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## PHOSPHORUS RECOVERY FROM SEWAGE SLUDGE ASH: CHEMICAL PROCESSING AND GRANULATION FOR SUSTAINABLE FERTILISER PRODUCTION

BY

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**Abstract.** The recovery of phosphorus from sewage sludge and sewage sludge ash (SSA) is a crucial step toward achieving sustainable resource management and closing nutrient cycles. This manuscript provides a comprehensive overview of current technologies for phosphorus recovery, focusing on both chemical and thermochemical processes, including acid leaching, struvite precipitation, and high-temperature treatments. Special attention is given to industrially implemented approaches such as the KomPhos, PHOS4green (GLATT/SERAPLANT), AshDec, and RecoPhos processes. The discussion addresses the technical, environmental, and economic aspects of each method, highlighting their advantages, limitations, and regulatory challenges. Economic evaluation criteria such as investment and operating costs, potential revenue, and environmental impacts are also examined. Additionally, the paper presents illustrative process flow diagrams and evaluates the prospects for large-scale implementation. By integrating technological innovation with sustainability goals, phosphorus recovery from SSA emerges as a vital strategy for reducing dependency on imported phosphate rock and promoting circular economy practices.

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**Keywords:** circular economy, fertilizer, phosphorus recovery, secondary phosphate recycling, sewage sludge ash

## 1. Introduction

Phosphorus (P) is an essential nutrient for agriculture and thus for global food production. At the same time, phosphorus is considered a finite resource whose exploitable reserves are limited and highly concentrated in geographically defined regions (Cordell *et al.*, 2009; Scholz *et al.*, 2014). In view of rising population figures and rising food requirements, the sustainable recovery and recycling of phosphorus is becoming increasingly important (Van Dijk *et al.*, 2016).

The wastewater treatment is a key starting point, as a large proportion of the phosphorus used in households, industry, and agriculture ends up in wastewater treatment plants (Abdoli *et al.*, 2024). Despite the high elimination rates (>90%) of modern sewage treatment plants, which specifically remove phosphorus from wastewater and bind it in sewage sludge, this obtained phosphorus residue remains largely unused. Sewage sludge is often thermally recycled or landfilled, causing the phosphorus it contains to disappear from the material cycle (Xu *et al.*, 2023). A sustainable circular economy therefore requires strategies for recovering and recycling the phosphorus contained in the sludge or ash.

This paper provides a comprehensive overview of current processes for phosphorus recovery from municipal sewage sludge and sewage sludge ash, analyzes the processes, their advantages and disadvantages, their market relevance, and their future prospects. Besides others, the KomPhos process is presented as a technically innovative approach with high application potential and is placed in the context of existing technologies.

## 2. Significance and challenges of phosphorus recovery

Phosphorus is a limiting factor in terrestrial and aquatic ecosystems. Uncontrolled inputs of bioavailable phosphorus lead to eutrophication of water bodies (Carpenter *et al.*, 1998).

Phosphorus and phosphate rock were once again designated as critical raw materials in the 2023 update of the Critical Raw Materials (CRM) List (European Commission, 2023; Santos *et al.*, 2025), underscoring their strategic importance and supply vulnerability. This reinforces the need to reduce phosphorus consumption, such as by minimizing its use in products, and to enhance recycling efforts by recovering and reusing phosphorus from various waste streams. The Critical Raw Materials Act, which came into effect on 23 May 2024, establishes targets aimed at strengthening the sustainability and circular use

of CRMs within the European Union (EU). Among its key measures are initiatives to boost the collection of CRM-rich waste and promote its recycling into secondary raw materials (European Commission, 2024). Complementing this, the revised Urban Wastewater Treatment Directive (EU Directive 3019, 2024) introduces further provisions to support resource recovery from municipal wastewater and revised regulations that introduce more rigorous requirements for monitoring chemical contaminants, pathogens, and antimicrobial resistance, while also encouraging the reuse of treated urban wastewater as a strategy to combat water scarcity. In relation to phosphorus management in wastewater treatment plants (WWTPs), the directive stipulates that tertiary treatment must be implemented by 2039. It also proposes specific discharge thresholds and phosphorus removal efficiency targets based on plant size: for facilities serving populations between 10,000 and 150,000, the limit is set at 0.7 mg P/L or an 87.5% reduction from influent levels, while for those serving over 150,000 people, the limit is 0.5 mg P/L or a 90% reduction (Santos *et al.*, 2025).

Modern wastewater treatment plants can now achieve high phosphorus removal rates, to avoid also the eutrophication phenomenon, which is increasingly attributable to diffuse agricultural inputs and legacy contamination in sediments (Sharpley *et al.*, 2000).

The recovery of phosphorus from sewage sludge and ash is therefore important from three perspectives in particular:

- Resource conservation: reduction of dependence on finite mining resources (Van Kauwenbergh, 2010).
- Environmental relief: avoidance of phosphorus inputs through sustainable management and recycling (Cordell and White, 2014).
- Import independence: strengthening security of supply by reducing dependence on imports from geopolitically unstable regions (Scholz *et al.*, 2014).

The greatest challenges lie in the efficient retrieval of phosphorus from complex matrices (wastewater, sewage sludge, sludge ash) and in the production of marketable fertilizer products with high levels of phosphorus available to plants (Pratt and Soares, 2025). Phosphorus fertilizers from sewage sludge ash are agronomically effective and also have favorable environmental properties (Jastrzebska *et al.*, 2022).

### 3. Processes for phosphorus recovery

In this work, phosphorus recovery processes are divided into three main categories: first, recovery directly from wastewater; second, recovery from sewage sludge; and third, recovery from sewage sludge ash, that is, after thermal treatment of the sewage sludge, which is more extensively described. This classification allows for a structured examination of the different technological

approaches along the wastewater or sewage sludge treatment chain (Pasalari *et al.*, 2024).

### 3.1. Phosphorus recovery from wastewater

One option is direct recovery from liquid wastewater, usually in a secondary clarifier or in separate precipitation stages (Santos *et al.*, 2024).

- *Struvite precipitation*: Struvite precipitation is the most widely used method for directly recovering phosphorus from liquid wastewater. Magnesium and ammonium ions are precipitated to form magnesium ammonium phosphate (struvite) and recycled as a fertilizer product (Ye *et al.*, 2014). The advantage is the utilization of the liquid medium, while the disadvantages are high costs for additives and limited yield (Nagarajan *et al.*, 2023).
- *Ion exchangers and membrane technologies*: Processes that can selectively retain and concentrate phosphate (Zheng *et al.*, 2022). However, they are cost-intensive and not yet widely used.

These processes are particularly suitable for wastewater treatment plants with low sewage sludge production and high phosphorus concentrations in the wastewater, but only achieve a share of the total phosphorus content.

Figure 1 presents a schematic overview of phosphorus recovery technologies applied directly to liquid wastewater streams. The diagram highlights two main approaches: struvite precipitation, and emerging technologies such as ion exchange and membrane filtration. Struvite precipitation involves the reaction of magnesium, ammonium, and phosphate ions to form a crystalline fertilizer product, while membrane and ion exchange systems selectively retain and concentrate phosphate ions for potential recovery. These processes are particularly suitable for wastewater treatment plants with low sludge production and high phosphorus concentrations, although they recover only a fraction of the total phosphorus and may be limited by economic or technical constraints.

### 3.2. Phosphorus recovery from sewage sludge

Municipal sewage sludge (MSS), the semi-solid byproduct generated during wastewater treatment, has emerged as a significant secondary source of phosphorus. As global reserves of high-grade phosphate rock decline and demand for fertilizers continues to rise, the recovery of phosphorus from MSS offers a promising pathway toward resource sustainability. Phosphorus in sewage sludge originates primarily from human waste, detergents, and food residues, and accumulates during biological and chemical treatment processes. Given the high phosphorus content and continuous generation of MSS, especially in urban areas, it represents a valuable and underutilized resource.

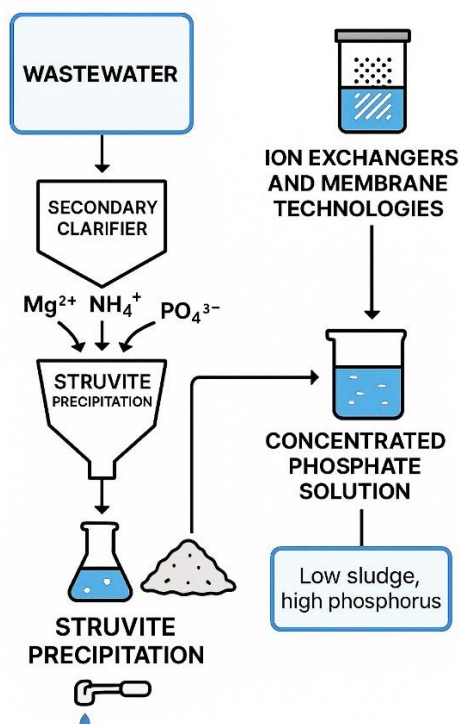


Fig. 1 – Schematic representation of phosphorus recovery processes from liquid wastewater. The figure illustrates two principal approaches: struvite precipitation, in which magnesium, ammonium, and phosphate ions form a solid fertilizer product; and phosphate-selective technologies such as ion exchange and membrane filtration. These processes are suited for wastewater streams with high phosphorus concentrations and low sludge production but differ in yield, cost, and implementation scale.

Efficient recovery and recycling of phosphorus from MSS not only support agricultural productivity but also contribute to closing nutrient loops and reducing environmental burdens associated with sludge disposal (Biney *et al.*, 2025; Di Giacomo and Romano, 2022; Romano *et al.*, 2025).

At present, there is no comprehensive global assessment of sewage sludge production, and existing data are largely confined to studies published within the last three years. Figure 2 presents an overview of annual municipal sewage sludge (MSS) generation and per capita production across selected countries. The data indicate that Europe, East Asia, and North America are the primary producers of MSS worldwide, with total global output estimated at around 56 million tons (Mt) of dry matter annually, a figure that could nearly double over the next three decades (Di Giacomo and Romano, 2022; Romano *et al.*, 2025). This projected increase underscores the urgent need to develop circular and low-carbon strategies for sludge valorization.

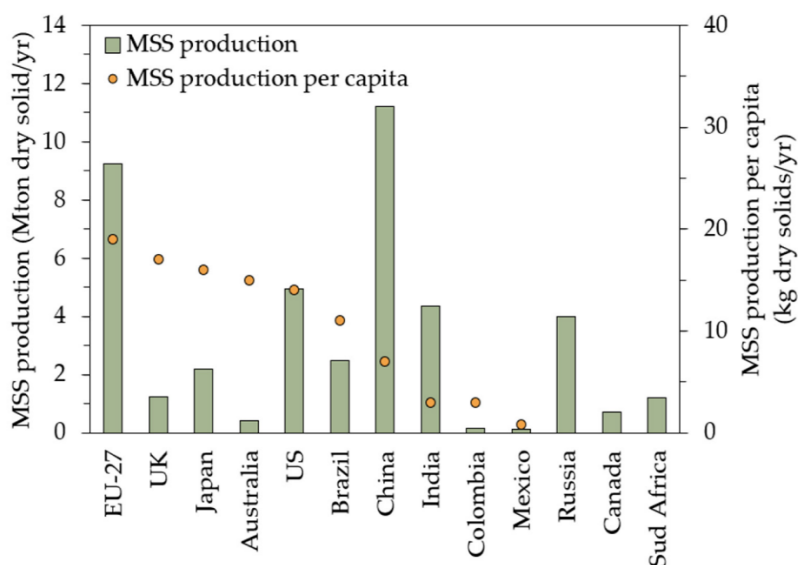


Fig. 2 – Annual MSS production and yearly MSS production per capita in selected countries (reuse from Romano *et al.*, 2025, under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>)).

The phosphorus separated in the sewage treatment plant and can be treated using various methods.

**Biological recovery:** Phosphorus is eliminated through microbiological processes, particularly as part of enhanced biological phosphorus removal (EBPR). This involves incorporating phosphorus into the microbial biomass. However, direct recovery of phosphorus is not possible in this process; phosphorus binding is indirect and requires further treatment processes (Gebremariam *et al.*, 2011; Oehmen *et al.*, 2007).

Figure 3 illustrates the operational sequence of the EBPR process, a biological approach widely used in wastewater treatment plants to reduce phosphorus concentrations (Chu *et al.*, 2022). This process exploits the metabolic capabilities of specialized microorganisms, as polyphosphate-accumulating organisms (PAOs) to remove phosphorus from wastewater and incorporate it into the microbial biomass. The treatment begins with raw wastewater containing phosphorus entering the system. It first passes through a pre-anaerobic stage, where oxygen is absent and favorable conditions are created for PAOs to become metabolically active. In this oxygen-deprived environment, PAOs uptake volatile fatty acids (VFAs) from the wastewater as an energy source. To facilitate this, they release previously stored polyphosphate compounds, resulting in a net

release of phosphorus into the surrounding liquid. Following the anaerobic treatment, the water enters the aerobic stage, where oxygen is supplied to promote microbial activity. Under these conditions, PAOs absorb the previously released phosphorus in excess of their normal metabolic requirements. The absorbed phosphorus is stored intracellular as polyphosphate, effectively removing it from the liquid phase. This leads to the accumulation of phosphorus-rich sludge, which is separated from the treated water. The phosphorus-free supernatant, meaning the clarified water now significantly depleted of phosphorus is discharged or passed on to further treatment stages. Meanwhile, a portion of the biomass (activated sludge) is recycled back to the anaerobic stage, a vital step that maintains a stable and active PAO population within the system, ensuring the continuity of biological phosphorus removal (Chu *et al.*, 2022).

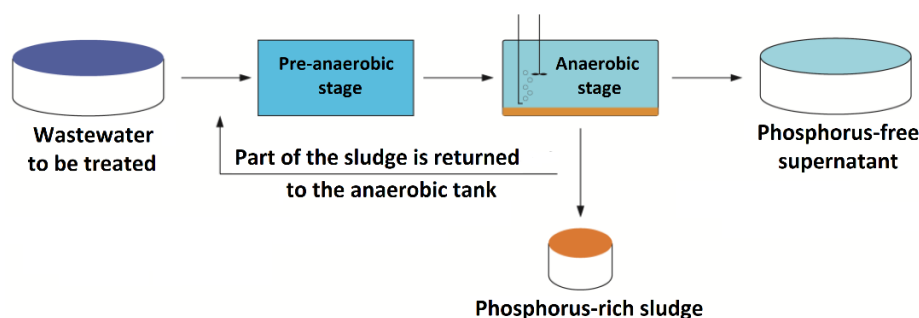


Fig. 3 – Diagram of traditional EBPR phosphorus removal method (reused from Chu *et al.*, 2022, under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>)).

Although this method does not directly yield a recoverable phosphorus product, it concentrates phosphorus in the sludge, making it amenable to subsequent recovery technologies such as incineration, ash processing, or chemical extraction. EBPR is valued for its low chemical input, reduced environmental impact, and compatibility with existing biological treatment systems, though it requires careful process control and favorable influent conditions to be consistently effective. Overall, the diagram provides a simplified yet accurate visualization of how EBPR separates phosphorus biologically, forming the basis for sustainable phosphorus management in wastewater treatment.

**Chemical extraction processes:** In these processes, sewage sludge is treated with acids or alkalis to convert the phosphorus into soluble forms and thus recover it. Despite their effectiveness, these processes are characterized by high chemical costs and the formation of chemical residues that require further treatment (Lin *et al.*, 2024).

The process of chemical phosphorus extraction from sewage sludge is illustrated Fig. 4, detailing each critical step in a logical and technically coherent flowsheet. The process begins with the introduction of dewatered sewage sludge, a byproduct of municipal wastewater treatment, which contains significant amounts of bound phosphorus in both organic and inorganic forms. In the first stage, the sludge undergoes chemical treatment using either acidic or alkaline reagents, typically sulfuric acid, hydrochloric acid, or sodium hydroxide. These chemicals facilitate the breakdown of complex phosphorus compounds, effectively converting the bound phosphorus into soluble forms within the liquid phase. Following the chemical digestion step, the mixture is subjected to a solid–liquid separation process (Pasalari *et al.*, 2024). This stage separates the phosphorus-rich leachate from the residual solid fraction, which consists primarily of inert or digested material now depleted in phosphorus. The solid residue is directed to appropriate disposal or further treatment, while the liquid, containing dissolved phosphorus along with various contaminants such as heavy metals, proceeds to purification.

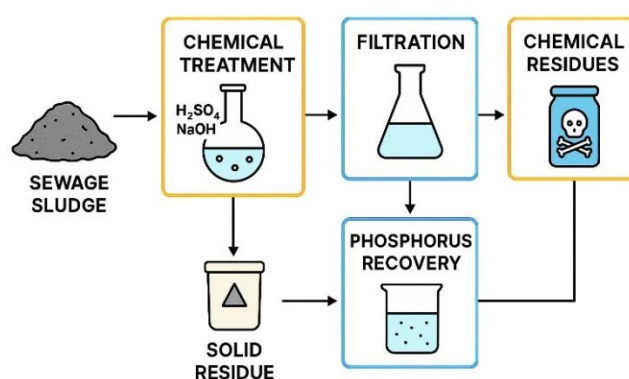


Fig. 4 – Technological flowsheet of phosphorus recovery from sewage sludge through chemical extraction. The process involves acid or alkaline digestion to solubilize phosphorus, followed by solid–liquid separation, purification of the leachate to remove contaminants, and precipitation of phosphate compounds suitable for reuse. Although effective in mobilizing phosphorus, the process is characterized by high chemical consumption and the generation of secondary residues requiring further treatment.

The purification stage plays a critical role in improving the quality of the phosphorus-rich solution. Depending on the composition of the leachate, methods such as precipitation, ion exchange, or adsorption are employed to selectively remove unwanted impurities, particularly toxic metals. This step ensures that the final phosphorus product meets environmental safety standards and is suitable for reuse. Once purified, phosphorus is recovered from the solution through a precipitation or crystallization process. By adjusting the pH and introducing

reagents like magnesium or calcium, soluble phosphate is transformed into solid compounds, such as struvite or calcium phosphate that can be collected as marketable fertilizer products. The recovered material is then dried and, if necessary, further conditioned to improve its physical properties and facilitate handling and storage.

Throughout the process, careful attention must be paid to the management of residual chemical solutions and byproducts. The generation of secondary waste streams, including spent acids and filter residues, requires additional treatment to prevent environmental harm and ensure compliance with regulatory standards (Pasalari *et al.*, 2024). Despite the effectiveness of chemical phosphorus recovery in achieving high yields, the approach remains chemically intensive and generates waste that adds to the operational complexity and cost.

### 3.3. Phosphorus recovery from sewage sludge ash

Sewage sludge ash (SSA), the waste remaining after the incineration of dewatered sewage sludge, has become a key focus in phosphorus recovery strategies due to its relatively high phosphorus content and reduced organic and microbial load. As phosphorus in SSA is predominantly present in inorganic, mineral-bound forms, it offers favorable conditions for chemical extraction and thermal recovery methods (Sun *et al.*, 2023). The valorization of SSA not only addresses the growing demand for alternative phosphorus sources, but also responds to increasing regulatory pressures aimed at diverting phosphorus-rich waste from landfilling and minimizing dependence on imported phosphate rock. However, efficient recovery from SSA presents several technical challenges, including the presence of heavy metals, the stability of phosphate compounds, and the energy or chemical demands of available treatment processes (Franz, 2008; Witek-Krowiak *et al.*, 2022). This section explores the main technologies applied to SSA for phosphorus recovery, highlighting their mechanisms, advantages, limitations, and potential roles within circular nutrient management systems.

The thermal treatment of sewage sludge through mono-incineration, a process in which sludge is burned in dedicated facilities without mixing with other waste streams, serves as an effective method to significantly reduce sludge volume while concentrating essential nutrients, particularly phosphorus, in the resulting ash. However, the chemical composition of sewage sludge ash (SSA) presents considerable challenges for phosphorus recovery. During incineration, phosphorus undergoes transformations and becomes embedded in a complex and heterogeneous mineral matrix. It is frequently associated with elements such as iron, aluminum, and calcium, leading to the formation of water-insoluble phosphate compounds like iron phosphate ( $\text{FePO}_4$ ), aluminum phosphate ( $\text{AlPO}_4$ ), and various calcium phosphates. These compounds are chemically stable and exhibit low solubility under neutral conditions, rendering the direct

agronomic use of SSA ineffective and complicating phosphorus extraction through simple leaching techniques. As a result, effective recovery from SSA typically requires intensive chemical or thermal processing, including acid leaching, thermal reduction, or complexing agents, to convert these insoluble forms into plant-available or recoverable products. Understanding the mineralogical and chemical speciation of phosphorus in SSA is therefore crucial for selecting or optimizing appropriate recovery technologies (Achat *et al.*, 2013).

Phosphorus recovery from sewage sludge ash (SSA) involves a variety of technological processes aimed at transforming the phosphorus present in mineral-bound, often insoluble forms into compounds that are either plant-available or suitable for use in fertilizer production:

**Acid treatment:** represents one of the most widely applied and technically mature approaches for recovering phosphorus from sewage sludge ash (SSA). Central to this method is the use of strong acids, particularly sulfuric acid ( $\text{H}_2\text{SO}_4$ ) and phosphoric acid ( $\text{H}_3\text{PO}_4$ ), to solubilize phosphorus bound in mineral forms such as iron, aluminum, and calcium phosphates. These compounds, typically present in SSA as a result of chemical dosing during wastewater treatment or combustion-induced mineral transformations, are largely insoluble in water. Acid leaching facilitates their conversion into plant-available phosphate forms, which can then be further processed into fertilizers or phosphate intermediates.

This approach is exemplified by the KomPhos process, an in-house developed method, and by the GLATT/SERAPLANT technology, which has been commercialized and implemented at an industrial scale. In these systems, SSA is mixed with a controlled quantity of sulfuric and/or phosphoric acid under optimized conditions, typically moderate temperatures and agitation, to ensure efficient leaching of phosphorus into the liquid phase. The resulting material is a phosphorus-enriched matrix with reduced heavy metal content and enhanced agronomic value (Xu *et al.*, 2023).

A key advantage of acid-based processes, particularly the SERAPLANT implementation, is the complete utilization of the input ash. Unlike other methods that separate soluble phosphorus and generate secondary residues requiring disposal, acid treatment allows the entire ash feedstock to be converted into a usable product, usually a granulated fertilizer. This greatly reduces or eliminates waste streams, aligning the process with circular economy principles and resource-efficiency goals. Furthermore, the use of phosphoric acid not only enhances phosphorus recovery efficiency, but also improves the final product's phosphorus content and solubility, making it more attractive for agricultural use.

Among all phosphorus recovery technologies, the SERAPLANT process currently stands out as the only one operating at full industrial scale, reflecting its technological readiness and market acceptance (Hu *et al.*, 2024). However, the method is not without challenges. It requires careful management of acid

consumption, corrosion-resistant infrastructure, and quality control of the final product to meet regulatory standards for fertilizers. Nevertheless, acid treatment remains a core strategy in the suite of phosphorus recovery options, particularly for regions seeking to minimize waste and maximize nutrient circularity using existing infrastructure and well-understood chemical principles.

**Struvite precipitation from ash solutions:** is a widely studied technique for recovering phosphorus in a usable form following chemical extraction from sewage sludge ash (SSA). After acid leaching solubilizes phosphorus from the ash matrix, the resulting solution is treated with magnesium and ammonium ions, typically by adding magnesium chloride ( $MgCl_2$ ) or magnesium oxide ( $MgO$ ), and a nitrogen source such as ammonium sulfate. Under controlled pH conditions, usually between 8 and 9, these components react with orthophosphate to form struvite ( $MgNH_4PO_4 \cdot 6H_2O$ ), a crystalline compound that can be separated from the liquid phase by sedimentation or filtration (Militaru *et al.*, 2020). This process is particularly attractive due to its low energy demand, relatively simple implementation, and the production of a slow-release fertilizer with high agronomic value. Moreover, struvite precipitation can serve as a polishing step to reduce residual phosphorus concentrations in leachates, minimizing environmental discharge.

However, despite its advantages, several limitations remain. The struvite produced from ash-derived leachates may contain impurities such as heavy metals, depending on the composition of the original sludge and the efficiency of prior purification steps (Wang *et al.*, 2018). These contaminants can restrict the use of the recovered product in agriculture without further treatment or quality control. In addition, struvite precipitation does not recover all of the phosphorus present in the solution, especially when other competing ions interfere with crystallization or when phosphorus is present in non-reactive forms. Therefore, supplementary purification and concentration steps, such as ion exchange or membrane filtration may be required to improve yield and product purity.

Overall, while struvite precipitation offers a promising pathway for phosphorus recovery from chemically treated SSA, its successful integration into full-scale recovery systems depends on careful process optimization, regulatory compliance, and market acceptance of the recovered product.

**Thermochemical processes:** are advanced high-temperature treatment methods designed to alter the mineralogical composition of sewage sludge ash (SSA) in order to enhance the solubility and bioavailability of phosphorus. During incineration, phosphorus in SSA is typically bound in stable, water-insoluble compounds such as iron, aluminum, or calcium phosphates. These forms have limited plant availability and pose challenges for direct agricultural application. Thermochemical treatment, often carried out at temperatures exceeding 900 °C, involves the addition of reactive additives, such as sodium

carbonate, calcium compounds, or reducing agents, to destabilize the inert phosphate phases and transform them into more soluble, plant-accessible forms (Jama-Rodzenska *et al.*, 2021).

This transformation is achieved through solid-state reactions that modify the crystalline structure of the ash, releasing phosphorus from its strongly bound matrix and converting it into water-soluble orthophosphates or alkali-metal phosphates. In some technologies, such as AshDec or Mephrec, the process simultaneously facilitates the volatilization and separation of heavy metals, thereby improving the safety and quality of the end product (Ohtake and Tsuneda, 2019). Despite the significant progress in thermochemical phosphorus recovery, these processes remain highly energy-intensive, contributing to elevated operational costs and raising concerns about their environmental footprint. The need for high-temperature furnaces, prolonged retention times, and sophisticated emission control systems makes them more complex and less economically attractive compared to chemical extraction or biological approaches. Moreover, while these processes can produce phosphorus-rich materials with promising agronomic properties, the regulatory status of such thermochemically treated ashes remains uncertain in many jurisdictions. As of now, they are not widely approved for use as fertilizers under European Union fertilizer regulations, which require extensive testing and validation to demonstrate safety, efficacy, and compliance with heavy metal limits.

As a result, thermochemical technologies are currently limited to pilot or demonstration-scale applications, and further efforts are required to optimize energy efficiency, reduce capital and operating costs, and secure regulatory acceptance. Nonetheless, their potential to recover phosphorus in a safe and sustainable manner, particularly from ashes with high contaminant loads, makes them an important component of the future phosphorus recovery landscape.

Recent European regulatory frameworks increasingly support phosphorus recovery from secondary resources such as sewage sludge and sludge incineration ash. The main legislative instrument governing these materials is Regulation (EU) 2019/1009, applicable since July 2022, which establishes harmonized rules for placing fertilizing products on the EU market. The regulation introduces Component Material Categories (CMCs) that allow certain recovered phosphorus materials, including precipitated phosphate salts (CMC 12) and thermal oxidation materials and their derivatives (CMC 13), to be used in CE-marked fertilizers provided that strict contaminant limits and quality requirements are met. In addition, amendments to Regulation (EU) 2021/1165 permit the use of recovered phosphates such as struvite in organic farming, further supporting nutrient recycling within the EU circular economy framework.

### 3.4. Granulation as a key step in the valorization of recovered phosphorus

Granulation represents a key downstream operation in the valorization of recovered phosphorus, particularly from sources such as sewage sludge ash (SSA) and leachate solutions. After phosphorus is efficiently extracted through precipitation, crystallization, or chemical transformation into bioavailable compounds (e.g., struvite, calcium phosphate), the material must be processed into a form suitable for practical agricultural use. This transition from recovery to application necessitates the conversion of fine powders or semi-liquid matrices into granules with specific mechanical and physical attributes. Granulation serves this essential function by producing stable, homogeneous particles characterized by adequate hardness, reduced hygroscopicity, enhanced flowability, and resistance to dust generation (Ma *et al.*, 2020). These characteristics are critical for downstream handling, including storage, transport, and field-level application, and help to mitigate operational problems such as caking or uneven nutrient distribution. From an agronomic perspective, granulation significantly contributes to the performance of recycled fertilizers. Granules offer improved nutrient release profiles, supporting gradual and targeted phosphorus availability, which reduces the risk of leaching and enhances nutrient uptake by crops. Uniform granule size and mechanical integrity also ensure compatibility with precision agriculture techniques and modern fertilizer spreaders, facilitating even application and minimizing environmental losses. Furthermore, the granulation process can be engineered to incorporate micronutrients, slow-release agents, or organic binders, thus enabling the formulation of tailored fertilizers with multifunctional benefits, such as improved soil health or reduced runoff potential.

The principle underlying this transformation is illustrated in Fig. 5, which depicts how input materials, such as fine powder or slurry derived from phosphorus recovery, are subjected to mechanical forces and/or additives within a granulation system to produce uniform, stable fertilizer granules.

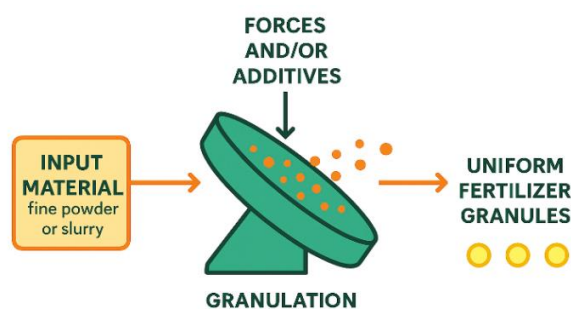


Fig. 5 – Schematic representation of the granulation principle used in fertilizer production (fine powder or slurry recovered from phosphorus sources is introduced into a granulator, where mechanical forces and/or additives facilitate agglomeration into uniform fertilizer granules suitable for handling, storage, and field application).

Technologically, the choice of granulation method, whether through drum granulators, disc pelletizers, fluidized bed granulators, or high-shear mixers is influenced by factors including the physicochemical properties of the feedstock, the moisture content, and the desired product specifications. In phosphorus recovery systems like PHOS4green, where acid-treated SSA is mixed with additives to form plant-available phosphate compounds, granulation follows the critical neutralization and blending steps. Similarly, in the KomPhos process, granulation finalizes the transformation of phosphorus-rich by-products into regulated, marketable fertilizers that comply with EU and national standards for heavy metals, nutrient content, and physical quality (Schott *et al.*, 2023).

By enabling the transition from raw recovered materials to user-friendly, value-added products, granulation closes a crucial loop in the circular phosphorus economy. It not only enhances the marketability and usability of secondary fertilizers but also strengthens their position as credible substitutes for conventional phosphate fertilizers derived from finite phosphate rock. In doing so, granulation contributes to resource conservation, environmental protection, and the broader goals of sustainable agriculture and nutrient recycling.

#### **4. Analysis of phosphorus recovery processes**

##### **4.1. Phosphorous recovery from wastewater: opportunities and limitations**

Struvite precipitation is currently one of the most popular methods in research for recovering phosphorus directly from liquid wastewater (Ye *et al.*, 2014). The reaction requires precise control of the pH value and magnesium and ammonium concentrations and is mainly carried out in sewage treatment plants using special reactors (Nagarajan *et al.*, 2023).

The advantages include the production of a high-grade product with high plant nutrient availability and the possibility of recovering phosphorus early in the material cycle (Puyol *et al.*, 2017). However, the total yield is limited because only the soluble phosphorus in the wastewater is used, while the majority remains in the sewage sludge (Abdoli *et al.*, 2024).

Economic efficiency is limited by the cost of additives such as magnesium chloride and the need for additional process steps. Alternative technologies such as membrane technologies and ion exchangers (Zheng *et al.*, 2022) offer further possibilities, but are currently often not economically or technically competitive.

##### **4.2. Phosphorous recovery from sewage sludge: complexity and efficiency**

Sewage sludge consists of a complex organic matrix in which phosphorus is present in both organic and inorganic forms (Lin *et al.*, 2024). Due to this

complexity, the recovery of phosphorus from unburned sewage sludge is technically challenging.

Biological processes are mainly based on enhanced biological phosphorus removal (EBPR), in which phosphate-accumulating organisms (PAOs) enrich phosphorus as polyphosphates in the biomass (Oehmen *et al.*, 2007). However, the actual recovery can only be achieved indirectly through following sludge treatments such as fermentation or composting.

Chemical extraction processes use strong acids or alkalis to dissolve phosphorus from the organic-mineral matrix (Ebbbers *et al.*, 2015; Ottosen *et al.*, 2023). The sewage sludge is treated in an acidic or alkaline environment to convert phosphorus into water-soluble forms, which can then be precipitated or further processed. However, these processes require large amounts of chemicals, corrosion protection, and complex neutralization of the process water.

Thermal processes such as incineration or pyrolysis only take place after sludge treatment in order to concentrate phosphorus in the ash and prepare it for further recovery processes.

Overall, biological and chemical processes require specific process control and involve different cost and environmental aspects. Biological processes enable sustainable enrichment, while chemical extraction allows direct phosphorus release at a higher cost.

#### **4.3. Phosphorus recovery from sewage sludge ash – Focus on the KomPhos process within the landscape of recovery technologies**

The mono-incineration of sewage sludge offers a significant reduction in waste volume and results in sewage sludge ash (SSA) enriched in phosphorus, typically containing 5–12% P by dry weight (Jama-Rodzenska *et al.*, 2021). However, phosphorus in SSA is mainly present as sparingly soluble iron, aluminum, or calcium phosphates (Achat *et al.*, 2013), which limits its direct application as fertilizer. To ensure phosphorus availability for crops, transformation into more soluble forms, such as orthophosphates, is essential.

A variety of technologies have emerged to recover phosphorus from SSA, with acid leaching being one of the most mature approaches. These processes differ in chemical reagents used, energy demand, residue management, scalability, and product characteristics.

##### **4.3.1. Acid-based chemical processing: The KomPhos Process**

The KomPhos process represents an advanced chemical strategy for phosphorus recovery from sewage sludge ash (SSA), designed to address the dual challenges of nutrient circularity and environmental safety. Developed as a response to increasing regulatory pressure to recover phosphorus from waste streams and reduce dependence on imported phosphate rock, the process is built

on well-established acid leaching principles, refined for optimized performance, scalability, and agronomic value.

At the core of the KomPhos process is the acidic solubilization of phosphorus, targeting poorly soluble mineral phases such as  $\text{FePO}_4$  and  $\text{AlPO}_4$  that dominate in SSA. These compounds exhibit low plant availability and persist in soils when directly applied as ash. To unlock their phosphorus content, the ash is treated with sulfuric acid ( $\text{H}_2\text{SO}_4$ ), which reacts with metal-bound phosphate species to form water-soluble orthophosphates, such as monocalcium phosphate ( $\text{Ca}(\text{H}_2\text{PO}_4)_2$ ) and ammonium phosphate ( $(\text{NH}_4)_2\text{HPO}_4$ ). In some configurations, phosphoric acid ( $\text{H}_3\text{PO}_4$ ) is added in precise quantities to enhance phosphorus extraction efficiency, optimize the N:P ratio in the final product, and balance solution pH. The chemical leaching step is followed by granulation, where the dissolved phosphorus is precipitated and formed into mechanically stable granules. This step is crucial from both agronomic and logistical perspectives. The dust-free, uniform granules meet the particle size requirements of modern fertilizer distributors, allow for accurate nutrient dosing, and facilitate long-term storage and transport. Additionally, the process ensures the absence of any secondary waste, as the entire ash volume is converted into a value-added product. The KomPhos process represents a well-established acid-based chemical route for recovering phosphorus from sewage sludge ash (SSA), enabling the transformation of waste into a valuable resource while addressing concerns related to heavy metal contamination. Figure 6 illustrates the sequential steps involved in this process, from feedstock preparation and acid leaching to leachate purification, phosphorus precipitation, and final product recovery, highlighting the integration of waste management practices to ensure environmental safety.

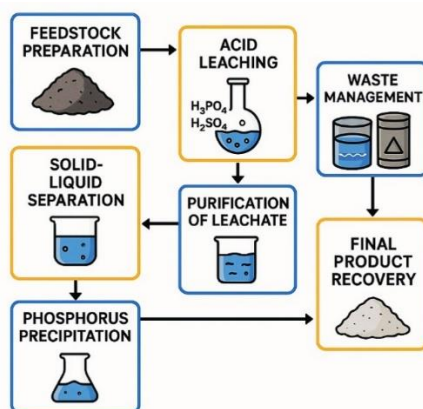


Fig. 6 – Schematic representation of the KomPhos process, an acid-based chemical approach for phosphorus recovery from sewage sludge ash involving leaching, purification, precipitation, and final product recovery for sustainable resource utilization.

### ***Key technical and operational features***

- **Complete utilization of ash:** One of the defining advantages of KomPhos is its zero-waste philosophy. All solid residues are incorporated into the final product, avoiding the generation of inert wastes or contaminated residues requiring costly disposal (Xu *et al.*, 2023). This contributes to both environmental compliance and process economics.
- **Adaptability to variable ash qualities:** The process is designed with operational flexibility, allowing it to accommodate a wide range of SSA compositions. Variations in metal content, moisture, or ash mineralogy can be managed through adjustments in acid dosing, pH control, and residence time (Havukainen *et al.*, 2016). This adaptability enhances its robustness across different wastewater treatment plant outputs.
- **Heavy metal control:** While SSA often contains trace heavy metals such as cadmium, zinc, and lead, the KomPhos process minimizes the risk of their incorporation into the final fertilizer. By selecting suitable input ashes and using optional pre-treatment or selective precipitation steps, the process ensures compliance with national and EU fertilizer regulations (e.g., Regulation (EU) 2019/1009). Where necessary, metal-removal modules (e.g., ion exchange or sulfide precipitation) can be integrated into the system without disrupting core process flows.
- **Process scalability and industrial maturity:** The KomPhos process has progressed beyond laboratory and pilot testing. A full-scale demonstration project with a planned annual capacity of 40,000 tonnes of sewage sludge ash is under development, demonstrating its technological readiness and economic viability (Egle *et al.*, 2016). The system design is modular and can be adapted to both centralized treatment hubs and regional waste management networks.
- **Environmental and circularity benefits:** By converting waste ash into a marketable, plant-available fertilizer, KomPhos directly supports the circular economy goals outlined in the EU's Circular Economy Action Plan. It also contributes to reducing the dependency on finite phosphate rock reserves, which are geopolitically sensitive and environmentally problematic to mine (Zhu *et al.*, 2023).
- **Cost-optimization focus:** In contrast to other acid-leaching systems with high energy demand or complex waste handling, KomPhos emphasizes process efficiency and cost minimization, making it suitable for broader deployment, including in medium-sized municipalities and regional waste treatment cooperatives (Sanchez, 2020).

### 4.3.2. Comparative technologies: The Glatt Process and beyond

In the landscape of phosphorus recovery from sewage sludge ash (SSA), several industrial and pre-commercial technologies have emerged as viable alternatives or complements to the KomPhos process. Among them, the **Glatt–Seraplant process** stands out as a prominent example implemented at industrial scale (<https://phos4green.glatt.com/>). This method similarly employs acid leaching to extract phosphorus from SSA, but distinguishes itself through the integration of a fluidized bed granulation system, which facilitates the production of granular fertilizers with consistent physicochemical properties (<https://phos4green.glatt.com/projects/seraplant-haldensleben/>). The fluidized bed approach allows for enhanced control over particle size distribution, nutrient content, and mechanical strength of the final product, which can be tailored for specific agronomic applications. However, these advantages come at the cost of increased thermal energy requirements, contributing to higher operational expenses and energy demand (Bagheri *et al.*, 2024).

Beyond Glatt, a range of other technologies have been developed, each with distinct process principles and end-product characteristics:

**AshDec process (Outotec):** This thermo-chemical technology involves the thermal treatment of SSA with alkaline additives, such as sodium carbonate, at elevated temperatures. The process facilitates the evaporation of heavy metals, which are later condensed and captured, and transforms phosphorus into plant-available, water-soluble forms (Adam *et al.*, 2009). AshDec is effective in minimizing contamination risks, yet it is highly energy-intensive, posing challenges for large-scale sustainability. Figure 7 illustrates the AshDec process, a thermo-chemical technology developed by Outotec for phosphorus recovery from sewage sludge ash (SSA). In this process, SSA is mixed with alkaline additives such as sodium carbonate and subjected to high-temperature treatment in a reactor. The elevated temperatures promote the evaporation of heavy metals, which are subsequently condensed and captured, thereby reducing contamination risks. Simultaneously, phosphorus is converted into water-soluble, plant-available forms. The schematic highlights the key material flows and treatment stages, emphasizing both the efficiency of heavy metal removal and the generation of phosphorus-rich output suitable for fertilizer production.

**RecoPhos process:** Based on high-temperature reduction smelting, the RecoPhos method recovers phosphorus as elemental white phosphorus, a highly reactive and valuable industrial chemical. While this process offers high phosphorus recovery efficiencies, its technical complexity, elevated capital costs, and the nature of the product make it less suited for direct application in agriculture, particularly where nutrient recycling and soil amendment are the primary goals (<http://www.recophos.org/>).

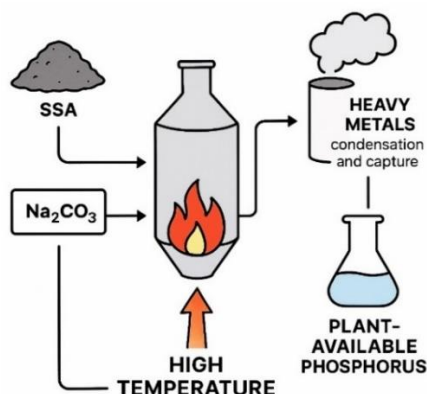


Fig. 7 – Schematic representation of the AshDec process for phosphorus recovery from sewage sludge ash (SSA). The process involves the addition of alkaline additives, such as sodium carbonate, followed by thermal treatment at high temperatures. Heavy metals are evaporated and subsequently captured through condensation, while phosphorus is transformed into plant-available, water-soluble compounds. The illustration outlines the main process steps, material inputs, and outputs, highlighting the dual objectives of resource recovery and contaminant reduction.

Figure 8 exemplifies the RecoPhos process, a high-temperature reduction smelting technology designed to recover elemental white phosphorus from sewage sludge ash. In this process, the ash is introduced into an electric arc furnace together with a reduction agent. Under reducing conditions at elevated temperatures, phosphorus is volatilized and subsequently condensed as elemental white phosphorus, while by-products such as slag and off-gas are separately managed.

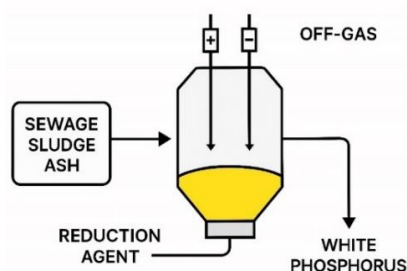


Fig. 8 – Schematic representation of the RecoPhos process for phosphorus recovery from sewage sludge ash via high-temperature reduction smelting (the process involves the use of a reduction agent and an electric arc furnace to volatilize phosphorus, which is then condensed and collected as elemental white phosphorus. Off-gas and slag are managed as by-products. The method enables high phosphorus recovery efficiency but is primarily suited for industrial applications due to the reactive nature of the product and the process complexity).

The schematic emphasizes the process configuration and the material flows, including the generation of high-purity white phosphorus, which is primarily suited for industrial use rather than agricultural application due to its chemical reactivity and handling requirements.

**EcoPhos process:** This method leverages phosphoric acid digestion to dissolve phosphorus from SSA, producing purified phosphate salts suitable for fertilizer production. A notable feature of the EcoPhos approach is its ability to integrate waste acids from other industrial sectors, thereby enhancing process circularity and reducing chemical input costs. Additionally, the process eliminates the need for ash disposal, contributing to environmental sustainability (Egle *et al.*, 2016).

Figure 9 illustrates the EcoPhos process, a chemical phosphorus recovery method based on phosphoric acid digestion of sewage sludge ash (SSA). In this process, phosphoric acid, often sourced from industrial waste streams is used to dissolve phosphorus from the ash, enabling the formation of purified phosphate salts suitable for fertilizer production. The diagram highlights the process flow, including the integration of waste acids, which enhances chemical circularity and reduces input costs.

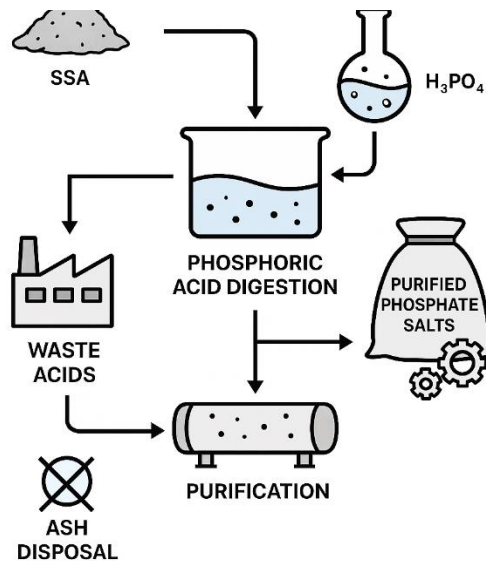


Fig. 9 – Schematic representation of the EcoPhos process for phosphorus recovery from sewage sludge ash (SSA) (The process involves phosphoric acid digestion to solubilize phosphorus, followed by the recovery of purified phosphate salts for fertilizer production. The integration of waste acids from other industrial sources enhances process circularity and reduces chemical input costs. The method eliminates the need for ash disposal, contributing to environmental sustainability).

Notably, the process avoids ash disposal by converting nearly all input material into usable or recoverable outputs, contributing to improved environmental sustainability and resource efficiency. Each of these technologies presents trade-offs between process complexity, energy consumption, contaminant removal efficiency, and suitability of the end products for agricultural or industrial use. Comparative assessments must consider these parameters in the context of local waste management infrastructure, regulatory frameworks, and market demand for recovered phosphorus products.

#### 4.3.3. Comparative assessment of acid leaching processes

Acid leaching processes represent one of the most mature and widely implemented strategies for phosphorus recovery from sewage sludge ash (SSA). While the underlying principle, as dissolution of sparingly soluble phosphorus compounds using mineral acids is common to all such processes, their operational characteristics, input requirements, and output products vary considerably (Ismailov *et al.*, 2023).

A comparative evaluation of selected acid-based phosphorus recovery processes: KomPhos, Glatt (Seraplant), EcoPhos, and AshDec is presented below, highlighting essential performance parameters such as chemical use, energy demand, fertilizer quality, scalability, and environmental considerations (Nardi *et al.*, 2025; <https://phos4green.glatt.com/>; [https://phosphorusplatform.eu/images/download/ESPP-NNP-DPP\\_P-recovery\\_tech\\_catalogue\\_v\\_3\\_9\\_21.pdf](https://phosphorusplatform.eu/images/download/ESPP-NNP-DPP_P-recovery_tech_catalogue_v_3_9_21.pdf)).

#### Chemical inputs and process efficiency

The type and concentration of acids used directly influence process efficiency and environmental impact. KomPhos utilizes a combination of sulfuric and phosphoric acids to enhance dissolution kinetics while maintaining cost-effectiveness. In contrast, EcoPhos relies on phosphoric acid, which can be partially sourced from waste acid streams, improving circularity but potentially increasing operational complexity. Glatt also employs sulfuric acid, yet integrates thermal processing that raises energy requirements. AshDec, though not a classical acid leaching method, uses sodium-based additives to promote phosphate transformation under thermal conditions.

#### Energy and resource demand

Energy consumption is a key differentiator. AshDec and Glatt involve intensive thermal treatment steps, making them less favorable in regions with high energy costs or decarbonization targets. KomPhos and EcoPhos are chemically driven and require less energy, making them more attractive from an energy efficiency perspective, especially when integrated with low-temperature waste heat sources.

**Product characteristics and agronomic value**

A central goal of phosphorus recovery from SSA is the production of fertilizers that are plant-available and meet market standards. KomPhos and Glatt both produce granulated mineral fertilizers suitable for agricultural machinery application. These products exhibit high phosphorus availability and compatibility with existing distribution systems. EcoPhos generates phosphate salts (e.g., mono- and di-calcium phosphate), which are typically used in the fertilizer and feed industries. AshDec, by converting phosphates into thermally stable mineral forms, achieves moderate agronomic value, often requiring downstream formulation to enhance plant availability.

**Heavy metal management and environmental compliance**

SSA frequently contains trace elements such as cadmium, lead, and zinc, which must be controlled in any recovery process. AshDec effectively removes volatile heavy metals during thermal treatment, producing a clean product with minimal post-treatment. EcoPhos integrates purification steps that isolate metals from the phosphate stream. KomPhos and Glatt rely on input ash quality and offer optional modules for metal removal. Thus, process selection often depends on the upstream control of ash composition and regulatory constraints for final fertilizer use.

**Scalability and industrial maturity**

From a technological readiness perspective, Glatt (Seraplant) and EcoPhos have reached full industrial-scale implementation, with operational plants in Germany and Belgium, respectively. KomPhos is currently transitioning from pilot to full-scale, with its first 40,000-tonne/year facility under development. AshDec, while technically mature, remains at the demonstration scale, in part due to its higher energy footprint and capital intensity (<https://phos4green.glatt.com/projects/seraplant-haldensleben/>).

**Economic viability**

Economic assessments indicate that operational costs are strongly influenced by acid consumption, energy demand, and residue management. KomPhos aims for cost-optimized operation by minimizing reagent use and avoiding by-product generation. Glatt, while commercially proven, has higher operating costs due to energy inputs. EcoPhos benefits from high phosphorus recovery rates and by-product valorization but may require more sophisticated infrastructure. AshDec entails higher capital investment and energy consumption, potentially limiting its deployment to centralized facilities with energy integration (Bagheri *et al.*, 2024; Sanchez, 2020).

### Integrated assessment

An integrated assessment shows that no single process dominates across all criteria. **KomPhos** appears particularly promising for regional wastewater treatment systems seeking low-waste, fertilizer-grade outputs with moderate investment. **Glatt** is suitable where infrastructure and energy access permit intensive processing. **EcoPhos** fits well in industrial symbiosis schemes. **AshDec** remains a niche solution for high-throughput facilities with available thermal energy and a need for heavy metal removal (Bianchini and Rossi, 2020; ESPP, 2024; Witek-Krowiak *et al.*, 2022).

Table 1 synthesizes these findings, providing a comparative snapshot of the selected technologies. The decision for implementation should consider local legislative requirements, feedstock characteristics, market demand for fertilizers, and existing waste infrastructure.

**Table 1**  
*Comparative assessment of acid leaching processes*

Feature	KomPhos	Glatt (Seraplant)	EcoPhos	AshDec
Chemical used	H <sub>2</sub> SO <sub>4</sub> / H <sub>3</sub> PO <sub>4</sub>	H <sub>2</sub> SO <sub>4</sub>	H <sub>3</sub> PO <sub>4</sub>	Na <sub>2</sub> CO <sub>3</sub>
Energy demand	Moderate	High	Moderate	Very high
Product form	Granulated fertilizer	Granulated fertilizer	Phosphate salts	Granulated fertilizer
Heavy metal removal	Optional module	Partial	Integrated	Efficient
Waste/by-product	None	Minimal	Liquid waste	Metal-rich slag
Scale	Pilot/industrial	Industrial	Industrial	Pilot/demo
Agronomic value	High	High	High	Moderate

### 5. Opportunity costs and economic evaluation of the processes

The selection of a suitable phosphorus recovery process by wastewater treatment plant operators and administrative decision-makers is a complex process influenced by various economic factors. Opportunity costs play a key role here, as they weigh up the potential advantages and disadvantages of alternative courses of action. The main cost and benefit aspects include:

- *Investment costs*: These include one-time expenses for the construction of new plants or the retrofitting of existing wastewater treatment plants with phosphorus recovery technologies. These costs can vary considerably depending on the complexity and scope of the processes used and often

represent a significant barrier to implementation (Sanchez, 2020).

- *Operating costs*: Running costs include, in particular, the consumption of chemicals, the energy required for process control, and personnel costs for operating and maintaining the plants. These variable costs have a direct impact on the economic efficiency and competitiveness of the processes (Nättorp *et al.*, 2017).
- *Disposal costs*: Recovering phosphorus from sewage sludge or sewage sludge ash reduces waste volumes, which leads to savings in the disposal of residual materials. This cost reduction is an important economic advantage, as disposal is often associated with high fees (Egle *et al.*, 2016).
- *Revenue from the sale of fertilizers*: The marketable phosphorus products resulting from the recovery process can generate additional income. The achievable sales prices depend on product quality, market demand, and regulatory conditions (Kok *et al.*, 2018).
- *Environmental costs and benefits*: The economic assessment should also take ecological aspects into account. Conventional disposal methods often cause environmental pollution, the costs of which are frequently not fully captured in decision-making. Sustainable phosphorus recovery, on the other hand, can create environmental benefits, such as resource conservation and reduced emissions, which reduce societal costs in the long term (Amann *et al.*, 2018).

Figure 10 provides a visual summary of the key economic factors and opportunity costs associated with the selection and implementation of phosphorus recovery technologies in wastewater treatment. The illustration highlights five main categories influencing decision-making: investment costs, operating costs, disposal costs, revenue from the sale of recovered phosphorus products, and environmental costs and benefits. These interconnected elements form the basis for a comprehensive economic evaluation, guiding both utility operators and policymakers in making informed and sustainable choices. The central balance scale metaphorically represents the trade-offs and equilibrium sought in optimizing economic efficiency and environmental performance.

The overall efficiency and sustainability of resource allocation in the context of phosphorus recovery depend largely on the extent to which these diverse cost and benefit factors are systematically integrated into business and political decision-making processes. Recent studies indicate that without adequate consideration of environmental costs, suboptimal investment decisions are often made that limit the potential for sustainable resource use (Cordell and White, 2014; Scholz *et al.*, 2014). Against this framework, instruments such as life cycle assessments, ecological evaluation methods, and incentive systems are becoming increasingly important in enabling a holistic and future-proof economic evaluation of phosphorus recovery processes.

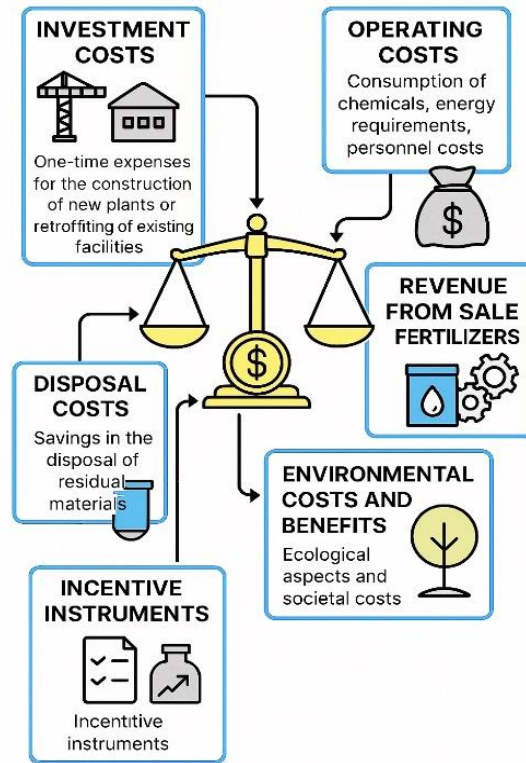


Fig. 10 – Schematic representation of the key economic components and opportunity costs associated with phosphorus recovery processes (the figure illustrates the main cost and benefit factors, such as investment costs, operating costs, disposal cost savings, revenue from fertilizer sales, and environmental impacts, which collectively influence the economic evaluation and strategic decision-making in wastewater treatment and resource recovery).

## 6. Outlook and future prospects

The efficient recovery of phosphorus from sewage sludge and sewage sludge ash is becoming increasingly important due to the limited global availability of primary phosphorus resources and increasing legal requirements for waste and resource utilization (Cordell *et al.*, 2011; Guedes *et al.*, 2014). Municipal wastewater treatment plants are faced with the challenge of implementing processes that are environmentally sustainable, technically efficient, and economically viable. Innovative technologies that enable a combination of chemical digestion and subsequent granulation offer potential for the production of marketable, plant-available fertilizers with minimized waste

streams (Jama-Rodzenska *et al.*, 2021; Ottosen *et al.*, 2023). Optimizing process parameters in terms of energy consumption, chemical use, and environmental impact is key to meeting both economic and ecological requirements (Abis *et al.*, 2018). Long-term agronomic studies and ecological assessments are necessary to evaluate the availability of phosphorus in the soil and the potential environmental impacts of the recovery products (Jama-Rodzenska *et al.*, 2021; Sheil *et al.*, 2016). Such studies are crucial to promote acceptance among farmers and other stakeholders. In addition, the economic efficiency of the processes compared to conventional mineral fertilizers is an important prerequisite for their market penetration (Cordell and White, 2014). Taking environmental costs into account and promoting a circular economy can contribute to the competitiveness of renewable phosphorus products in the future (Scholz *et al.*, 2014).

Figure 11 provides a conceptual overview of the key dimensions shaping the future of phosphorus recovery from sewage sludge and sewage sludge ash.

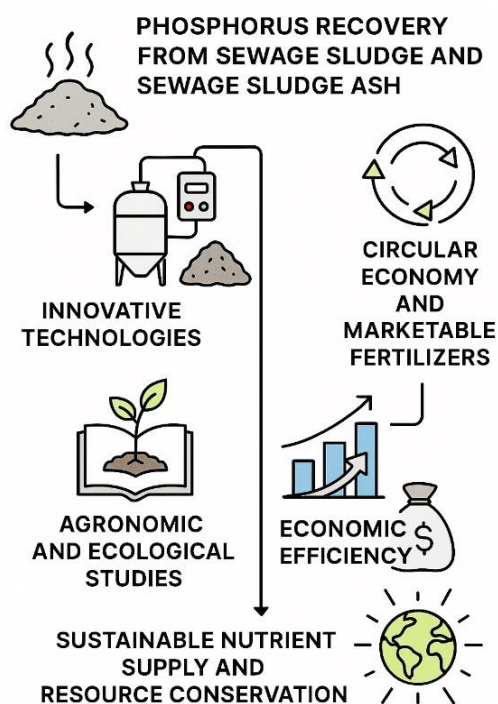


Fig. 11 – Illustration of the outlook and future prospects for phosphorus recovery from sewage sludge and sewage sludge ash. The figure highlights key elements for sustainable implementation, including innovative recovery technologies, integration into the circular economy, long-term agronomic and ecological assessments, and economic efficiency. These factors collectively contribute to achieving sustainable nutrient supply and resource conservation.

Figure 11 highlights the role of innovative technologies in transforming waste into valuable, plant-available fertilizers, thereby supporting the development of a circular economy. The diagram also emphasizes the importance of agronomic and ecological studies in assessing the long-term impacts and availability of recovered phosphorus in soils. In parallel, it illustrates the need for economic efficiency and market viability to ensure that recovered phosphorus products can compete with conventional mineral fertilizers. Collectively, these interconnected elements contribute to the broader vision of achieving a sustainable nutrient supply and effective resource conservation in the context of environmental and agricultural systems.

Overall, phosphorus recovery is a key component of sustainable nutrient supply and resource conservation in agriculture. The further development and scaling of appropriate technologies are essential for a sustainable circular economy recovery process.

## 7. Conclusions

The sustainable management of phosphorus, a finite and non-renewable resource, is a global environmental and agricultural priority. Phosphorus recovery from sewage sludge and sewage sludge ash (SSA) represents a strategic response to the dual challenges of resource scarcity and environmental pollution. This manuscript offers a comprehensive examination of the state-of-the-art recovery technologies, their implementation at pilot and industrial scale, and their integration into broader sustainability and circular economy frameworks.

The analysis demonstrates that phosphorus recovery is technically feasible and increasingly economically and environmentally justified. Among the main technological pathways, acid leaching processes such as those used in the KomPhos and PHOS4green (GLATT/SERAPLANT) systems allow for the efficient conversion of phosphorus in ash into plant-available forms. These processes are notable for their compatibility with existing infrastructure and their capacity to generate fertilizers with high agronomic value. Their scalability has been proven through successful industrial applications, such as in the Seraplant plant in Haldensleben, Germany.

Thermochemical processes, such as AshDec and RecoPhos, offer alternatives that target both phosphorus mobilization and the simultaneous removal of contaminants like heavy metals. While promising in terms of product purity and environmental safety, these processes remain challenged by their high energy requirements, significant capital investments, and limited acceptance of their products within existing fertilizer regulations. The case of RecoPhos illustrates the technological complexity of recovering elemental white phosphorus, a material of industrial value but of limited relevance for direct soil application, thus restricting its use in the context of nutrient recycling.

The struvite precipitation pathway, primarily suited for phosphorus-rich liquid streams, has been examined as a downstream treatment option following ash dissolution. Although the struvite generated is a recognized slow-release fertilizer, the presence of impurities and the need for tight process control limit its widespread adoption from ash leachates. Similarly, ion exchange and membrane technologies, while offering high selectivity, are still cost-prohibitive for large-scale use.

An important dimension of the phosphorus recovery discussion is the granulation and post-processing phase, which enhances the practicality, storability, and marketability of the final fertilizer products. This step is crucial for aligning secondary phosphorus products with market standards and farmer expectations, particularly regarding nutrient content, solubility, and handling characteristics.

From an economic standpoint, the manuscript underscores the importance of comprehensive cost-benefit analyses. Investment and operating costs, chemical consumption, potential revenue from fertilizer sales, and avoided disposal costs are essential components in determining the economic feasibility of phosphorus recovery systems. However, it is increasingly recognized that traditional financial models do not capture the full environmental and societal value of phosphorus recovery. Incorporating environmental costs, such as avoided eutrophication, reduced greenhouse gas emissions, and preservation of natural phosphorus reserves, through life cycle assessments and ecological accounting methods is vital for informed decision-making.

The regulatory context is also rapidly evolving. The inclusion of phosphate rock and phosphorus on the European Union's 2023 Critical Raw Materials List and the entry into force of the Critical Raw Materials Act (May 2024) reflect growing political will to support phosphorus recovery initiatives. Additionally, the revised Urban Wastewater Treatment Directive (Directive (EU) 2024/3019) mandates enhanced phosphorus removal, introducing minimum thresholds for tertiary treatment and recovery, thereby creating a legal imperative for the implementation of recovery technologies in wastewater treatment plants.

Looking toward the future, research should focus on:

- Optimizing the energy and material efficiency of existing processes.
- Scaling pilot systems to industrial capacities in diverse regional contexts.
- Demonstrating the long-term agronomic performance and environmental safety of recovered products.
- Developing new incentive frameworks and market instruments to stimulate uptake.

There is also a critical need for cross-sectoral collaboration, bringing together researchers, technology developers, wastewater utilities, policymakers, and farmers to ensure that recovered phosphorus is not only technically viable but also socially accepted and economically competitive.

Hence, phosphorus recovery from sewage sludge and its ash is no longer an optional add-on but a core component of a circular and sustainable bioeconomy. It provides an opportunity to transform an environmental burden into a valuable resource, reduce dependence on imported raw materials, mitigate ecological impacts, and contribute to global food security. The successful implementation of recovery processes will require not only technological innovation but also adaptive governance, supportive policy environments, and sustained public and private investment. With appropriate action, phosphorus recovery can become a flagship example of how waste streams can be transformed into strategic resources in the 21st century.

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RECUPERAREA FOSFORULUI DIN NĂMOLUL DE EPURARE ȘI DIN CENUȘA  
ACESTUIA: TEHNOLOGII, EVALUARE ECONOMICĂ ȘI PERSPECTIVE DE  
IMPLEMENTARE

(Rezumat)

Recuperarea fosforului din nămolurile de epurare și din cenușa acestora (SSA) reprezintă un pas esențial pentru atingerea unui management sustenabil al resurselor și

pentru închiderea ciclurilor nutrienților. Acest manuscris oferă o prezentare a tehnologiilor actuale de recuperare a fosforului, concentrându-se pe procesele chimice și termochimice, inclusiv levigarea acidă, precipitarea struvitului și tratamentele la temperaturi înalte. Se acordă o atenție specială metodelor implementate industrial, precum procesele KomPhos, PHOS4green (GLATT/SERAPLANT), AshDec și RecoPhos. Lucrarea abordează aspectele tehnice, de mediu și economice ale fiecărei metode, evidențiind avantajele, limitările și provocările de reglementare. Sunt analizate criteriile de evaluare economică, cum ar fi costurile de investiție și operare, potențialul de profit și impacturile asupra mediului. De asemenea, lucrarea prezintă diagrame de proces ilustrative și evaluează perspectivele de implementare la scară largă. Integrarea inovației tehnologice cu obiectivele de sustenabilitate face din recuperarea fosforului o strategie-cheie pentru reducerea dependenței de rocile fosfatice importate și promovarea economiei circulare.