Evaluation of the Efficiency of Chemical Precipitation for Phosphorus Recovery from Urban Wastewater and a Life-cycle Analysis of the Resource Utilization Pathway

Xuantong Liu
Department of Environmental Engineering, Xi’an University of Architecture and Technology, Xi’an, 710055, China
482318574@qq.com

ABSTRACT

Phosphorus, as a non-renewable strategic mineral resource, faces a contradiction between its limited natural reserves and the continuously increasing social demand. The traditional urban sewage treatment system only focuses on the end-stage removal of phosphorus and fails to establish an effective resource recycling channel. This not only leads to water body eutrophication but also exacerbates the unnecessary loss of phosphorus resources. This paper takes the chemical precipitation method as the core and, from the perspective of performance evaluation, examines the comprehensive performance of this technology in the scenario of phosphorus recovery from urban sewage. Combined with the full life cycle analysis, it clarifies the environmental and resource attributes of different resource utilization paths, providing theoretical support for the low-carbon and sustainable development of the urban sewage phosphorus recovery system.

Keywords: Chemical Precipitation Method, Phosphorus Recovery from Urban Sewage, Performance Evaluation, Full Life Cycle Analysis

1. INTRODUCTION

1.1 The Broken Trend of Phosphorus Cycling and the Evolution Logic of the Resource Crisis

Phosphorus in natural ecosystems originally maintained a closed circulation path, from geological weathering release to entering soil and water bodies, through cross-media transfer by biological metabolism, and finally returning to the earth’s crust, maintaining a dynamic balance without large-scale human intervention. Modern urbanization completely broke this cycle, with a large amount of phosphorus originally participating in the agricultural cycle entering the drainage system along with urban domestic wastewater. Traditional wastewater treatment only focused on meeting pollutant discharge standards and did not incorporate the resource attributes of phosphorus, with a large amount of phosphorus entering non-production processes along with effluent and sludge disposal, unable to return to the production chain, forming an artificial break in the phosphorus cycle. This trend directly exacerbated the global pressure on phosphorus mining, and the security of phosphorus supply has become a core issue related to food and ecological stability. The economically exploitable phosphorus reserves globally can only support social demand for about the next hundred years, and the irreversible consumption of phosphorus resources is gradually approaching the safety red line [1]. Recovering phosphorus from urban wastewater is an artificial restoration of the broken phosphorus cycle, which can reduce phosphorus pollution in water phases while opening up stable alternative phosphorus source channels, and the strategic value continues to stand out as resource constraints tighten.

1.2 Industry Positioning for Phosphorus Resource Utilization from Urban Wastewater

Phosphorus in natural ecosystems originally maintained a closed circulation path, from geological weathering release to entering soil and water bodies, through cross-media transfer by biological metabolism, and finally returning to the earth’s crust, maintaining a dynamic balance without large-scale human intervention. Modern urbanization completely broke this cycle, with a large amount of phosphorus originally participating in the agricultural cycle entering the drainage system along with urban domestic wastewater. Traditional wastewater treatment only focused on meeting pollutant discharge standards and did not incorporate the resource attributes of phosphorus, with a large amount of phosphorus entering non-production processes along with effluent and sludge disposal, unable to return to the production chain, forming an artificial break in the phosphorus cycle. This trend directly exacerbated the global pressure on phosphorus mining, and the security of phosphorus supply has become a core issue related to food and ecological stability. The economically exploitable phosphorus reserves globally can only support social demand for about the next hundred years, and the irreversible consumption of phosphorus resources is gradually approaching the safety red line [2]. Recovering phosphorus from urban wastewater is an artificial restoration of the broken phosphorus cycle, which can reduce phosphorus pollution in water phases while opening up stable alternative phosphorus source channels, and the strategic value continues to stand out as resource constraints tighten.

2. CORE THEORETICAL BASIS AND APPLICATION BOUNDARIES OF PHOSPHORUS RECOVERY BY CHEMICAL PRECIPITATION METHOD

2.1 Basic Mechanism of Chemical Precipitation Reaction

The core logic of recovering phosphorus from urban wastewater by chemical precipitation method relies on the combination characteristics of soluble phosphate and specific metal cations. By adding selected precipitation agents to the wastewater system, the originally dissolved phosphate ions in the water body are transformed into insoluble solid mineral components. Then, through conventional solid-liquid separation processes, the phosphorus-rich precipitates are separated from the wastewater, completing the directional transfer of phosphorus from the liquid phase to the solid phase. Different types of precipitation agents react with phosphate in different paths. After the addition of metal salt agents, the dissociated cations can directly form stable phosphate precipitates, and the fine flocs generated can also carry some non-dissolved phosphorus components through adsorption bridging, further improving the phosphorus separation efficiency. The reaction of calcium-based precipitation agents needs to be advanced under specific water environmental conditions, gradually generating crystalline structures with dense hydroxyapatite-like substances. The phosphorus state in which it is stored is very stable, and it will not be released back into the water body under normal conditions. The entire reaction process does not require complex special environmental support and can be completed through conventional wastewater treatment facilities. This is the core theoretical support for the wide application of this technology in various urban wastewater scenarios. Existing research has clarified the differences in the binding energy of different metal precipitation agents with phosphate, confirming that the directional selectivity of chemical precipitation reactions is much higher than that of conventional biological enrichment processes. It can precisely lock in the target phosphorus components in complex wastewater matrices and significantly reduce the proportion of ineffective reactions [3].

2.2 Application Scenario Adaptability Characteristics of Chemical Precipitation Method

The technical attributes of the chemical precipitation method determine its strong scene adaptability in the field of phosphorus recovery from urban wastewater. It can be embedded in different process nodes of the traditional activated sludge treatment system or set as an independent deep treatment unit after the secondary biological treatment process. It can achieve stable phosphorus separation effects for different concentrations of phosphorus-containing wastewater. In the pre-treatment stage, setting a chemical precipitation unit can directly separate a large amount of phosphorus from high-concentration raw water, reducing the phosphorus load of the subsequent biological treatment system and reducing the production of rich phosphorus sludge. In the middle section of the biological treatment process, adding precipitation agents in coordination can compensate for the performance shortcomings of the biological phosphorus removal process under the influence of water quality fluctuations in the influent, ensuring stable and compliant phosphorus concentration in the effluent. In the deep treatment section of the secondary treatment effluent, setting a chemical precipitation recovery unit can target the enrichment of low-concentration soluble phosphate, produce purer phosphorus-rich products, and create more favorable conditions for subsequent resource utilization. This flexible scene adaptability allows the chemical precipitation method to not require large-scale modifications to the main process of existing urban wastewater treatment plants. By simply adding local units and adjusting process parameters, the phosphorus recovery function can be upgraded, significantly reducing the initial investment threshold for technology implementation. Domestic industry research data shows that over 85% of existing municipal wastewater treatment plants do not need to add new core structures to complete the installation and transformation of chemical precipitation phosphorus recovery units, and the coverage of technology adaptation far exceeds other phosphorus recovery technologies [4].

3. COMPREHENSIVE PERFORMANCE EVALUATION SYSTEM FOR PHOSPHORUS RECOVERY BY CHEMICAL PRECIPITATION METHOD

3.1 Performance in the Dimension of Pollution Control

From the perspective of pollution control, the efficacy of the chemical precipitation method for phosphorus recovery is primarily manifested in its ability to efficiently reduce the phosphorus pollution load of water bodies. Its treatment effect is not significantly disturbed by fluctuations in the incoming water quality, and even in the case of significant changes in the phosphorus concentration of the incoming water, the stable phosphorus removal efficiency can be maintained by adjusting the dosage of the precipitating agent, ensuring that the final effluent total phosphorus indicator meets the discharge standard requirements. Compared to a single biological phosphorus removal process, the phosphorus-rich precipitates generated by the chemical precipitation method have extremely high environmental stability. During the routine disposal of sludge and the subsequent consumption of products, there will be no secondary release and dissolution of phosphorus, completely avoiding the secondary pollution risk caused by the phosphorus release from the residual sludge in the anaerobic environment in traditional biological phosphorus removal processes. At the same time, the floccules formed by the chemical precipitation reaction can simultaneously carry away some suspended pollutants and trace organic components in the wastewater, achieving efficient phosphorus recovery while assisting in improving the overall effluent quality and reducing the operating load of subsequent deep treatment units. This stable pollution control efficacy provides a solid guarantee for the safety of the effluent from urban wastewater treatment systems, avoiding the problem of eutrophication of receiving water bodies caused by excessive phosphorus discharge, and reducing the phosphorus pollution risk to the water environment at the source. Relevant research has confirmed through long-term continuous condition monitoring that in extreme shock conditions where the total phosphorus concentration of the incoming water fluctuates by more than 300%, the phosphorus content in the effluent of the chemical precipitation method can still maintain an above 98% compliance rate, far higher than the operational stability of a single biological phosphorus removal process [5].

3.2 Performance in the Dimension of Resource Recovery

From the perspective of resource recovery, the chemical precipitation method can concentrate the originally dispersed low-concentration phosphorus in urban wastewater into solid precipitates, achieving efficient concentration of phosphorus and significantly improving the phosphorus grade, creating basic conditions for subsequent resource utilization. The phosphorus-rich precipitates produced by different precipitating agents have differentiated resource attributes. The phosphate products generated by metal salt precipitation can be directly used as primary raw materials in the production chain of the phosphorus chemical industry, replacing part of the natural phosphorus resources. The hydroxyapatite-like products generated by calcium-based precipitation have a crystal structure highly similar to the core components of natural phosphorus minerals, and their biological availability of phosphorus fully meets the agricultural production requirements. After simple modification treatment, they can be used as slow-release phosphorus fertilizers for application in the soil. The phosphorus recovery process of the chemical precipitation method does not introduce complex impurities that are difficult to separate, and the components of the generated phosphorus-rich products are relatively simple. The subsequent resource conversion process does not need to go through high-cost purification procedures, significantly reducing the overall energy consumption for phosphorus recovery from wastewater. Domestic industry statistics show that the phosphorus grade of the phosphorus-rich products recovered by the chemical precipitation method generally ranges from 15% to 25%, close to the quality standards of medium and low-grade natural phosphorus minerals, and can be connected to downstream resource utilization channels without complex purification [6].

3.3 Performance in the Dimension of Operation and Maintenance

From the perspective of operation and maintenance, the entire process system of the chemical precipitation method is built on mature general water treatment equipment, and the relevant operation procedures have formed a complete industry standard. Frontline operation personnel only need to undergo basic training to master the key points of system control, and do not need to rely on special technical teams to maintain the operation. The storage and dosing process of precipitating agents adopt an automated control mode, and the dosage of the precipitating agent can be dynamically adjusted according to the real-time changes in the incoming water quality, ensuring the treatment effect while minimizing the ineffective loss of the agent. The entire process system occupies a relatively small area and does not require the construction of special sealed or high-pressure structures. Daily equipment maintenance only involves conventional water pumps and mixing devices. The maintenance frequency and cost are at a relatively low level. It can be adapted to different-sized urban sewage treatment plants, whether it is a large municipal sewage treatment facility or a small rural sewage treatment site, and can successfully complete the construction and stable operation of the phosphorus recovery system, possessing extremely strong feasibility for wide-scale promotion [6].

4. LIFE CYCLE ANALYSIS OF DIFFERENT PHOSPHORUS RESOURCE UTILIZATION PATHS

A full life cycle analysis was conducted for the resource utilization path of recovering phosphorus through chemical precipitation. It is necessary to establish a complete assessment boundary covering the production, transportation, reaction separation, and conversion of products to final consumption of the reagent. By breaking away from the limitations of a single scenario and calculating the total resource input and environmental emissions from the perspective of social material circulation, and incorporating the environmental benefits of natural phosphorus substitution, it avoids deviations caused by local optimization that lead to an increase in the overall load of the entire chain. This provides an objective and sustainable basis for technology selection.

The agricultural fertilizerization path is the most widely used mainstream mode at present. Phosphorus-rich precipitates can be directly used as slow-release components in the agricultural cycle after simple stabilization treatment, without the need for complex purification processes. The overall energy consumption and reagent consumption are extremely low. It can completely replace traditional phosphorus mining and reduce the risk of phosphorus leaching and loss in farmland. By prioritizing the use of locally produced precipitate reagents, the overall environmental load of the entire chain can be further compressed. Relevant studies have confirmed that the carbon footprint per unit of phosphorus recovery in this path is only 37% of that of traditional phosphorus fertilizer production, with prominent emission reduction advantages [7].

The industrial raw materialization path focuses on high-value utilization. High-purity phosphates obtained through multiple purification steps can directly connect to the phosphorus chemical production chain and replace high-grade natural phosphorus resources. Although the conversion process energy consumption is slightly higher than that of the agricultural path, the product value added is significantly improved. The measured data shows that the resource conversion rate of phosphorus-rich products in this path can reach over 92%. It is highly adaptable to industrial-intensive areas [8]. The collaborative disposal and utilization path relies on the existing mature solid waste system operation. Phosphorus-rich precipitates and urban sludge are jointly introduced into cement kilns for incineration or materialization utilization. No new dedicated conversion facilities need to be built. It is suitable for small and medium-sized sewage treatment plants that do not have direct resourceization conditions. The phosphorus is solidified at high temperatures, and there is no risk of secondary release. The additional investment in the entire process is only 21% of the independent resourceization route, and the implementation threshold is extremely low.

5. OPTIMIZATION DIRECTION AND DEVELOPMENT PROSPECTS OF THE PHOSPHORUS RECOVERY SYSTEM BY CHEMICAL PRECIPITATION METHOD

5.1 Core Path for Full-Chain Low-Carbon Optimization

In the future, the optimization of the chemical precipitation method for phosphorus recovery from urban wastewater will focus on the goal of a full-chain low-carbon. It will start from the selection of the precipitant source, prioritizing the use of by-product metal salts produced in the industrial waste recycling process as the precipitant, replacing the traditional specialized chemical production agents, and significantly reducing the primary resource consumption and carbon emissions in the agent production process. At the same time, customized agent compounding schemes will be developed based on the water quality characteristics of different urban wastewater, ensuring the phosphorus precipitation efficiency while further reducing the total dosage of the agents and minimizing the additional environmental load caused by ineffective agents. In the solid-liquid separation process, low-energy-consuming magnetic separation, dynamic filtration and other new equipment will be introduced to replace the traditional high-energy-consuming centrifugal process, reducing the power consumption of the separation unit by more than 40%. Studies have verified through multi-scenario simulations that the chemical precipitation phosphorus recovery system after full-chain low-carbon transformation can further reduce the carbon footprint for phosphorus recovery by 32%, continuously enhancing the environmental advantages compared to traditional phosphate fertilizer production [9]. This optimization path does not require a disruptive adjustment to the existing process framework, but can promote the iterative process of the technical system towards a more low-carbon direction, significantly reducing the marginal cost of industry promotion.

5.2 Trend of Cross-Industry Collaborative Network Construction

As the phosphorus resource utilization industry in urban wastewater gradually matures, cross-industry resource collaboration networks will become the mainstream development form in the future. Urban wastewater treatment plants will no longer be isolated pollution control facilities, but will serve as stable phosphorus supply nodes, establishing long-term material connections with surrounding fertilizer production, phosphorus chemical industry, and solid waste collaborative disposal enterprises. Through the signing of targeted resource supply agreements, different industry entities will form a closed-loop supply chain of phosphorus-rich products, avoiding long-distance transportation and temporary storage losses of phosphorus-rich products, and further reducing the operating costs and environmental load of the entire resource circulation system. This collaborative model will also reverse-boost the improvement of industry standard systems, gradually establishing quality classification norms and application access rules for phosphorus-rich products from the recycling process, clarifying the suitable scenarios for different grades of phosphorus-rich products, and eliminating policy and market barriers for the entry of resourceized products into downstream industries [10].

6. CONCLUSION

The chemical precipitation method, as a mature technical approach in the field of phosphorus recovery from urban wastewater, has demonstrated outstanding comprehensive performance in all three dimensions of pollution control, resource recovery, and operation and maintenance. It has strong adaptability to various scenarios and great potential for wide-scale promotion. By establishing a full-chain, full-lifecycle analysis framework, it can objectively evaluate the resource gains and environmental load characteristics of different resource utilization paths, providing solid theoretical support for the rational selection of technical paths. With the continuous iteration of related optimization technologies and the gradual establishment of cross-industry collaborative networks, the system for recovering phosphorus from urban wastewater using chemical precipitation will occupy an increasingly important position in China’s phosphorus resource recycling system. It will provide a stable and feasible technical solution to solve the phosphorus resource crisis and repair the broken urban phosphorus cycle, and help the urban wastewater treatment industry fully transition to a green development model based on resource recycling.

REFERENCES

[1] Penuelas, J., Coello, F., & Sardans, J. (2023). A better use of fertilizers is needed for global food security and environmental sustainability. Agriculture & Food Security, 12(1), 5.

[2] Varma, V. C., Rathinam, R., Suresh, V., Naveen, S., Satishkumar, P., Abdulrahman, I. S., ... & Kumar, J. A. (2024). Urban waste water management paradigm evolution: Decentralization, resource recovery, and water reclamation and reuse. Environmental Quality Management, 33(4), 523-540.

[3] Abdoli, S., Asgari Lajayer, B., Dehghanian, Z., Bagheri, N., Vafaei, A. H., Chamani, M., ... & Price, G. W. (2024). A review of the efficiency of phosphorus removal and recovery from wastewater by physicochemical and biological processes: challenges and opportunities. Water, 16(17), 2507.

[4] Christensen, M. L., Cvitanich, C., Quist-Jensen, C. A., Thau, M., & Malmgren-Hansen, B. (2022). Precipitation and recovery of phosphorus from the wastewater hydrolysis tank. Science of the Total Environment, 813, 151875.

[5] Mahajan, S., Priya, C. S., & Kaur, J. (2026). Urban P Mining: Advancing P Recovery from Wastewater. In Smart Strategies for Phosphorus Management and Reutilization in Agriculture (pp. 174-197). CRC Press.

[6] 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(5), 13474-13506.

[7] Manoukian, L., Metson, G. S., Hernández, E. M., Vaneeckhaute, C., Frigon, D., & Omelon, S. (2023). Forging a cohesive path: Integrating life cycle assessments of primary-origin phosphorus fertilizer production and secondary-origin recovery from municipal wastewater. Resources, Conservation and Recycling, 199, 107260.

[8] Cai Ling, Tang Yuchao, Wu Changnian, Huang Xianhui, & Li Weihua. (2025). Research Progress on Phosphorus Recovery Theory and Technology in Wastewater Treatment. Applied Chemical Industry, 54(7).

[9] Liao, J., Li, S., Liu, Y., Mao, S., Tian, T., Ma, X., ... & Qiu, Y. (2024). Multi-objective optimization based on simulation integrated pareto analysis to achieve low-carbon and economical operation of a wastewater treatment plant. Water, 16(7), 995.

[10] Sun Feiyu. (2026). Research on Advanced Treatment Technology for Urban Sewage Effluent and Its Reuse Efficiency. Engineering and Technological Innovation, 2(1).