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ANALYSIS AND SELECTION OF TECHNOLOGY FOR PHOSPHORUS REMOVAL FROM MUNICIPAL WASTEWATER

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Phosphorus removal from municipal wastewater is essential to prevent eutrophication and support the transition toward a circular economy. Efficient treatment requires not only compliance with discharge standards but also consideration of the potential for resource recovery.

Aim. To analyze modern phosphorus removal technologies and to develop recommendations for process optimization using mathematical modeling.

Methods. The study was based on the analysis of EU regulatory documents, Ukrainian standards, EPA (Environmental Protection Agency) guidelines, and scientific literature (2000–2026). Special attention was given to enhanced biological phosphorus removal (EBPR), combined treatment systems, phosphorus recovery technologies, and modeling approaches such as ASM2d.

Results. Chemical precipitation provides high phosphorus removal efficiency (up to 90–95%), but it also significantly increases sludge production. EBPR reduces sludge formation and operational costs but is sensitive to influent conditions. Systems that combine EBPR with chemical post-treatment achieve the highest efficiency (up to 99,6%) with a moderate increase in sludge (10–20%).

Conclusions. The combination of biological phosphorus removal with chemical polishing is the most effective and economically viable solution. This approach enables phosphorus removal efficiencies exceeding 95% while minimizing sludge production and supporting resource recovery strategies.

Key words: biotechnology, microorganisms, wastewater treatment, phosphorus removal, modelling.

Anthropogenic phosphorus is one of the main drivers of eutrophication, manifested in water blooms, oxygen deficiency, ecosystem degradation, and risks to water use, and therefore controlling its input is critical [1, 2]. In the European context, achieving a satisfactory level of water body cleanliness (as defined by the Water Framework Directive, 2000) is directly related to the management of biogenic compounds. However, specific numerical criteria may differ between countries and types of water bodies [2, 3].

Municipal wastewater is a significant source of phosphorus: according to the EPA, the total phosphorus (TP) content in municipal wastewater is 4–15 mg TP/dm^3, and for orthophosphate, 2–12 mg TP/dm^3 [4]. Such concentrations create significant mass flows of phosphorus even for medium-sized agglomerations; given the strengthening of regulatory requirements, treatment plants are increasingly considered not only from the perspective of removing phosphorus from wastewater, but also from the perspective of the possibility of reusing phosphorus extracted from sludge (due to the formation of minerals such as struvite, vivianite, extraction from sludge ash, etc.) [5–17].

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From the standpoint of modern practice, the approach to phosphorus removal from wastewater at municipal treatment plants should be considered as a system of interconnected sub-tasks: (i) achieving the limit for TP in treated water, (ii) regulating recirculation flows, (iii) minimizing the volumes of formed sludge, (iv) creating conditions for resource recovery of phosphates and minimizing environmental impact [4, 7–13, 18–20].

This study aimed to analyze modern biotechnologies for phosphorus removal from municipal wastewater and to formulate recommendations for modernizing treatment processes at treatment plants, with subsequent application of mathematical modeling to select their technological parameters.

Materials and Methods

Materials for the review included EU regulatory acts (URBAN WWT recast 2024, UWWTD 91/271/EEC), national normative documents of Ukraine regarding acceptance of wastewater into centralized municipal sewerage networks, official EPA data on control of organic substances and biogenic elements (nitrogen, phosphorus), and review articles from 2000–2026 on advanced biological phosphorus removal and phosphorus-accumulating organisms (PAO), combined biotechnologies, recycling of phosphorus accumulated in excess activated sludge. Publications of the International Water Association (IWA) describing activated sludge models were also included in the analysis. Sources were selected based on their relevance to the research topic, the availability of quantitative performance indicators, and their practical applicability for mathematical modeling of treatment processes. The study employed methods of analytical literature review, comparative analysis of technologies, and engineering data synthesis [4–14, 20–29].

Results and Discussion

These regulatory documents also establish a framework for increasing the recycling of phosphorus compounds from sludge [5].

For Ukraine, a practical limitation to the stability of EBPR processes and sludge dewatering is the regulation governing the acceptance of wastewater into centralized municipal sewerage networks, particularly regarding toxic or inhibitory impurities and industrial components of pollutants [14].

From the perspective of real influent conditions, it is important to remember that in municipal wastewater TP varies widely (usually 4–15 mg P/dm^3), and the fraction of orthophosphate is often high; after primary settling at the beginning of biological treatment, part of the organophosphorus or polyphosphate forms is rapidly converted to orthophosphate, which directly affects reagent demand or loading on facilities when EBPR is used [4].

The following methods are used for wastewater treatment from phosphates: chemical, physicochemical, biological, and combined (a combination of physical, chemical, and biological methods).

Chemical removal (with the participation of trivalent iron or aluminum salts) is based on the formation of sparingly soluble metal phosphates, which are subsequently removed in settling tanks, filters, or membranes [4–14, 18–31]. For dose selection, a common approach is to use the molar ratio of metal to influent soluble phosphorus (Me/P). Practical EPA recommendations indicate that doses above 1.5–2.0 (mol/mol) are sufficient to remove 80–98% of soluble phosphorus, whereas achieving “bottom” limits requires increasing the ratio to 6–7 (mol/mol) [4].

The main disadvantage of chemical precipitation is the large volume of sludge produced. When reagents are introduced into primary clarifiers, sludge volume may increase by 50–100%, and total sludge generation at the plant by approximately 60–70% (here and below, the change in sludge generation is considered relative to aerobic biotechnology of treatment using activated sludge for the removal of organic pollutants and partially biogenic elements). Adding reagents at the biological treatment stage increases sludge locally by 35–45% and at the plant scale by 5–25%. Post-treatment to achieve low phosphorus concentrations (< 0.10 mg/dm^3) results in an additional 10–40% increase in sludge volume [4].

Physicochemical methods for phosphorus removal include membrane separation, adsorption on mineral or organic sorbents, ion exchange, electrocoagulation, and tertiary filtration. Such approaches are capable of achieving low residual phosphorus concentrations (< 0.1 mg P/dm^3), especially during post-treatment stages; however, their widespread implementation for municipal wastewater treatment is limited by high capital and operational costs, membrane fouling, sorbent regeneration requirements, or increased energy consumption [23–25, 29–31]. Therefore, physicochemical technologies are more often considered as supplementary polishing stages rather than standalone large-scale solutions for municipal wastewater treatment plants.

Biological methods achieve high phosphorus removal efficiency without the addition of chemical reagents, thereby saving on operating costs associated with reagent dosing and reducing sludge volumes.

One promising approach is considered EBPR, which is based on the metabolic cycle of PAO: under anaerobic conditions, PAO accumulate volatile fatty acids (VFA) in the form of intracellular polyhydroxyalkanoates (PHA) using the energy of polyphosphate hydrolysis; under aerobic (and partly anoxic) conditions, they carry out “excess” uptake of orthophosphate and restore polyphosphate [21, 32–38]. The main practical difficulty of EBPR is sensitivity to influent carbon, the presence of nitrates in the “anaerobic” zone, and microbiological competition (e.g., with glycogen-accumulating organisms) [4, 32, 39].

An important “suitability criterion” of wastewater for EBPR is the ratio of available substrate to TP. According to EPA data, the recommended minimum ratios for achieving TP <1.0 mg/dm^3 are: COD:TP = 40–45; BOD: TP = 20; rbCOD: TP = 10–16 (where rbCOD is the readily biodegradable fraction of organic pollutants); VFA: TP = 4–16 [4, 40].

Due to the practical instability of EBPR alone under fluctuating wastewater composition, modern practice often uses a combined scheme: EBPR as the main method of wastewater phosphate removal, followed by reagent treatment (mainly Fe/Al) with subsequent filtration or sedimentation in the secondary clarifier [4, 20, 29].

Phosphorus removal technologies have evolved from simple reagent methods to biological processes and combined schemes, and modern approaches are additionally focused on its extraction and reuse as a resource (see Table 1) [4–5, 21, 29, 32–33, 41–45].

Below (see Table 2), a comparison of technological approaches based on guiding documents and studies [4, 20, 29] is provided.

Along with the tasks of achieving normative phosphorus concentrations in treated wastewater, modern approaches are increasingly oriented toward its extraction and use as a secondary resource. This is due to both the limited availability of natural phosphorus sources and the requirements of the circular economy, which drive a shift from removal to phosphorus recovery. In this context, technologies that convert phosphorus into stable mineral forms suitable for reuse become particularly important.

One promising product derived from such technologies is struvite ($MgNH_4PO_4 \cdot 6H_2O$), which allows phosphorus to be simultaneously removed from the water cycle and converted into a stable mineral form suitable for reuse. Struvite precipitation can achieve a high degree of phosphorus recovery: experimental studies show phosphate removal efficiencies up to 93% in model wastewater, with crystals of about 97% purity [7, 46–47]. At the same time, electrochemical or reagent precipitation technologies (e.g., in fluidized-bed reactors) enable recovery of approximately 18–33% of phosphorus from anaerobically digested sludge, with the formation of struvite and a reduction in phosphorus loading on the main wastewater treatment line [9].

Another by-product of sludge processing may be vivianite ($Fe_3(PO_4)_2 \cdot 8H_2O$) in digested sludge (an increase in the share of phosphorus in

Table 1. **Development of technologies for the removal of phosphorus-containing compounds at municipal treatment plants during 1970–2024**

Year	Stage of development
1970s	Introduction of the reagent precipitation of phosphorus compounds
1991	Declaration and regulation of the content of nitrogen and phosphorus compounds in wastewater (according to the UWWTD Directive)
1999	Development of the mathematical model ASM2d as a standard basis for modeling nutrient removal processes in activated sludge systems
2010	Introduction of new biotechnologies based on EBPR in the design of water treatment plants
2015–2020	Introduction of combined technologies
2024	Declaration of stricter standards for total phosphorus concentration in treated wastewater discharged into natural water bodies; reuse of phosphorus compounds from formed sludge becomes relevant

the mineral from 20% to 50% was achieved); a reduction in phosphorus in treated water to 0.42 mg P/dm^3 was noted under the corresponding conditions [10]. This opens the way to controlled binding of phosphorus in the solid phase with the potential for further extraction/use, although practical implementation depends on the balance of impacts on EBPR, sludge formation, and economic costs.

Ash after incineration of wastewater sludge (SSA — sewage sludge ash) is considered a promising secondary phosphorus-containing raw material for obtaining phosphate products, since during incineration phosphorus passes into the mineral phase and concentrates in the solid fraction, where its content may be 35–99 g/kg (P) (≈ 3.5–9.9 wt.% P), together with metal impurities, which requires selective extraction and purification [12]. To recover phosphorus from SSA, chemical technologies are most often used (acid leaching followed by precipitation), and literature data show the potential for almost complete P extraction (up to 100%) for certain extractants/modes, but with the risk of co-leaching of metals and increased reagent demand [11–12]. At the level of industrial solutions, processes such as Ash2Phos already claim 90–95% P recovery with a simultaneous reduction of heavy metals in the phosphorus product by at least 96%, forming fertilizer calcium-phosphate raw material (e.g., hydroxyapatite ($Ca_5(PO_4)_3OH$)) containing at least 16.5% P and 35% Ca [12, 13].

The EU Fertilizing Products Regulation establishes a framework for market entry for certain categories of fertilizers and components (CE marking), which is one of the elements of institutional support for recovered products [43]. The water reuse regulation provides additional context: treated water with low suspended solids and biogenic compound content becomes a resource, which stimulates post-treatment (reagent treatment, together with separation of sludge on filters/membranes) [29, 48].

Modern treatment plants are nonlinear systems with time-varying loading and interaction between wastewater and activated sludge microorganisms. EPA guidance explicitly emphasizes that next-generation design guidelines are based on applying mathematical models and simulations to study kinetics and mass balances, and to select modernization solutions [4].

Table 2. **Comparison of phosphorus removal technologies**

Technology	Removal efficiency of TP, %	Residual TP, mg/dm^3	Increase in sludge volume, %	Main cost items
Chemical precipitation using Fe/Al salts ($FeCl_3$, $Fe_2(SO_4)_3$, $Al_2(SO_4)_3$ etc.)	80–98	0.5–1.0	60–70	Capital costs: reagent storage and dosing systems, mixing equipment, sludge handling units Operating costs: chemical reagents, and sludge dewatering, sludge disposal, electricity consumption
Membrane methods (membrane bioreactor + chemical post-treatment)	Up to 99.8	Up to 0.05	Increase by 10–20	Capital costs: membrane bioreactor, pumping stations, blowers Operating costs: electricity, chemical reagents
A combination of chemical precipitation and biological treatment	80–98	0.5–1.0	5–25	Operating costs for reagents and mechanical sludge dewatering
EBPR (A/O, A2O, etc.	96–98	0.5–1.0; however, there is a risk of “breakthroughs”	0	Capital costs: construction of reinforced concrete biological treatment facilities (aeration tank, secondary clarifier)
Combined scheme: EBPR and subsequent reagent post-treatment	up to 99.6	up to 0.1	10–20	Capital costs: construction of reinforced concrete biological treatment facilities (aeration tank, secondary clarifier), pumping

Note: quantitative estimates of sludge generation are given as guidelines from engineering manuals; actual values depend on wastewater composition and pollutant concentrations, pH/alkalinity, location of the dosing point, suspension separation efficiency, and operating mode [4, 20, 29].

ASM2d is an extension of the IWA family of activated sludge models for describing biological phosphorus removal and denitrifying activity of PAO, with the potential to reproduce nitrate/phosphate dynamics and the influence of oxygen conditions (anaerobic, anoxic, and aerobic zones) [21–22]. Practically important are the correct characterization of influent water (in particular, fractions of phosphorus compounds), control of nitrite/nitrate and dissolved oxygen entering the anaerobic zone, as well as integration with sludge models and recirculation flows [4, 21–22].

In modeling practice, it is important to avoid "overcalibration." Classical approaches to parameter identification (using ASM2d as an example) have shown that not all parameters are practically identifiable; a systematic selection of parameter subsets and a focus on those that most strongly affect the target outputs (TP, nitrites/nitrates, etc.) are appropriate [49, 50]. This is consistent with the general principles of Good Modeling Practice (IWA): first, defining the objective; second, obtaining the minimum necessary data; third, adopting a transparent calibration strategy; and fourth, validating [18, 41–43, 51].

For phosphorus, the critical controlled variables are often indirect: the dissolved oxygen control regime in aerobic zones (affecting PAO, denitrification, and energy consumption), recirculations (nitrate flow and recirculated activated sludge), and the ratio of anaerobic volume to reagent dosage [4, 34, 52]. In the context of BSM2, typical dissolved oxygen control schemes are implemented in aerobic reactors by regulating the oxygen mass transfer coefficient (KLa); for example, studies analyzing BSM2 report oxygen regulation at a constant concentration ($2\ g\ O_2/m^3$) [41].

The study examined the fact that chemical precipitation increases phosphorus removal efficiency to 90–95%, but causes a significant increase in sludge volume — approximately 60–95% (depending on reagent dose). Reagent dosing at the biological stage also increases treatment efficiency; the increase in sludge volume is smaller, at 10–40%. Deep wastewater treatment reduces P by about 80–90% (total removal), but increases sludge volume by only 5–15%. In combined schemes (combining EBPR with a small reagent dose), the total increase in sludge volume is 10–20%, since most of the phosphorus has already been removed biologically. In view of this, the optimal technology is a combination of biological phosphorus removal and reagent addition at the outlet, resulting in the smallest increase in sludge volume and the highest economic efficiency.

Thus, the selected technology will serve as the basis for further modeling and the search for optimal technological parameters, enabling an increase in the efficiency of phosphorus compound removal from wastewater by more than 95%. The study also examined phosphorus recovery technologies from sludge and showed significant differences in recovery efficiency and applicability. Struvite precipitation can achieve phosphorus recovery efficiencies of up to 93%, with crystal purity of approximately 97%. In comparison, electrochemical and reagent-assisted struvite systems can recover approximately 18–33% of phosphorus from anaerobically digested sludge streams and simultaneously reduce phosphorus recirculation loads in the main treatment line. In contrast, vivianite formation requires increased iron dosing and control of anaerobic digestion processes, while phosphorus extraction from SSA involves additional thermal and chemical treatment stages. In view of these findings, struvite crystallization can be considered the most balanced phosphorus recovery strategy due to its high recovery efficiency, production of a marketable fertilizer-grade product, and integration potential with existing sludge treatment lines.

Therefore, struvite-based phosphorus recovery was selected as the preferred technology for further mathematical modeling and optimization studies, aiming to maximize phosphorus recovery while reducing environmental and operational impacts.

Authors' contribution

Kyrychenko K.S. — literature selection, data analysis, writing; Sablii L.A. — formulation of the objective and direction of researches.

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АНАЛІЗ ТА ВИБІР ТЕХНОЛОГІЇ ВИДАЛЕННЯ ФОСФОРУ З МІСЬКИХ СТІЧНИХ ВОД

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Видалення фосфору з міських стічних вод є необхідною умовою запобігання евтрофікації та підтримання переходу до циркулярної економіки. Ефективне очищення потребує не лише дотримання нормативів скиду, але й урахування потенціалу ресурсного відновлення.

Мета. Проаналізувати сучасні технології видалення фосфору та розробити рекомендації щодо оптимізації процесів із використанням математичного моделювання.

Методи. Дослідження базується на аналізі нормативних документів ЄС, українських стандартів, рекомендацій *EPA* (*Environmental Protection Agency*), а також наукової літератури за 2000–2026 рр. Особливу увагу приділено технологіям поглибленого біологічного видалення фосфору (*EBPR*), комбінованим системам очищення, технологіям вилучення фосфору та підходам до моделювання, зокрема ASM2d.

Результати. Хімічне осадження забезпечує високу ефективність видалення фосфору (до 90–95%), проте суттєво збільшує утворення осаду. *EBPR* дозволяє зменшити обсяги утворення осаду та експлуатаційні витрати, однак є чутливим до складу вхідних стічних вод. Комбіновані системи, що поєднують *EBPR* із хімічним доочищенням, забезпечують найвищу ефективність (до 99,6%) при помірному прирості осаду (10–20%).

Висновки. Поєднання біологічного видалення фосфору з хімічним доочищенням є найбільш ефективним та економічно доцільним рішенням. Такий підхід дозволяє забезпечити ефективність видалення фосфору понад 95 % при мінімізації утворення осаду та підтримці стратегій ресурсного відновлення.

Ключові слова: біотехнологія, мікроорганізми, очищення стічних вод, видалення фосфору, моделювання.

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