Adoption of advanced phosphorus removal technology, continuous monitoring and focus on sludge resource utilization	UWWTD,91/271/EEC

USA	1.0mg/L or 0.5mg/L	Some coastal or water protection zones may require 0.1 mg/L	Joint Federal-Local Regulation, Encouragement of Joint Application of Multiple Technologies, and Strict Penalties for Exceeding Emissions Standards	33 U.S.C. §1251 et seq.
Australia	Big city or sensitive water bodies: 0.5mg/L others: 1.0mg/L	Water quality protection areas require advanced treatment, 0.1 mg/L	Multi-process, Sewage phosphorus resource utilization	AS/NZS1547:2012

6 Future Directions and Prospects

The future development of phosphorus removal technologies in wastewater will focus on innovative, high-efficiency, low-cost, and environmentally friendly approaches, while integrating multiple methods through composite processes to enhance removal performance. Additionally, phosphorus resource recovery and recycling will become key directions, combined with intelligent and automated management to achieve real-time optimization and cost control in wastewater treatment processes. Table 3 shows the future directions and prospects of phosphorus removal technologies in wastewater treatment.

Table 3. Future Directions and Prospects of Phosphorus Removal Technologies in Wastewater Treatment

Direction	Main Strategies/Technologies	Advantages/Characteristics
Technological Innovation and Diversification	Nanomaterials for enhanced phosphorus removal efficiency / Photocatalytic technology / Electrochemical technology	High efficiency and low cost / Environmentally friendly / Suitable for low-concentration phosphorus wastewater / Improved reaction rates and removal efficiency [23]
Research and Utilization of Composite Processes	Combination of chemical precipitation, biological methods, and emerging technologies	Maximizes phosphorus removal / Overcomes limitations of single technology / Tailored solutions for complex wastewater conditions [24]
Resource Recovery and Recycling	Efficient extraction and conversion of phosphorus / Circular economy approach	Reduces wastewater treatment costs / Alleviates pressure on phosphate mining / Supports sustainable agriculture and soil conditioning [25]
Intelligent and Automated Management	Real-time monitoring using sensors / AI-based process optimization / Automated control of operational parameters	Improves efficiency and reduces manual intervention / Reduces energy and chemical consumption / Enhances adaptability to fluctuating wastewater conditions [26]

6.1 Technological Innovation and Diversification

Future phosphorus removal technologies in wastewater will focus on the development of novel technologies that are highly efficient, low-cost, and environmentally friendly, especially strategies for treating waters with low concentrations of phosphorus. Experimental studies have shown that nanomaterials can effectively improve phosphorus removal efficiency due to their large surface area and high reactivity. Photocatalytic technology excites the catalyst through light energy and has low energy consumption. Electrochemical technology utilizes electric current to guide the reaction process, which can also improve the phosphorus removal rate [23]. These new technologies show different advantages in different wastewater treatment scenarios and needs, and provide diversified solutions for phosphorus removal from wastewater.

6.2 Research and utilization of composite processes

As a result of a single technology in the practical application of different types of limitations, the future of phosphorus removal technology in wastewater will be relocated to the composite process of in-depth research and application. The advantage of this model is to fully utilize the advantages of various technologies while fully surpassing the inadequacy of a single technology. The effective combination of chemical precipitation, biological methods, and emerging technologies can achieve better phosphorus removal.[24]

6.3 Resource recovery and recycling of phosphorus

As a finite and non-renewable resource, future technologies for phosphorus removal from wastewater will no longer simply pursue wastewater treatment goals, but will instead aim to efficiently extract and convert phosphorus from wastewater into valuable products such as fertilizers or soil conditioners. This circular economy model will not only reduce the cost of wastewater treatment, but will also reduce the pressure on phosphate mining.[25]

6.4 Intelligent and automated management

With the rapid development and popularization of artificial intelligence and big data technology, the future wastewater treatment process will achieve a more intelligent control scheme to achieve real-time monitoring and optimization of the phosphorus removal process. For example, real-time monitoring of water quality changes through sensors to adjust the consumption of energy and chemicals to improve phosphorus removal efficiency and reduce costs. Use artificial intelligence to predict the trend of phosphorus content in wastewater, to take appropriate treatment measures in advance. It is also possible to increase the level of automation of the system, automatically adjusting relevant process parameters to improve treatment efficiency and reduce manual intervention.[26]

7 Conclusions

Currently, the primary methods for phosphorus removal from wastewater include chemical precipitation, adsorption, and biological treatments, often applied in combination. Traditional physicochemical methods are widely applicable and efficient but often produce phosphorus products that are difficult to recover, especially from low-concentration wastewater. Biological treatments, while effective at trace levels, exhibit instability, efficiency limitations, and excessive sludge generation. Emerging approaches such as ion exchange and membrane technologies, despite technological advantages, still face barriers due to high operational costs and stringent influent quality requirements. Integrated physicochemical-biological systems have improved phosphorus recovery efficiencies, but research gaps persist, especially concerning resource recycling.

This paper systematically reviews traditional phosphorus removal methods, evaluating their strengths and existing challenges, and critically examines innovative technologies to address current limitations. Furthermore, by comparing international phosphorus discharge standards, the paper identifies global regulatory trends and requirements. Through this comprehensive review, we aim to provide clear theoretical insights and practical guidance, assisting policymakers, researchers, and practitioners in optimizing phosphorus removal strategies and advancing sustainable wastewater management practices.

References

1. Cordell D, Drangert J O, White S. The story of phosphorus: global food security and food for thought[J]. Global environmental change, 2009, 19(2): 292-305.
2. Bunce J T, Ndam E, Ofiteru I D, et al. A review of phosphorus removal technologies and their applicability to small-scale domestic wastewater treatment systems[J]. Frontiers in Environmental Science, 2018, 6: 8.
3. Molinos-Senante M, Hernández-Sancho F, Sala-Garrido R, et al. Economic feasibility study for phosphorus recovery processes[J]. Ambio, 2011, 40: 408-416.
4. Ye H, Yang H, Han N, et al. Risk assessment based on nitrogen and phosphorus forms in watershed sediments: A case study of the upper reaches of the Minjiang Watershed[J]. Sustainability, 2019, 11(20): 5565.
5. Kim T, Lee J, Kim J, et al. Behavioral characteristics of phosphorus in sediments according to the forms of phosphorus[J]. Journal of Ecology & Environment, 2015, 38(3).
6. Jupp A R, Beijer S, Narain G C, et al. Phosphorus recovery and recycling–closing the loop[J]. Chemical Society Reviews, 2021, 50(1): 87-101.
7. Krishnamoorthy N, Dey B, Unpaprom Y, et al. Engineering principles and process designs for phosphorus recovery as struvite: A comprehensive review[J]. Journal of Environmental Chemical Engineering, 2021, 9(5): 105579.
8. Yan Y, Sun X, Ma F, et al. Removal of phosphate from etching wastewater by calcined alkaline residue: Batch and column studies[J]. Journal of the Taiwan Institute of Chemical Engineers, 2014, 45(4): 1709-1716.
9. Edet U A, Ifelebuegu A O. Kinetics, isotherms, and thermodynamic modeling of the adsorption of phosphates from model wastewater using recycled brick waste[J]. Processes, 2020, 8(6): 665.
10. Jiang X, Yuan Y, Ma F, et al. Enhanced biological phosphorus removal by granular sludge in anaerobic/aerobic/anoxic SBR during start-up period[J]. Desalination and Water Treatment, 2016, 57(13): 5760-5771.
11. Liu Z, Zhang Y, Zhou W, et al. Comparison of nitrogen and phosphorus removal between two typical processes under low temperature in a full-scale municipal wastewater treatment plant[J]. Water, 2022, 14(23): 3874.
12. Mehta C M, Khunjar W O, Nguyen V, et al. Technologies to recover nutrients from waste streams: a critical review[J]. Critical Reviews in Environmental Science and Technology, 2015, 45(4): 385-427.
13. Kopecký M, Kolář L, Konvalina P, et al. Modified biochar—a tool for wastewater treatment[J]. Energies, 2020, 13(20): 5270.
14. Wu X, Quan W, Chen Q, et al. Efficient adsorption of nitrogen and phosphorus in wastewater by biochar[J]. Molecules, 2024, 29(5): 1005.

15. Zhang Y, Zhang W, Zhang H, et al. Nano-Zero-Valent Zinc-Modified Municipal Sludge Biochar for Phosphorus Removal[J]. Molecules, 2023, 28(7): 3231.
16. Meng R, Lv P, Yang Y, et al. Low-temperature alkali-modified fly ash as an effective adsorbent for removal of ammonia nitrogen, phosphorus and COD from the wastewater[C]//IOP Conference Series: Earth and Environmental Science. IOP Publishing, 2020, 569(1): 012026.
17. Abdoli S, Asgari Lajayer B, Dehghanian Z, et al. A Review of the Efficiency of Phosphorus Removal and Recovery from Wastewater by Physicochemical and Biological Processes: Challenges and Opportunities[J]. Water, 2024, 16(17): 2507.
18. Nguyen D D, Ngo H H, Guo W, et al. Can electrocoagulation process be an appropriate technology for phosphorus removal from municipal wastewater? [J]. Science of the total Environment, 2016, 563: 549-556.
19. Hu B, Qi Q, Li L, et al. Study on Fe-C-Al three-phase micro-electrolysis treatment of low concentration phosphorus wastewater[J]. Water Science & Technology, 2022, 86(10): 2581-2592.
20. Jiang S, Cao Y, Han P, et al. Parameters optimization for eutrophic lake water treatment by a novel process of iron-carbon micro-electrolysis coupled with catalytic ozonation using response surface methodology[J]. Water Supply, 2021, 21(5): 2414-2424.
21. Yi Z, Shibin X, Dandan K, et al. Phosphorus removal from domestic sewage by adsorption combined photocatalytic reduction with red mud[J]. Desalination and Water Treatment, 2013, 51(37-39): 7130-7136.
22. Mao Y, Xiong R, Gao X, et al. Analysis of the status and improvement of microalgal phosphorus removal from municipal wastewater[J]. Processes, 2021, 9(9): 1486.
23. Du J, Waite T D, Feng J, et al. Coupled electrochemical methods for nitrogen and phosphorus recovery from wastewater: a review[J]. Environmental Chemistry Letters, 2023, 21(2): 885-909.
24. Parasana N, Shah M, Unnarkat A. Recent advances in developing innovative sorbents for phosphorus removal—perspective and opportunities[J]. Environmental Science and Pollution Research, 2022, 29(26): 38985-39016.
25. Ghimire U, Sarpong G, Gude V G. Transitioning wastewater treatment plants toward circular economy and energy sustainability[J]. ACS omega, 2021, 6(18): 11794-11803.
26. Alprol A E, Mansour A T, Ibrahim M E E D, et al. Artificial intelligence technologies revolutionizing wastewater treatment: Current trends and future prospective[J]. Water, 2024, 16(2): 314.