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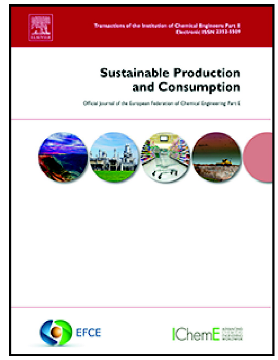

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Economic feasibility and direct greenhouse gas emissions from different phosphorus recovery methods in Swedish wastewater treatment plants

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Abstract

Phosphorus (P) is a finite, non-renewable resource that is a critical component of fertilizers; therefore, recovering P from municipal wastewater can provide an alternative sustainable source of this nutrient. This work analyses economic impacts and greenhouse gas emissions of P recovery in Swedish municipal wastewater treatment plants. The study examines different scenarios, including P recovery technologies in individual plants and hubs, and considers various P-rich streams (supernatant, sludge, and ash) in plants, different plant sizes, and multiple sludge management strategies such as land application, incineration, and hydrochar production, under current market conditions. The goal is to identify and offer solutions tailored to local conditions, addressing both technical opportunities and strategies to reduce costs.

The results show varying recovery rates: 5% from supernatant, 36-65% from sludge, and 17% from sludge ash relative to total P in wastewater. Despite technical feasibility, P recovery costs are not covered at current market prices of P, indicating a lack of financial incentive, especially for smaller treatment plants. The least expensive recovery method costs about 7 k€/t P for ash, compared to 30-187 k€/t P for supernatant, however with the latter coming with the co-benefit of mitigated greenhouse gas emissions. The emissions from studied plants range from 84-123 Kt CO2 eq (CO2 equivalent) for supernatant, 94-141 Kt CO2 eq for sludge, and 75-102 Kt CO2 eq for ash among different P recovery methods. Comparatively, P recovery methods from supernatant showed the lowest emissions, while the lower emissions range for ash is due to the consideration of fewer plants. Developing hub networks and converting sludge into products like hydrochar are crucial for attracting investments, enhancing P recovery, and leveraging economies of scale. Results highlight the urgency for localized strategies and proactive policy interventions to reconcile economic and environmental objectives in P recycling. Furthermore, P recovery from wastewater treatment plants, although more resource-intensive than mineral fertilizer, promotes circularity in the food chain and mitigates the risk of eutrophication.

Keywords: sewage sludge management, phosphorus recovery, techno-economic analysis, hub strategy.

Nomenclature

P: phosphorus; PR: phosphate rock; MWWTP: municipal wastewater treatment plant; CaP: calcium phosphate; Ca: calcium; Mg: magnesium; TRL: technology readiness level; p.e: population equivalents; HTC: hydrothermal carbonization, AD: anaerobic digestion; CHP: combined heat and power; UWWD: European Urban Wastewater Directive; DS: dry solid content; P_in: phosphorus content in wastewater; P_out: recovered phosphorus by recovery technology; CO2 eq: CO2 equivalent.

1 Introduction

Phosphorus (P) is an essential mineral, crucial for life and food production, yet phosphate rock (PR), the main source of P, is finite and unevenly distributed among countries (Mayer et al., 2016). P utilization efficiency in many countries is less than 20% (Li et al., 2019), reflecting losses in mining, agriculture, food processing, and the capacity of crops to transform P into biomass or grain yield effectively. This inefficiency, combined with growing global food demands and the uneven distribution of PR, predicts an escalation in both demand and price of P fertilizer (Al Rawashdeh, 2022), which points to an urgent need to improve P use efficiency (Jupp et al., 2021).

From the 39 Mt P fertilizer used in global agriculture, only 10 Mt reach the consumers (Vu et al., 2023). Nearly 98% of the P consumed by humans in urban areas ends up in sewage sludge after collection through sewer systems and processing in municipal wastewater treatment plants (MWWTPs) (Xie et al., 2023). Therefore, P recovery from MWWTPs can hypothetically cover up to 25% of global P fertilizer demand, yet this is limited in practice. Due to the significant dependency on P import (Smol, 2019), Europe promotes efforts and research into recycling P from secondary streams such as sewage sludge (Ravi et al., 2022). Land application is Europe's most common practice for sewage sludge management (Eurostat, 2023). This practice, although widespread, is becoming increasingly controversial since P in sludge is in a slow-release form and frequently contains considerable amounts of heavy metals, organic contaminants, and other harmful substances (Hamilton et al., 2017; Ravi et al., 2022). Despite its technical feasibility and potential to reduce reliance on virgin resources, P extraction faces several hurdles (Shaddel et al., 2019), with economic challenges foremost. High-yield extraction technology incurs substantial costs, representing the primary limitation (Rahimpour Golroudbary et al., 2020).

Concerns over sludge land application and pursuing a circular economy have influenced policy shifts, phasing out land application in favor of mandatory P recycling in countries like Germany and the Netherlands (Bauer et al., 2020). In Sweden, the primary methods for disposing of sewage sludge include land application (46%), plant soil production (23%), and covering landfills (16%) (SCB, 2020). Despite four attempts to revise sewage sludge legislation since 2001, the future direction for sludge management in Sweden remains unclear (Bauer, 2023; Ekman Burgman, 2022). A recent government investigation recommended continuing land application with stricter heavy metal limits, noting that P extraction costs exceed its value (Holmgren, 2020). Despite government support for land application, incineration may still emerge as the primary sludge disposal method. The inquiry underscores the unpredictability of meeting ever-tightening quality standards and finding farms willing to accept sludge (Dagerskog, Linus & Olsson, 2020). Farmers prefer extracted P from sludge over direct land application (McConville et al., 2023). This legislative ambiguity creates insecure conditions for potential investors.

Many studies investigate the technical details of P extraction methods. For instance, Aragón-Briceño et al. (2021) focus on enhancing anaerobic digestion (AD) performance as the most common sludge treatment method, while Gao et al. (2020b) advocate for thermal treatment such as gasification and pyrolysis as the future pathway for sludge treatment, emphasizing thermal treatment ability to address contamination concerns. Chrispim et al. (2019) offer guidance on selecting P recovery options within the municipal wastewater treatment sector, specifically tailored for large cities in developing countries. Concurrently, other research focuses on evolving sewage sludge management trends and legislative frameworks (Bauer et al., 2020). Furthermore, the environmental effects of P recovery from sewage sludge have been explored from multiple angles (Pradel and Aissani, 2019; Ravi et al., 2022).

The field of P recovery from sewage sludge is diverse and multifaceted. No one-size-fits-all strategy exists for recycling P from sewage sludge (Milojevic and Cydzik-Kwiatkowska, 2021). The optimal method for P recovery should prioritize a high recovery rate, economic viability, and products with minimal environmental impact (Egle et al., 2015), and be tailored to the specific location (Amann et al., 2018).

Recent trends in the sustainability assessment of waste management systems emphasize the integration of environmental, economic, and social dimensions to ensure comprehensive evaluations (Gadaleta et al., 2022). For example, Shaddel et al. (2019) present an overview of nutrient recovery routes and technologies from sewage sludge, proposing measures to improve sustainability in P management. Barquet et al. (2020) identify barriers and opportunities towards a circular P economy, focusing on the wastewater and agriculture sectors in the Baltic Sea region. Jupp et al. (2021) explored mineral and secondary sources of P, showing the shift in focus on P management from pollution prevention to recycling. However, challenges remain in aligning recovery and recycling processes, creating value chains, and overcoming economic and legislative barriers. Table S1 includes a summary of recent research on P recovery from MWWTPs. The studies mentioned highlight the higher cost of recovered P than mineral P as a major barrier to sustainable P management and underscore the need for regulatory policies. However, the economic aspect of sewage sludge management research is often overlooked (Bagheri et al., 2023).

This study focuses on assessing the costs associated with P recovery within Swedish MWWTPs, aiming to clarify technical feasibility, implementation challenges, local opportunities and barriers, and financial requirements for P recovery under current market conditions. Sweden was chosen as the focus due to its significant reliance on land application of sewage sludge and potential legislative shifts towards favoring extraction methods over land application. A techno-economic analysis, as conducted here, establishes essential parameters for P recovery and offers recommendations to guide future legislative initiatives.

The P-REX project in Europe has offered a comprehensive techno-economic and environmental analysis of various P recovery technologies (Jossa et al., 2015). However, its base case is restricted to MWWTPs with 1,000,000 p.e (population equivalents), narrowing the applicability of its findings to only a few MWWTPs. To our knowledge, no study has yet explored the techno-economic implications of integrating P recovery technologies into Swedish MWWTPs, considering the importance of local conditions and opportunities. The overall aim of this study is to demonstrate possible approaches for economically feasible P recovery in Sweden. To achieve this, we have set the following specific objectives:

1. Assess the economic viability of P recovery in Swedish MWWTPs, considering the technological alternatives that are commercially available (described in section 2.1).
2. Identify specific challenges in implementing P recovery and propose tailored solutions suited to the local conditions, focusing on technical opportunities and strategic approaches to reduce costs.

Understanding the cost dynamics of P recovery across MWWTPs can provide valuable guidance for investment considerations, policy formulation, and crafting strategic environmental protection.

2 Methods and data

This section outlines the methodology used to evaluate P recovery technologies, the data collection process, and analysis. It includes the identification of target streams for P recovery, the development of scenarios for implementing recovery technologies, greenhouse gas emissions, and economic evaluation and sensitivity analysis.

2.1 Target streams for phosphorus recovery and technologies

P recovery in MWWTPs can target multiple P-rich streams, such as digested sewage sludge (post-dewatering), supernatant (separated water during dewatering), and sludge ash (after dewatered, sludge undergoes mono-incineration and turns into ash) (Cieślik and Konieczka, 2017). P recovery from the supernatant is typically achieved through precipitation and crystallization by adding Ca or Mg salts to form calcium phosphate (CaP) or struvite (Li et al., 2019). P recovery from sewage sludge primarily involves a wet-chemical method where sulfuric acid leaches P, followed by struvite formation by adding magnesium and sodium hydroxide (Jupp et al., 2021). An alternative method leaches phosphate with carbonic acid under pressure, leading to CaP precipitation. The same process applies to P recovery from sludge ash. Moreover, thermochemical processes at high temperatures and under a reduced atmosphere, using specific additives, can remove volatile heavy metals from the ash, enhancing its value as a fertilizer (Herzel et al., 2016).

While advancements in P recovery technologies continue to emerge (Vu et al., 2023), our study focuses exclusively on options already commercialized or nearing commercialization, mainly suggested by the P-REX project, as listed in Table 1. We extracted data on energy and chemical demand, recovery efficiency, the type and characteristics of the end products, and waste generation for each technology from peer-reviewed literature.

Table 1- list of technologies used in this study (Canziani et al., 2023; Desmidt et al., 2015). *Further details on scales, efficiency ranges, chemical usage, and products and their characteristics can be found in the Supplementary Material. TRL refers to the technology readiness level.*

Commercial names	**Process**	**TRL[a]**	**P recovery efficiency (%)**	**Product**
P recovery from the supernatant				
REM NUT	Ion exchange and precipitation	5-6	90	CaP
AirPrex	Precipitation/ Crystallization	9	80-90	Struvite
DHV Crystalactor	Crystallization	9	70-80	Struvite
Ostara Pear Reactor	Crystallization	9	85	Struvite
PRISA	Precipitation/ Crystallization	5-6	90	Struvite
P-RoC	Crystallization	5-6/8	85	Struvite
P recovery from sludge				
Aqua Reci	Supercritical water oxidation	5-6/7-9	80-90	Cap
MEPHREC	Metallurgic melt-gassing	5-6/7-10	90	Struvite/Cap
PHOXNAN	Acidic wet-chemical extraction	5-6	40-60	CaP
Gifhorn process	Acidic wet-chemical extraction	7	90	Struvite/Cap
Stuttgart process	Acidic wet-chemical extraction	5-6/9	65	Struvite/Cap
P recovery from ash				
AshDec	Thermo-chemical	5-6/9	85-90	CaP
LEACHPHOS	Acidic wet-chemical, leaching	5-6/7-9	85-90	CaP
PASCH	Acidic wet-chemical, leaching	5-6/7-9	85-90	CaP
RecoPhos	Acidic wet-chemical extraction	9	85-90	CaP

a- The technology readiness level (TRL) ranges from 1, where only basic principles of technology are observed, to 9, where the technology is proven in operational conditions. A TRL 5-6/8 designation indicates the following: At level 5, the technology is validated in an industrial environment. At level 6, the technology is demonstrated in the same environment and is anticipated to advance to level 8, where the technology is fully complete and qualified. For more details see (Egle et al., 2016)

2.2 Scenarios

This section includes scenario definitions, data collection and plant categorization, the introduction of P recovery technology in MWWTPs, and the development of hubs as a collaborative sludge management strategy.

2.2.1 Scenario description

For our economic and greenhouse gas emission analysis, we develop two sets of scenarios; with and without using hub networks, to improve the economy of scale of P recovery. Each scenario set is further split into scenario variants that reflect different target streams for P recovery, supernatant, sewage sludge, and sludge ash. Table 2 presents scenario sets and variants, for each defining relevant size classes, sludge destinations, and available technology options.

Table 2- Scenario Sets and their characteristics

Sets	Target streams	Sizes (p.e.)	Sludge destination	Technologies
Set 1- Without hub networks	Supernatant	• 10,000-50,000 • 50,000-100,000 • 100,000-500,000 • >500,000	The same practices as before introducing P recovery, such as land application and soil production.	• REM NUT • AirPrex • DHV Crystalactor • Ostara Pear Reactor • PRISA • P-RoC
	Sewage sludge			• Aqua Reci • MEPHREC • PHOXNAN • Gifhorn process • Stuttgart process
	Sludge ash	• >500,000	Sludge converts to ash during combustion.	Incineration[a] (fluidized bed combustion with flue gas cleaning system) along with P recovery technologies: • AshDec • LEACHPHOS • PASCH • RecoPhos
Set 2- With hub networks	Sewage sludge	• 10,000-50,000 • 50,000-100,000 • 100,000-500,000 • >500,000	The same practices as before introducing P recovery, such as land application and soil production.	• Aqua Reci • MEPHREC • PHOXNAN • Gifhorn process • Stuttgart process
			Sludge is converted to hydrochar by hydrothermal carbonization (HTC).	HTC P recovery by acid leaching followed by precipitation. The investment includes an AD with CHP (combined heat and power) for biogas to treat the process water produced by HTC. The cost data for AD with CHP unit is sourced by Das et al. (Das et al., 2024)
	Sludge ash	• >500,000	Sludge converts to ash during combustion.	Incineration[a] (fluidized bed combustion with flue gas cleaning system) along with P recovery technologies: • AshDec • LEACHPHOS • PASCH • RecoPhos

a. Mass and energy balance data, as well as costs, is sourced from Bagheri et al. (2022) and Bagheri and Wetterlund (2023)

2.2.2 Data collection and plant categorization

The first step in scenario development is estimating the annual production of sewage sludge, supernatant, and sludge ash across Swedish MWWTPs. We gathered data on the distribution and sizes of MWWTPs (in p.e.) (EEA, 2022) and statistics on population and sludge production rates (Eurostat, 2023; Statistics of Sweden, 2020). Given the heterogeneous nature of sewage sludge—affected by factors such as wastewater sources and treatment processes—the impact of upstream treatment processes on sludge characteristics is significant. Although detailed data on the processes used in each MWWTP are not available, it is common to employ enhanced biological phosphorus removal, chemical precipitation of metal phosphates, or a combination of both for phosphorus removal from wastewater. This combination is particularly common in Sweden (Åkerblom et al., 2020). To address the variability in sludge characteristics, we narrowed our focus to plants employing AD and utilized mean values from several digested sludge samples to ensure representativeness (see Table S2).

AD is the most widespread sludge treatment method in Europe, producing biogas. In accordance with the new European Urban Wastewater Directive (UWWD), plants with capacities exceeding 10,000 p.e. are required to move toward energy neutrality and expected to adopt AD in the future (European Commission, 2022). Therefore, our evaluation concentrates on plants larger than 10,000 p.e. and categorizes them into four size brackets: 10,000-50,000 p.e., 50,000-100,000 p.e., 100,000-500,000 p.e., and above 500,000 p.e. We exclude plants smaller than 10,000 p.e. due to limited sludge quality data and small-scale P recovery technologies. Despite this, we still analyze 70% of Swedish sewage sludge, noting that 282 of 432 plants are in the ≤10,000 p.e. category.

2.2.3 Introducing phosphorus recovery technology in MWWTPs

For the reference scenario, we define a reference MWWTP (Figure 1), which remains consistent across all scenarios in all aspects except capacity scale and P recovery approach. Capacity scales are adapted to the actual capacity of individual Swedish MWWTPs, while the P recovery approach varies across analyzed scenarios. We assume various P recovery technologies (see Table 1) are to be incorporated into the reference plant, and we assess the economic viability across Swedish MWWTPs when recovering P from the supernatant, sludge, and sludge ash, respectively.

The sludge treatment process at the reference plant includes thickening, AD, and dewatering, with polymers added during the dewatering process. Digested sewage sludge has a dry solid content (DS) of 4%, increasing to 25% after dewatering (Savage, 2003). We assume that wastewater contains 10 mg/l P (Egle et al., 2015). Sludge characteristics are provided in Table S2, with figures based on average values from multiple samples to ensure representativeness. We calculate the per-capita sludge production in Sweden using annual sludge production and population data in 2020 (Eurostat, 2023; SCB, 2021, 2020). To align this data with each MWWTP's capacity, available in p.e., we estimate a conversion factor of 0.73 p.e. per actual inhabitant, as applicable to Swedish conditions. Finally, we calculated sludge production values for each MWWTP. This allows us to determine the capacities for sewage sludge, supernatant, and sludge ash and their respective P content based on reference MWWTP characteristics detailed in Tables S1 and S2.

First, we investigate Swedish MWWTPs investing in different technical processes to recycle P from supernatant (blue box in Figure 1). P recovery from supernatant offers two-fold advantages for MWWTPs; it recycles P while alleviating operational challenges, such as pipe clogging. Once P is recovered, the supernatant is returned to the wastewater treatment. The plant produces less sludge with reduced P levels in the supernatant compared to the reference scenario. Simultaneously, the potential to recycle nitrogen alongside P can diminish the plant's energy consumption for nitrogen removal. These beneficial impacts of P recovery are estimated based on data in Tables S2 and S9 and are reflected in the economic evaluation.

We also consider P recovery from sludge using different alternatives (green box in Figure 1). This study does not explore simultaneous P recovery from both supernatant and sludge. Although the P content of sludge decreases after P recovery, leftover sludge can be used as a soil conditioner or amendment to improve soil structure, moisture retention, and microbial activity. Different options for handling leftover sludge depend on local conditions, sludge characteristics, and legislation. We assume sludge remaining after P recovery from both supernatant and sewage sludge can be treated as if no P recovery has occurred. The economic evaluation accounts for the decreased sludge volume and energy consumption in MWWTPs resulting from P recovery.

Another sludge management strategy is incineration, which is economically viable only on a large scale (Gao et al., 2020). Therefore, our study focuses on P recovery from sludge ash in plants with capacities exceeding 500,000 p.e. In these instances, the total sludge handling costs are offset by the investment in mono-combustion and subsequent P recovery from the ash. Detailed processes and data on sludge mono-incineration are based on Bagheri et al. (2022).

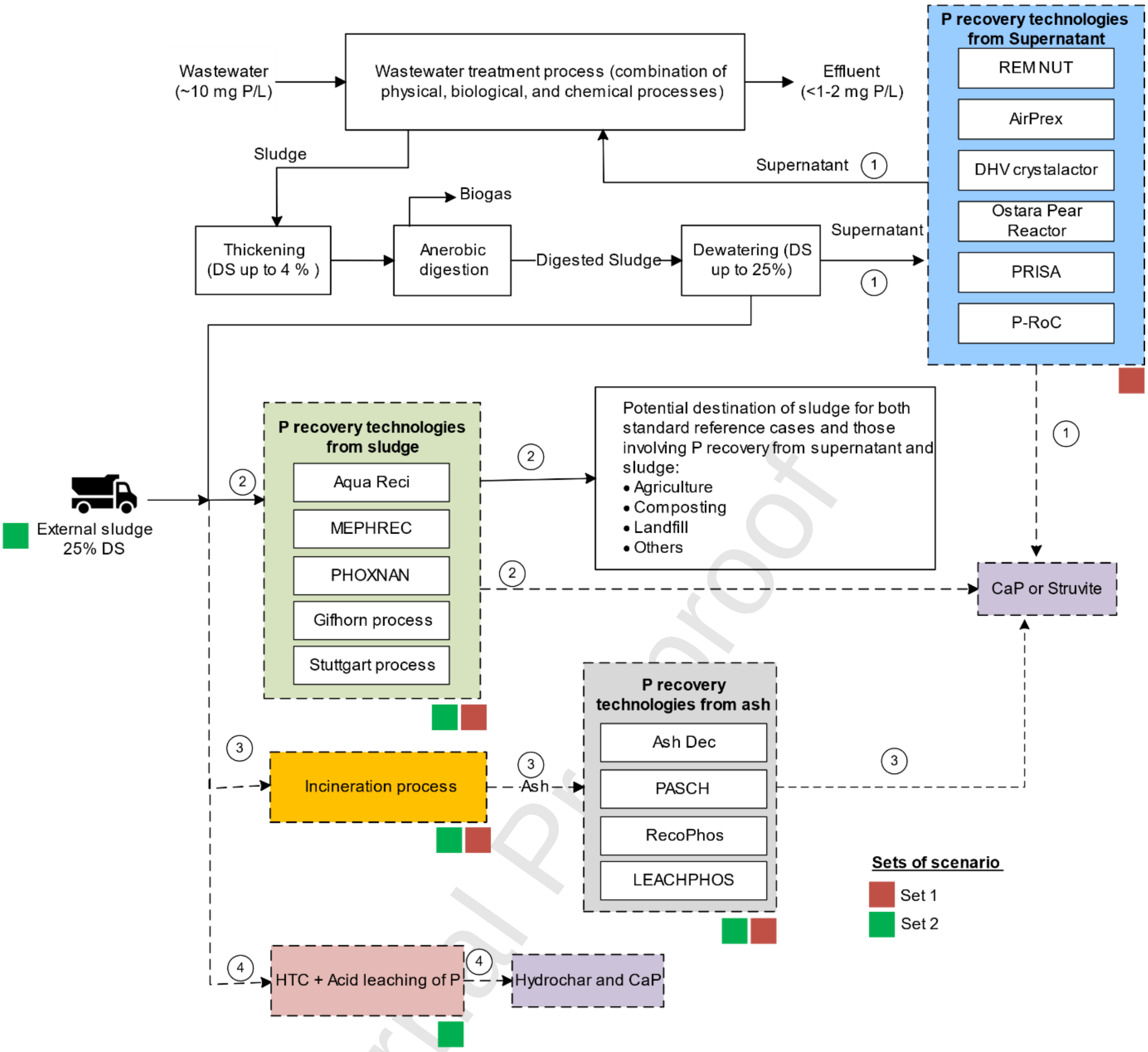

Figure 1- Overview of scenarios addressing study objectives: The first scenario set introduces P recovery technologies in Swedish MWWTPs serving over 10,000 population equivalents (p.e.) to address the first objective. The second set addresses the second objective by examining the impact of hub development on the potential and cost of P recovery in Sweden. The dashed blue box illustrates P recovery technologies from supernatant; the green dashed box represents P recovery from sludge, and the grey dashed box denotes P recovery from ash. Small colored boxed present options included in set 1 and set 2 of scenarios. "DS" denotes dry solid content. Solid black boxes represent the reference plant, while dashed boxes and numbered lines illustrate the potential pathways and technologies within each scenario set.

2.2.4 Developing hubs as a collaborative sludge management strategy

In the second set of scenarios, we aim to investigate local solutions that enhance the economic feasibility of P recovery as it can be a main trigger for recycling P in MWWTPs. To fulfill the second objective of our study, we examine the potential for improved economies of scale through collaborative sewage sludge management among neighboring plants. The concept involves creating hubs where one MWWTP receives digested and dewatered sewage sludge (with 25% DS) to enhance P recovery capacity and benefit from economies of scale. A gate fee is a charge that a MWWTP would need to pay to an external plant for sludge disposal. The hub receives a gate fee from the MWWTPs affiliated with the hub, with the fees acting as a revenue stream for the hub. In the hub scenarios, P recovery focuses mainly on sewage sludge and sludge ash, as transporting supernatant is impractical due to its volume and the additional treatment required. We assumed that the upstream treatment in the hub remains unchanged, except for the benefit of P recovery from the sludge produced in the hub. We established a sewage sludge hub network based on the following criteria:

- A plant must have a capacity greater than 100,000 p.e. to qualify as a hub.
- Plants smaller than 10,000 p.e. are excluded.
- The distance between a hub and any plant connected must not exceed 100 km (we employed QGIS to generate a distance matrix by implementing a buffer zone strategy. Specifically, we established a 100 km buffer around potential hub plants to determine which plants fall within this defined radius).
- Overlaps between hubs are not allowed, ensuring each MWWTP is linked to only one hub.
- When choosing among multiple hubs capable of receiving sludge from neighboring treatment plants, preference should be given to the hub that serves a greater number of plants.

Finding a low-cost method to handle leftover sludge after P recovery is essential. Therefore, estimating the final impact of the gate fee for sludge, depends heavily on the sludge destination after P recovery. An initial assumption is that the sludge destination at the hub will remain consistent after P recovery. In this context, we assume the fee the hub receives for sewage sludge aligns with the cost incurred to manage that sludge. Hence, the advantages for the hub in terms of P recovery and accepting external sludge are confined to the P revenue from their recycling technology (applied to both internal and external sludge) and the operational benefits derived from P recovery from the sludge generated within the plant.

Reducing sludge handling costs can lead to substantial savings for MWWTPs (Hasan et al., 2017), offering an economic incentive for new investments. This is crucial, as an economically viable approach for P recovery can expedite an otherwise slow process. Hydrothermal carbonization (HTC), a process operating under high pressure (10–50 bar) and temperature (180–250 °C) (Wang et al., 2019), directly converts wet sludge into hydrochar, improving sludge dewaterability up to 70% dry solids (Merzari et al., 2019). Therefore, we consider the impact of introducing HTC to produce hydrochar with potential market value while P is leached out from the process water produced during the reaction and separated later in the process. The introduction of HTC into MWWTPs is based on Bagheri and Wetterlund (2023), with a comprehensive summary of the technology and data provided in Supplementary Material. Therefore, the second set of scenarios (Figure 1) evaluates investing in P recovery technologies from sludge, mono-incineration for P recovery from ash (only plants larger than 500,000 p.e.), and sludge conversion into hydrochar with P recovery.

We examine the impact of accepting external sludge and expanding the capacity on P recovery costs compared to the additional investment needed in sludge management for P recovery. The gate fee for municipal solid waste in Sweden is used as a representative value for sewage sludge, and we assume this includes the transportation of sludge (Swedish Energy Agency, 2022). Therefore, plants that send sludge to hubs pay a fixed gate fee. From the standpoint of plants sending sludge to the hubs, the gate fee may exceed their usual sludge handling cost. This is mainly because land application and composting, standard practices in Sweden, are generally more cost-effective than incineration.

Consequently, redirecting sludge to a hub could result in higher costs than current sludge management practices. However, looking forward, the viability of land application is uncertain, suggesting that overall sludge handling costs might rise, especially if a shift towards centralized sludge incineration necessitates longer-distance transportation. Typically, gate fees encompass transportation costs, applied uniformly across all plants. This could raise the overall fee for plants closer to the waste processing plant, as they effectively subsidize the transportation costs of more distant facilities. A strategic solution can be to repurpose and expand an existing wastewater treatment plant into a hub. This approach mitigates the need to develop entirely new incineration plants and optimizes transportation costs by processing sludge from neighboring plants locally.

2.3 Direct impacts on greenhouse gas emissions

P recovery from municipal wastewater, despite being more costly than mineral fertilizer use (Pradel and Aissani, 2019), offers significant benefits. These include promoting sustainability in the food chain, aligning with circular economy principles, and mitigating the risk of eutrophication. Within the scope of this study, we suffice to conclude that these benefits exist but refrain from attempting to quantify them due to a lack of detailed information on these complex systems. For the same reason, we also refrain from quantifying emissions embedded in the supply chain for synthetic fertilizers, as well as the broader environmental and economic impacts of P recovery on e.g., jobs and income inequality. While these factors are critical, they are beyond the scope of our current analysis. We do however conduct a partial environmental analysis by evaluating the direct impacts on greenhouse gas emissions when implementing the different MWWTPs technologies described here in Sweden. Such information was found to be readily available from Amann et al. (2018).

We evaluate greenhouse gas emissions comprising CO2, CH4, and N2O (expressed in CO2 equivalent) by incorporating each technology into MWWTPs in Sweden compared to plants without these technologies. The aim is to provide an initial national-level perspective on the potential benefits and trade-offs associated with different P recovery technologies. The emission data of MWWTPs and their changes by the implementation of P recovery technology were sourced from Amann et al. (2018) and listed in Table S10.

2.4 Economic evaluation and sensitivity analysis

Projects related to wastewater and sewage sludge management are often estimated unprofitable without public subsidies (Medina-Martos et al., 2020). Recovering P from municipal wastewater is currently more expensive for investors than mineral fertilizer P (Rahimpour Golroudbary et al., 2020). Therefore, while we consider P recovery in MWWTPs as a non-profitable practice, understanding the cost dynamics of this approach is crucial for investors and decision-makers to shape future strategies for sewage sludge management.

The economic evaluation focuses on estimating the P recovery cost for each technology listed in Table 1 as applied to Swedish MWWTPs. In the first set of scenarios, these recovery costs comprise the investment cost of introducing the recovery technologies to reference MWWTPs and the associated operational costs. Operational costs are split into fixed and variable components. The fixed operational costs account for labor, scheduled maintenance, and insurance and are estimated using the method detailed by Towler and Sinnott (2021) and explained in Supplementary. Variable operational costs encompass chemical costs and energy demands specific to the recycling technology.

Reducing P levels in supernatant could lower the need for flocculating agents for P-removal from wastewater. Meanwhile, decreasing nitrogen concentrations (recovered with P) would reduce the oxygen and aeration requirements in the biological treatment steps for nitrogen nitrification and removal (Egle et al., 2016). Recovering P from sludge reduces polymer demand during dewatering and decreases sludge volume. The economic impact of reducing P and N back-flow is calculated based on the recovery yield of each technology (Tables S4-S6) and the product characteristics of each technology (Table S10). After estimating the reduced amounts of P and N, we calculated the corresponding reductions in energy and chemical demand using the data listed in Table S3. Introducing incineration and HTC technologies to MWWTPs produces co-products such as heat, electricity, and hydrochar. These benefits have been factored into our economic calculations.

Sewage sludge management in Sweden encompasses various strategies, including agricultural use, composting, and other applications (SCB, 2020). Given the variability and lack of specificity regarding which strategy a MWWTP will employ, we simplify the economic assessment by assuming that the hub gate fee covers the sludge handling expenses after P recovery. This is supported by equating the gate fee for sewage sludge to that of municipal solid waste, typically linked to waste incineration costs, which are generally higher than fees for agricultural sludge use.

The gate fee from receiving external sludge is considered a net income when hubs invest in HTC or incineration. While this approach indicates a favorable economic balance for the hubs, it is crucial to interpret results with the understanding of these assumptions, especially in the absence of detailed data on individual MWWTP strategies. The gate fee, assumed uniform across all plants, includes the cost of transporting sludge to hubs.

The purchase cost of recovery technologies is obtained from publicly available sources and inflation-adjusted to the 2020 price level using the Chemical Engineering Plant Cost Index and also adjusted to the actual plant sizes following Equation 1(Towler and Sinnott, 2021):

$$Cost_{\,2} = Cost_{\,1}\left(\frac{S_2}{S_1}\right)^{0.6} \qquad (1)$$

Where $cost_2$ is the purchase cost in the desired scale (*S2*), and $cost_1$ is the reported purchase cost of a technology in the scale of *S1*. We estimate the total investment cost using the method by Towler and Sinnott (2021) (Table S11). The investment cost is annualized, applying an annuity factor of 11%, corresponding to an internal rate of return of 8% and 15 years of lifetime. Minimum P recovery cost is the selection criteria for the best technology for each targeted stream.

For economic analysis of pre-mature processes, it is crucial to measure and report uncertainties associated with technological advancements and future price fluctuations of raw materials and products. This study employs sensitivity analysis and Monte Carlo simulations to evaluate the probability of future uncertainties in the economic analysis of P recovery. We conducted a sensitivity analysis to measure the impact of varying important parameters on the recovery cost, such as investment cost, energy and chemicals, gate fee, and fertilizer price. This analysis flowed by a Monte Carlo analysis with 100,000 iterations to capture the combined impacts of the important variables on the recovery cost, with detailed assumptions provided in Table S12.

3 Results and discussion

This section provides the results, focusing on P recovery potential, recovery costs, and the impact of leveraging local opportunities through hub development to reduce sludge management and P recovery cost.

3.1 Phosphorus recovery potential and greenhouse gas emissions

Estimated total P recovery potentials in Swedish MWWTPs from supernatant, sludge, and sludge ash, respectively, when applying different technologies as listed in Table 1, are 5%, 36 % to 65%, and 17% of the total P content in the wastewater (see Table 3). The differences in recovery potential arise from the varying P recovery efficiency of each technology (see Table 1), the number of MWWTPs implementing recovery technology for each target stream, and the P concentration in each target stream.

Due to the high concentration of P in the ash, P recovery potential from ash can be 5-10 times higher compared to supernatant and sludge (Cieślik and Konieczka, 2017). However, P recovery from ash is restricted to large plants due to the investment required for the combustion process, which is not economically feasible for smaller plants (Cieślik and Konieczka, 2017). Therefore, only 3 plants (larger than 500,000 p.e.) are eligible to recover P from ash, which limits the amount of recovered P. The concentration of P in the supernatant varies significantly between chemical and biological P removal methods from wastewater. Chemical methods result in a reduced dissolved P content and fixed P within the sludge, thereby limiting P recovery potential from the supernatant to less than 10% of the influent of the treatment plant (Melia et al., 2017).

Table 3 presents the greenhouse gas emissions from the studied MWWTPs after the implementation of each studied recovery technology, along with the estimated minimum and maximum P recovery costs within each size category of plants. The emissions vary significantly across the alternative technologies, and better recovery yield and economic performance do not necessarily mean a better environmental effect. Crystallization for supernatant (by P-Roc) and wet chemical extraction methods for sludge (by Gifhorn process) and sludge ash (by RecoPhos) show the lowest recovery cost among the alternatives.

P recovery from supernatant generally reduces the return load of P and N to the treatment process, thereby decreasing the energy demand and gas emissions of the plant. However, P recovery from sewage sludge is more energy and chemical-intensive (Amann et al., 2018), and gas emissions show an increasing trend compared to treatment plants without P recovery technology. Amann et al. (2018) reported a decreasing trend in gas emissions with P recovery from ash. However, the estimated emission for ash is limited to only 3 MWWTPs in Sweden and is not comparable with P recovery from supernatant and sewage sludge, which cover all studied plants.

Table 3. P recovery costs of all studied technologies in set 1 of scenarios and their greenhouse gas emission when applied in studied MWWTPs in Sweden. The minimum and maximum ranges indicate the cost variations based on minimum and maximum capacity, chemical and energy usage, and efficiency reported for each technology. Detailed data on these parameters can be found in the Supplementary Material.

Technologies	P recovery cost in different scales (€/ kg recovered P)					Total recovered P (t/a)	Recovered P /total P in WW[a] (%)	Greenhouse gas emission (kt CO2e)[b]
P-rich stream	Size distribution (p.e.)	10000-50000	50000-100000	100000-500000	larger than 500000			
Supernatant								
REM NUT	Max	1.06×10^3	397	266	125	280	5.3	84.0
	Min	405	285	135	106			
AirPrex	Max	266	123	88.2	53.6	264	5.0	75.2
	Min	125	93.3	48.2	46.1			
DHV Crystalactor	Max	2.98×10^3	1.51×10^3	1.10×10^3	392	233	4.4	122.6
	Min	1.54×10^3	1.16×10^3	603	332			
Ostara Pear Reactor	Max	1.17×10^3	600	438	109	264	5.0	77.1
	Min	608	460	241	91.0			
PRISA	Max	1.43×10^3	694	500	141	280	5.3	83.1
	Min	705	526	270	119			
P-RoC	Max	374	185	134	34.6	264	5.0	94.0
	Min	187	142	73.9	29.6			
Sludge								
Aqua Reci	Max	303	143	104	63.2	3.2×10^3	61.1	175
	Min	146	110	59.4	55.2			
MEPHREC	Max	433	206	153	35.8	3.39×10^3	64.7	95.9
	Min	208	161	94.8	34.6			
PHOXNAN	Max	508	222	157	144	1.88×10^3	35.9	95.9
	Min	226	166	86.3	129			
Gifhorn process	Max	70.8	32.3	24.5	14.7	3.39×10^3	64.7	141.4
	Min	32.7	25.5	16.5	13.5			
Stuttgart process	Max	121	52.5	39.8	33.2	2.45×10^3	46.7	94.0
	Min	53.3	41.4	27.5	24.8			
Ash								
Ash Dec	Max	No investment in these scales			16.2	902	17.2	84.9
	Min	No investment in these scales			11.8	902	17.2	
LEACHPHOS	Max	No investment in these scales			39.2	902	17.2	86.3
	Min	No investment in these scales			31.4	902	17.2	
PASCH	Max	No investment in these scales			6.6	902	17.2	102
	Min	No investment in these scales			3.9	902	17.2	
RecoPhos	Max	No investment in these scales			14.8	902	17.2	74.6
	Min	No investment in these scales			11.2	902	17.2	

a. Total P in WW in studied MWWTPs in Sweden was estimated at 5.24 kt/a
b. The estimated greenhouse gas emissions for studied WWTPs in Sweden was 89.03 kt CO2e/year

In conclusion, the varying P recovery potentials from different target streams in Swedish MWWTPs highlight the significance of technology efficiency, implementation scale, and stream-specific P concentrations in determining overall recovery outcomes. It is crucial to consider the impact of plant availability of different recovered P and to conduct comprehensive environmental studies for each technical alternative to prevent exchanging one problem (wasting P) with another (other negative impacts on the environment). The supply chain of synthetic fertilizers involves significant geospatial resources, energy footprints, and social and economic aspects (Shaddel et al., 2019). However, our current study focuses on a simplified greenhouse gas emission assessment and does not encompass the full complexity of the synthetic fertilizer supply chain. We recognize the importance of these factors and the need for a comprehensive comparison to achieve local environmental, social, and economic benefits in developing a sustainable circular economy of fertilizers. Due to the significant influence of detailed operational conditions in MWWTPs on the performance and economic feasibility of P recovery technologies, a more in-depth operational analysis is recommended.

3.2 Phosphorus recovery cost without hubs

Across all technologies, the lowest cost per tonne of P recovered is observed in the largest plant due to the economy of scale effect, with costs increasing for smaller plants (see Figure 2). P recovery from ash has the lowest cost at 3.9- 6.6 k€/t of recovered P but applies only to the three largest MWWTPs in Sweden, while supernatant exhibits the highest cost at 29- 187 k€/t of recovered P (the lowest estimated cost among all technical options) and the lowest recovery potential. The low cost of P recovery from ash mainly benefits from a high P concentration, which improves the recovery rate and avoids sludge handling after P recovery. Egle et al. (2016) reported that for plants with capacities ranging between 100,000-500,000 p.e., P recovery costs from supernatant range between 6-28 k€/t P, with the lowest costs when P is already in dissolved form. They also noted that P recovery costs from sludge using wet-chemical processes range from 9-16 k€/t P, and from ash range from 5-6 k€/t P.

The results of the Monte Carlo analysis demonstrate that the ultimate cost of recovered P from supernatant is notably contingent upon the investment cost and the efficiency of the recovery process. Conversely, in recovering P from sludge and in smaller MWWTPs, the recovery cost exhibits a heightened sensitivity to investment costs, chemical costs, and recovery yield. However, in larger plants, the impact of chemical costs becomes the main impacting variable on the recovery cost, followed by recovery yield and investment cost. For sludge ash, the main impact on the P recovery cost is the cost for sludge disposal and investment cost since costs for sludge handling are avoided through combustion.

Across all technical alternatives and target streams, a notable gap persists between the recovered P and the cost of commercial fertilizer, even under optimal conditions (see Figure 2). The cost per cumulative tonne of recovered P experiences a steeper increase in supernatant due to less recovered P, while the cost increase per additional tonne of P decreases when the target streams are sludge and ash. While the cost of recovered P is consistently higher than that of mineral fertilizer P, larger plants demonstrate relatively stronger economic performance than smaller ones. Here, we identify a practical difficulty in promoting P recovery in MWWTPs. Providing widespread access to a sanitation system without simultaneously requiring a sustainable solution for sludge management has led to a large number of small MWWTPs in Sweden, which is a barrier to further investment in P recovery (Chrispim et al., 2019) . As mentioned, 282 out of 432 MWWTPs have a capacity smaller than 10,000 p.e. and were excluded from this study. Hence, a significant share of sludge production is not economically feasible for P recovery.

This situation applies to many European countries and constitutes a conflict between economic and environmental objectives. While the economic results suggest focusing on larger plants, environmental goals (high recovery of P and other valuables from sludge) require widespread P recovery, including smaller MWWTPs. Policy measures like grants, subsidies, or tax breaks are therefore essential for encouraging P recovery from smaller plants. Another interpretation is that the economic results suggest building large-scale centralized facilities for better economic performance of P recovery; however, this is at the environmental cost of long-distance sludge transportation.

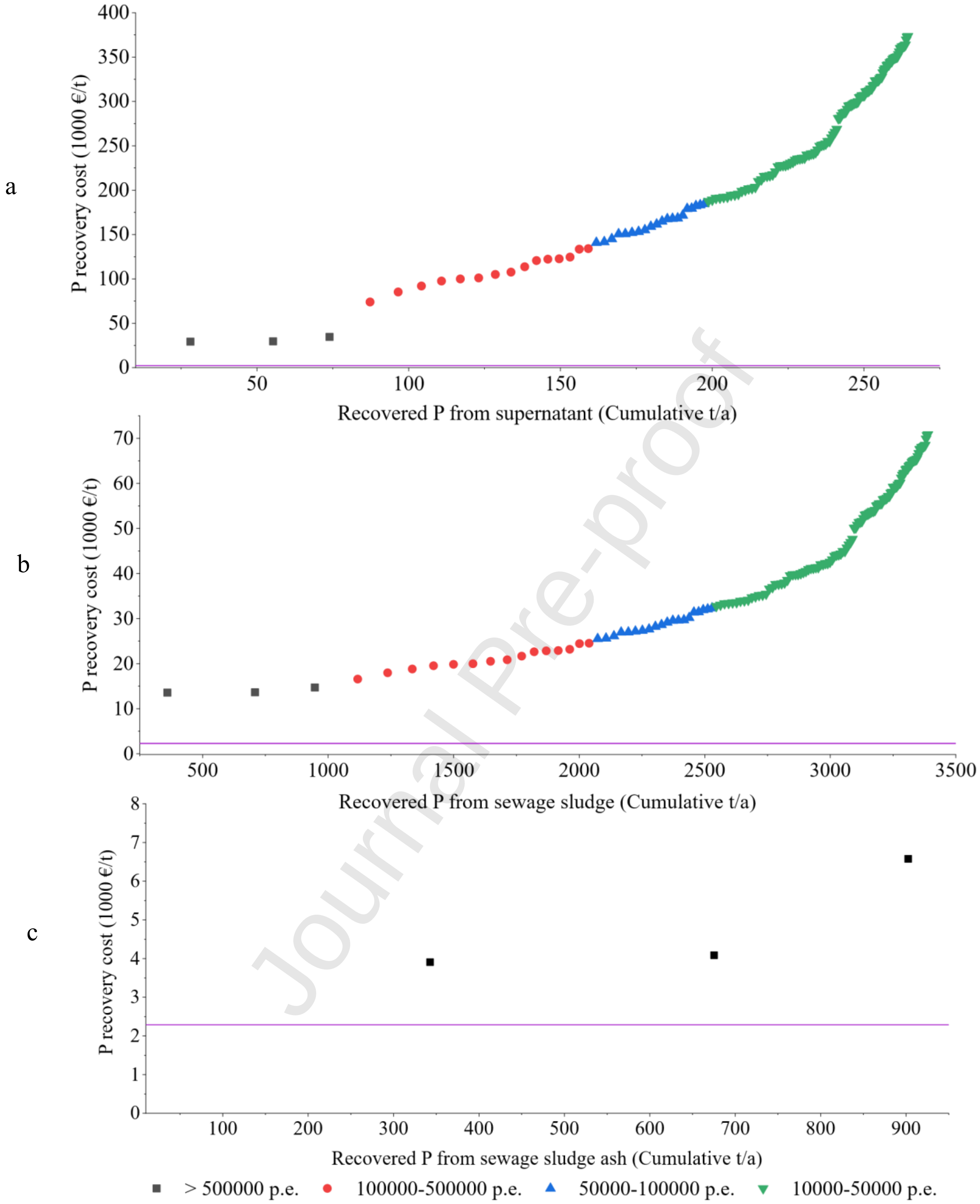

Figure 2- Cost of recovered P from supernatant (panel a), sewage sludge (panel b), and sludge ash (panel c) across studied Swedish MWWTPs categories based on population equivalent (p.e.). Each point represents a MWWTP ordered from lowest to highest P recovery cost. The recovery costs from supernatant using crystallization, as well as from sewage sludge and sludge ash, are calculated using chemical extraction methods that yield the lowest estimated costs among the studied technologies. Purple lines show the market price of fertilizer.

3.3 Phosphorus recovery cost in hubs

Figure 3 shows the plants included in hub development based on the criteria mentioned in section 2.2.3. The dense clustering of MWWTPs in southern Sweden facilitates the potential expansion of existing plants to act as central hubs without extensive long-distance transportation. Plants in the north of Sweden are too dispersed to meet the criteria for hub development and are therefore excluded from further evaluation. Results show that 8 MWWTPs can receive sewage sludge from 78 adjacent plants with a maximum distance of 100 km.

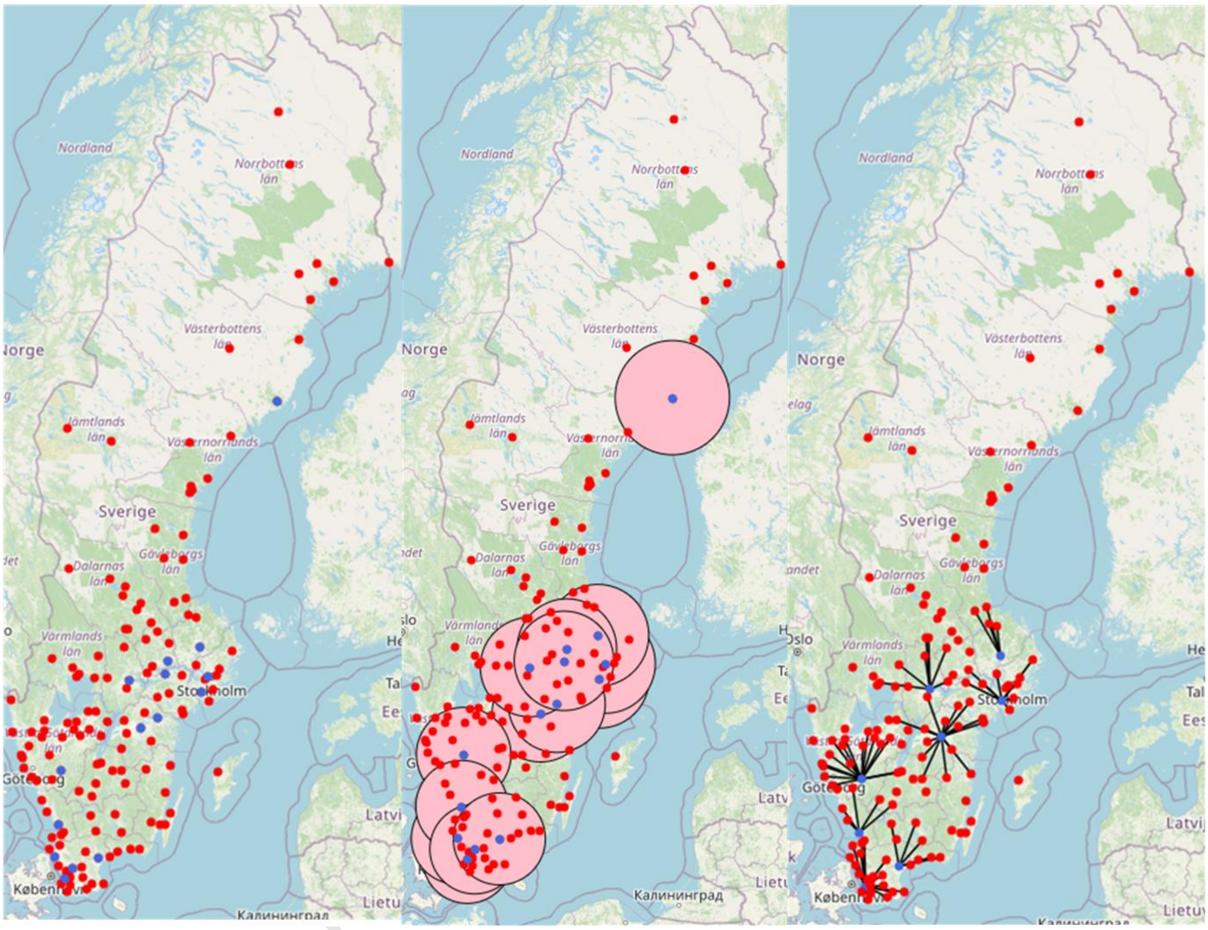

Figure 3- Step-by-step development of hub networks across Swedish MWWTPs based on criteria in section 2.2.3. The left panel indicates plants meeting the hub criteria in blue, with other examined MWWTPs shown in red. The middle panel displays groups of plants within a 100 km buffer zone around the selected hubs. The right panel illustrates the final hubs and the plants connected to them.

Figure 4 shows P recovery costs in Swedish MWWTPs after developing a hub network. This strategy helps to expand the economy of scale effect that keeps the P recovery cost at a minimum. As shown in Figure 2, without the hub approach, the cost to recover P from sludge would change from 14 k€/t (the estimated minimum cost) to 42.5 k€/t for an annual recovery rate of 3,000 tonnes, while within the hub strategy, with the same recovery technology (see Figure 4, panel a), the cost reduces from 13 k€/t to 29.4 k€/t for the same recovery volume. However, the recovery cost still exceeds the market price of mineral fertilizer. This means that hub development among MWWTPs is driven by factors other than market mechanisms, such as restrictions on land application and legislative mandates on P recovery. Under these conditions, hub development reduces P recovery costs for MWWTPs compared to adding recovery technology to individual plants.

With the hub strategy, the total annual P recovery from ash increases by 57% compared to scenarios without hub establishment. With the hub strategy, the sludge volumes are larger, which means 7 plants can implement incineration, compared to only 3 plants without hubs (Figure 4, panel b). The advantage of "collaborative" sludge management among MWWTPs is that it facilitates a higher amount of P recovery at a lower cost, also when the final price of P is yet higher than the price of mineral fertilizer P. Only one plant shows a negative cost for recovering P when the hubs invest in incineration infrastructure with P recovery from ash (Figure 4, panel b). For that specific plant, the new investment is economically viable, allowing for a potential reduction in the gate fee for external sludge. This results in cost savings not just for the central hub but also for other MWWTPs directing their sludge there for processing.

The land application of sludge can cost between 19 and 50 €/t of sludge (25% DS), and composting ranges from 45 to 110 €/t of sludge (25% DS) (Amann et al., 2021; Kacprzak et al., 2017). We considered 74 €/t of sludge with 25% DS as a gate fee in Sweden. From the perspective of WWTPs sending sludge to a hub, this strategy can increase sludge disposal costs and is not preferable. On the other hand, sludge mono-combustion can cost 70-139 €/t of sludge (25% DS) without P recycling (Amann et al., 2021; Kacprzak et al., 2017). Therefore, if policymakers move toward sludge mono-incineration with P extraction from ash, which is a probable future path (Harder et al., 2019), the cost burden of sludge mono-incineration in a centralized plant can motivate the hub strategy, as it utilizes existing infrastructure and limits sludge transport.

When the hubs invest in HTC (Figure 4, panel c), investment costs are lower than for incineration and revenues higher due to sales of hydrochar, and several plants display a negative cost for P recovery. One conclusion is that the economic feasibility of the investment is independent of P revenues. Recovered P can then be sold at a lower price than mineral fertilizer P, which would make sludge-based P competitive in markets (Jupp et al., 2021). Another conclusion is that through reduced gate fees, the sludge management cost can be reduced for many MWWTPs, while at the same time, the gap narrows between the cost of recovering P and the market price of mineral fertilizer P. Moreover, from a regulatory standpoint, the economic viability of a collaborative approach means there is less need for market interventions. The process becomes self-sustaining, accelerating the adoption of P recovery practices without a need for regulations to prevent P wastage in sludge.

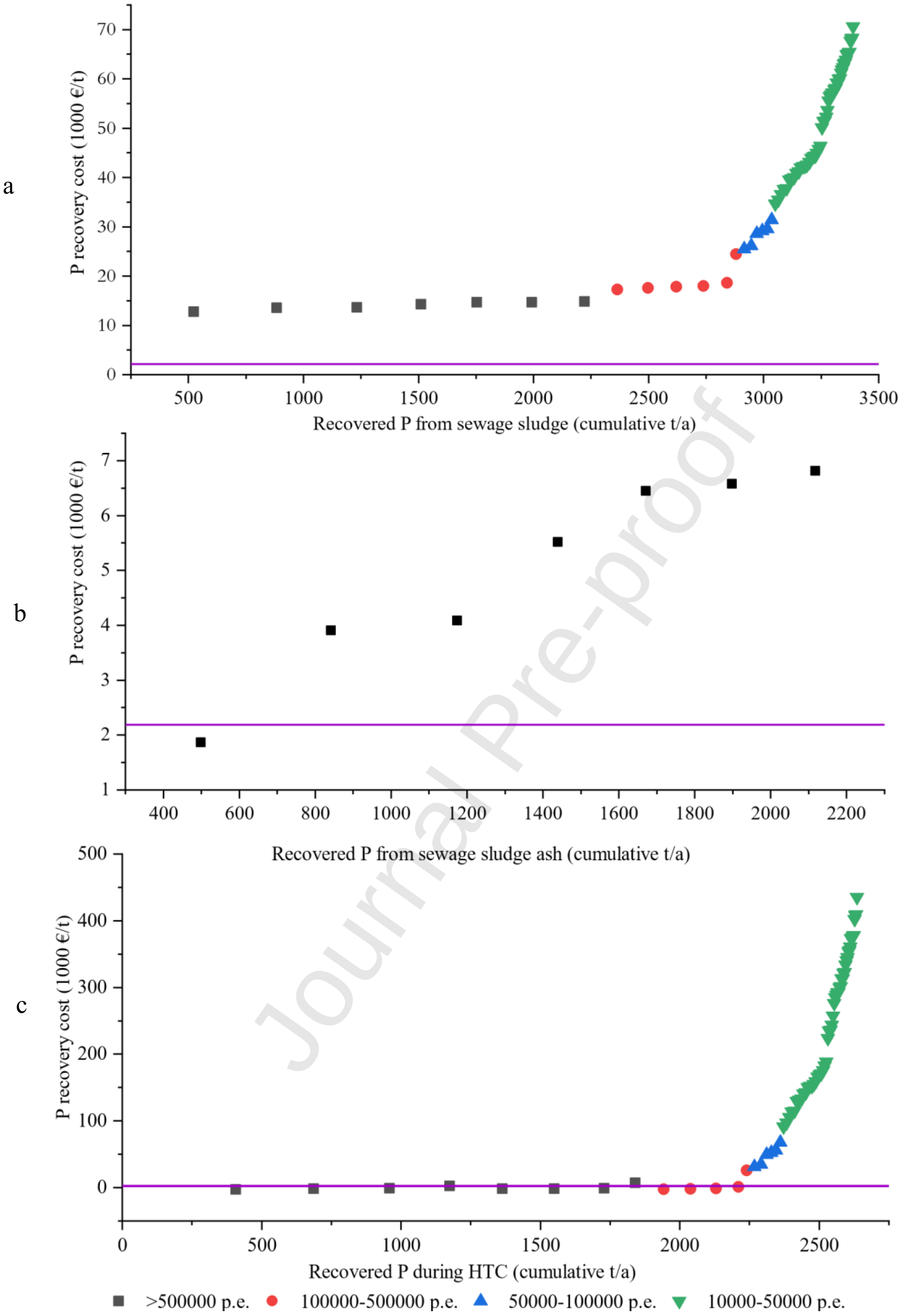

Figure 4- P recovery cost in hub scenarios (Paper V) from sewage sludge (panel a), sludge ash (panel b), and after HTC reactor (panel c) across studied Swedish MWWTPs categories based on population equivalent (p.e.). Each point represents a MWWTP ordered from lowest to highest P recovery cost. The recovery costs from sewage sludge and sludge ash are calculated using chemical extraction methods that yield the lowest estimated costs among the studied technologies. P recovery during HTC is achieved through chemical extraction downstream of the process. Purple lines show the market price of fertilizer.

Table 4 shows the cost dynamic of P recovery from sewage sludge in Swedish MWWTPs, with and without hub networks, revealing significant insights across four size classes. Notably, within plants larger than 500,000 p.e. the recovery cost increases by 8% from the estimated minimum cost (14 k€/t), with a recovery potential of up to 18%. In the 100,000 and 500,000 p.e. size class, the recovery cost is 18% to 45% above the minimum cost, with a P recovery potential of up to 39%. Smaller plants (50,000 to 100,000 p.e.) experience up to a 58% higher cost than the minimum with up to 48% recovery potential (only 8 % more recovery potential), while the smallest plants (10,000 to 50,000 p.e.) see an 81% higher cost with up to a 65% recovery potential. When considering the implementation of hub networks (Figure 4, panel a), the cost of P recovery for plants larger than 500,000 p.e. is up to 14% higher than the minimum cost and with a recovery potential of up to 42%. However, in the other three size classes, costs are higher than for comparable size classes without hubs and offer limited additional P recovery potential.

Table 4. Comparing the cost dynamics of P recovery from sewage sludge in Swedish MWWTPs with and without hub strategy. The recovery costs refer to the same technology that incurs the lowest cost for P recovery. P_in is the total P estimated within the wastewater of the studied plants. P_out is the accumulated recovered P from sludge within MWWTPs in each size category.

Size groups (p.e)	Without hubs (see Figure 2, panel b)		With hubs (see Figure 4, panel a)	
	Increase in p recovery cost relative to minimum cost at the largest MWWTP (%)	Recovery potential (P_out/P_in) (%)	Increase in p recovery cost relative to minimum cost at the largest MWWTP (%)	Recovery potential (P_out/P_in) (%)
>500,000	0- 8	7-18	0-14	10-42
100,000-500,000	18-45	19-39	26-48	45-55
50,000-100,000	47-58	40-48	50-59	56-58
10,000-50,000	59- 81	49-65	63-82	58-65

Table 4 illustrates significant disparities in recovery potential and associated costs among treatment plants of varying sizes. It is essential to recognize the pivotal role plant size plays. While we have excluded 65% of Swedish MWWTPs from our study, our results indicate that the economic feasibility of adding P recovery technologies to many of these plants is limited. Therefore, even though there are efforts to standardize the level of P recovery across all MWWTPs—to prevent P wastage or limit land application—under the existing conditions of MWWTPs, there are insufficient incentives for investment. This is further corroborated by the latest government investigation (Holmgren, 2020), particularly when decisions are constrained to a single technical solution.

Techno-economic analysis, as conducted here, offers recommendations to guide future legislative initiatives. It informs policymakers on creating supportive regulations for P recovery. Additionally, it provides perspective to operators in MWWTPs dealing with uncertainty in sludge management and introduces strategies such as hub development that extend beyond a single technology. A unified legislative framework may lead to imposing a single solution for all MWWTPs, such as mono-incineration with P extraction from ash (Barquet et al., 2020). Our findings, however, make it clear how this kind of approach could result in a significant recovery cost for a low recovery possibility. Policies that promote particular P recovery technologies run the risk of creating biases that hinder creativity and reduce adaptability to a range of site-specific and economic conditions. This approach may inadvertently prioritize high-infrastructure investments and long-distance transport (Mayer et al., 2021) and overlook potentially more sustainable solutions, ultimately impeding the growth of a resilient and adaptable P recovery market (Barquet et al., 2020).

Utilizing local infrastructure and resources in sewage sludge management is essential, emphasizing the need for strategies and roadmaps customized to fit the local economy and geographic context (Carrillo et al., 2024). This ensures that solutions are environmentally sustainable, economically viable, and socially acceptable, emphasizing a balanced approach between sustainability and economic feasibility.

4 Conclusions

The analysis reveals significant variations in P recovery costs and potentials across different plant sizes and technologies. Notably, while P recovery from ash shows a lower cost than recovery from supernatant and sludge, the recovery cost remains higher than that of mineral fertilizer P, highlighting economic challenges that deter widespread adoption without supportive policies. Although P recovery from supernatant contains operational benefits and reduces greenhouse gas emissions from MWWTPs, its recovery potential is limited and expensive. The P recovery from sludge consumes a significant amount of chemicals, while sludge leftovers after P recovery need to be handled.

The prevalence of smaller, widespread MWWTPs in Sweden has been pinpointed as a central obstacle, creating substantial economic and logistical hurdles that discourage investments in P recovery. Due to the low market price of fertilizer, P extraction will raise the expenses associated with sludge treatment in particular for smaller MWWTPs. Therefore, other external conditions, such as a legislative mandate or a long-term sharp rise in fertilizer prices, need to motivate P recovery for MWWTPs. Although the hub strategy can increase sludge disposal costs, it can prevent significant cost increases for MWWTPs compared to centralized, resource-intensive options that require long-distance transport. The development of hub networks and the transformation of sludge into marketable products like hydrochar generate revenue and compensate for sludge disposal costs for the hubs. Sludge management costs are thereby reduced for the hubs and the connected plants, which also lowers the need for gate fees. Given that this economically driven approach can be established long-term, e.g., by offering certain P price guarantees, it can diminish the reliance on other more command type legislative measures, whose implementation may offer less flexibility to plant owners. An attractive solution for both plant owners and the environment is needed to amplify the recycling of a limited resource vital for life and our long-term food security.

CRediT authorship contribution statement

Marzieh Bagheri: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Lena Höglund-Isaksson:** contribution to development of cost analysis approach, review and editing**, Adriana Gómez-Sanabria:** contribution to methodology, investigation, review and editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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