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Phosphorus recovery potential of conventional municipal wastewater treatment plants with low-strength influent

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ABSTRACT

In response to increasingly stringent legislative requirements and the limited availability of studies addressing phosphorus recovery in wastewater treatment plants (WWTPs) treating low-strength wastewater, this study evaluated the phosphorus recovery potential of six municipal WWTPs in Bulgaria. The methodology combines operational monitoring data provided by water operators with supplementary laboratory analyses. The phosphorus recovery potential was assessed with respect to both the requirements of currently available recovery technologies and the regulatory criteria established in Austria, Switzerland, and Germany. Three phosphorus-bearing streams were analysed: sludge dewatering liquor, dewatered sludge, and sludge ash. The results indicate that lower influent wastewater dilution (higher influent phosphorus loads), and the presence of biological phosphorus removal are generally associated with higher phosphorus contents in the sludge line. Among the recovery pathways evaluated, phosphorus recovery from sludge dewatering liquor appears to be the most feasible option, with five of the six studied WWTPs exhibiting the conditions compatible with available recovery technologies. In contrast, phosphorus recovery from sludge ash is unlikely to be feasible for most of the investigated WWTPs, as the phosphorus content in the ash was generally below the levels required for the efficient application of currently available full-scale recovery technologies. The findings further suggest that the direct adoption of existing European phosphorus recovery requirements would be challenging for the studied Bulgarian WWTPs, primarily due to the high dilution of influent wastewater. The study highlights the importance of considering wastewater strength and plant-specific phosphorus distribution when developing phosphorus recovery strategies and regulatory frameworks for countries characterised by low-strength municipal wastewater.

Keywords: circular economy, low-strength wastewater, legislative requirements, phosphorus recovery, phosphorus recovery technologies, phosphorus recovery potential.

INTRODUCTION

Of all the potential resources that can be recovered in wastewater treatment plants (WWTPs), phosphorus (P) has received the greatest attention due to several driving factors, including the anticipated depletion of phosphate rock reserves and the inclusion of phosphate on the Critical Raw Materials list (COM 297, 2014; COM 160, 2023). To address this challenge, the revised EU Urban Wastewater Treatment Directive (Directive (EU) 2024/3019), which entered into force on January 1st 2025, strengthens the circular economy requirements by obliging Member States to promote phosphorus recovery from sewage sludge. More specifically, Article 20 empowers the European Commission to establish a combined minimum reuse and recycling rate for the phosphorus recovered from sewage sludge and urban wastewater. Consequently, EU-wide quantitative targets for phosphorus recovery are expected to be introduced through delegated acts (Directive (EU) 2024/3019). Accordingly, phosphorus recovery from sewage sludge has already become a legal requirement in several European countries. For example, the revised Sewage Sludge Ordinance (AbfKlärV) in Germany mandates phosphorus recovery for all WWTPs with a treatment capacity above 100 000 population equivalent (p.e.) by 2029, while the plants with capacities between 50 000 and 100 000 p.e. must comply by 2032. These requirements apply only when the phosphorus content of the sewage sludge exceeds 20 g P/kg dry matter (DM), equivalent to 2% of DM (AbfKlärV, 2017; Sewage Sludge Disposal in the Federal Republic of Germany, 2018; Sichler et al., 2022). Moreover, the direct utilisation of sewage sludge for agricultural purposes will remain a viable option only until the stipulated deadlines have been reached, at which point it will be phased out (AbfKlärV, 2017; Sewage Sludge Disposal in the Federal Republic of Germany, 2018; Sichler et al., 2022). In Switzerland, phosphorus recovery is mandatory from municipal wastewater, sewage sludge from central WWTPs, or sewage sludge ash. According to the Swiss Waste Ordinance (VVEA/ADWO), the obligation applies from January 1st 2026. The implementation guidance of the Federal Office for the Environment (FOEN) exempts only central WWTPs with capacities below 1000 p.e., meaning that the WWTPs above this threshold are subject to the recovery obligation. Under the revised Swiss framework, at least 16 kg P must be recovered per tonne of sewage sludge DM (Phosphorreiche Abfälle, 2020; Phosphorrecycling, 2024). In 2024, Austria became another European country to adopt obligatory national measures for P recovery. The Abfallverbrennungsverordnung (AVV) 2024 makes P recovery mandatory from January 1st 2033 for the WWTPs with a design capacity of ≥20,000 p.e. The ordinance requires incineration of sewage sludge followed by recovery of at least 80% of the phosphorus from the resulting ash, or use of the entire ash for fertiliser production. Alternatively, plants may avoid the incineration requirement if at least 60% of the influent phosphorus is recovered at or near the WWTP (AVV, 2024). To structure phosphorus recovery options, Zhao et al. (2023) introduced the concepts of "unplanned P recovery path" and "semi-planned P recovery" (Zhao et al., 2023). Unplanned P recovery occurs when sludge is used as a fertiliser, and no specific sludge treatment is required. However, the WWTPs still absorb the phosphorus in the biomass.

Semi-planned P recovery necessitates specific technologies. Current full-scale applications for phosphorus recovery (semi-planned P recovery) are predominantly focused on liquid side streams and ash-derived phosphorus recovery. Phosphorus recovery from dewatered sludge is also technically feasible through a range of chemical, electrochemical and thermochemical processes. However, these technologies are less mature and less widely implemented than phosphorus recovery from sludge dewatering liquors or sewage sludge ash (Pasalari et al., 2024). The phosphorus concentration requirement is among the most critical factors for all recovery technologies (Gherghel et al., 2019; Di Capua et al., 2022; Vu et al., 2023). The minimum influent P concentration required for recovery from the liquid phase varies substantially among technologies, ranging from 25 mg P/L for the Crystalactor process to 600 mg P/L for the Seaborne Gifhorn process (Vu et al., 2023). For most technologies, phosphorus recovery is generally considered economically attractive when the initial phosphorus concentration is above approximately 50 mg P/L (Di Capua et al., 2022; Vu et al., 2023). Regarding the influent P content, required for recovery from the sludge ash, its values should be in the range of 0.07 to 0.09 t P/t ash according to the technology (Chrispim et al., 2019; Abdolrezayi et al., 2025).

Despite the existence of recovery technologies and requirements for their applicability, the recovery potential for a specific group of WWTPs that treat wastewater with a low pollutant load (low strength wastewater) has not been adequately summarised. The term 'low strength wastewater' has been used in a number of research publications (Liu et al., 2007; Wang et al., 2015; Zhang et al., 2020). However, there is no generally accepted definition or established concentrations of pollutants that determine whether a particular influent can be classified as 'low strength' (Borisov et al., 2026).

Low-strength wastewater has various adverse impacts on the sewage treatment process and associated costs (Saletti et al., 2023). The unsteady quantity and quality of I/I (infiltration/inflow water) water could violate the necessary ratio between carbon, nitrogen, and phosphorus, contributing to unreliable nutrient removal in the bioreactors, and consequently, nutrient loading of the sludge (Park et al., 2011). This will subsequently affect the phosphorus recovery potential. Around 41% of Bulgarian WWTPs recover phosphorus by using sludge as fertiliser, 24% for compost production, and 6% for reclamaiton of lands (Valchev et al., 2024). All these routes contribute to the unplanned P recovery path, whilst the remaining WWTPs (approx. 29%) do not recover phosphorus at all. Currently, none of the Bulgarian WWTPs applies semi-planed phosphorus recovery. Although the soil application of sewage sludge remains a relatively cost-effective and technically simple route for nutrient recycling, it may pose risks to soil quality because sludge can act as a vector for contaminants of emerging concern, including microplastics, pharmaceuticals, personal care products, PFAS, PAHs, hormones, and other organic micropollutants that are not consistently regulated or monitored in current sludge-management frameworks (Popoola et al., 2023; Leino et al., 2025; Lyubomirova et al., 2026). Furthermore, recent regulatory developments in some countries indicate a shift away from the direct agricultural use of sewage sludge as an unplanned P recovery pathway. This trend strengthens the need to explore alternative phosphorus recovery strategies.

In this regard, the aim of this paper was to assess the potential of targeted phosphorus recovery (semi-planned P recovery) from conventional WWTPs with low-strength influent. The study is based on the data from six WWTPs in Bulgaria.

MATERIALS AND METHODS

Main characteristics of the WWTPs included in the study

Six municipal WWTPs in Bulgaria were included in the study. They are identified by numbers because some water operators (WOs) do not wish to disclose parts of the data and the information that will be published. The WWTPs are briefly presented in Table 1.

Collected data and chemical analyses

The analysis presented in this study is based on two types of data: 1) the data provided by the WOs and 2) laboratory analysis of sludge samples for specific inquiries conducted at authors' research centre. The data provided by the WOs are summarised in Borisov et al. (2026). The laboratory analyses conducted at authors' centre Clean&Circle are presented below.

Grab samples

Dewatered sludge and sludge dewatering liquor grab samples were taken three times from each of the WWTPs over a period of six months. The chemical analyses of the phosphorus content were then conducted on each sample. The results used in the paper represent an average value of the chemically analysed content from all dewatered (mechanically and naturally) sludge samples for the respective plant. The total amount of samples for the average value calculations is presented in Table 2.

Dry mass and ash content of the sludge

The dry mass (DM) and the ash content of each sludge sample was determined according to the BS EN 15934:2012 and BS EN 15935:2021 standardised methods.

Phosphorus content in the dewatered sludge

The chemical analysis of the phosphorus content in the dewatered sludge was done using the following procedure: The sewage sludge samples were dried to constant weight, ground and well

Table 1. General information for the studied WWTPs (as of 2022)

WWTP	Connected people (NSI data)	Generated sludge	Primary clarifiers	Nitrogen removal	Phosphorus removal	Sludge stabilisation	Dewatering	Current sludge utilisation
	Number	t DW/year						
WWTP1	1 126 694	16005	yes	DN	$FeCl_3$+Bio	MT	Belt press	Agriculture
WWTP2	131 769	526	yes	DN	$FeCl_3$	OD	Centrifuge	Reclamation
WWTP3	112 415	1264	yes	DN	$FeCl_3$+Bio	MT	Belt Press	Agriculture
WWTP4	48 578	154	yes	DN	$FeCl_3$+bio	AS	Screw Press	Kept On Site
WWTP5	36 633	193	yes	DN	$FeCl_3$	AS	Centrifuge	Kept On Site
WWTP6	5 413	95	no	DN	$FeCl_3$	AS	Centrifuge	No Data

Note: abbreviations used in the table: NSI – National statistical institute; DW – dry weight; DN – Denitrification/Nitrification; Bio – biological phosphorus removal; MT – methane tank; OD – open digester; EA – extended aeration; AS – aerobic stabilisation.

Table 2. Amount of samples taken from each WWTP

WWTP	1	2	3	4	5	6
Mechanical dewatering	2	3	3	3	3	3
Natural dewatering (drying beds)	3	3	3	3	3	3
Total for average content calculation	5	6	6	6	6	6

homogenised. For the sample preparation, HNO_3 (67–69%, Fisher Chemicals, Ultra-TraceMetal Grade, Loughborough, UK), H_2O_2 (30% Fisher Chemicals, Ultra-Trace Analysis Grade, Loughborough, UK), HF (47–51%, Fisher Chemicals, Ultra Trace Metal Grade, Loughborough, UK) and double deionised water (Millipore purification system Synergy, Molsheim, France) were used. Samples of 0.20–0.25 g (three parallels of each sample) were accurately weighed using an analytical balance (KERN & Sohn GmbH - Ziegelei 1 · 72336 Balingen, Germany, Type ABT 100-M), and transferred into PTFE vessels. Then 5 mL HNO_3, 3 mL H_2O_2 and 2 mL HF were added and acid digestion of the samples was performed in a microwave reaction system (Anton Paar, Multiwave 3000, Graz, Austria) using four steps with the following power: 6 00 W (10 min), 800 W (20 min), 900 W (10 min) and 0W (20 min). Afterwards, the solutions were transferred in Teflon vessels and evaporated to about 1 mL on a heating plate. Finally, 5 mL HNO_3 were added and the samples were heated on a heating plate (Stuart CB 500, China) until the volume was reduced to 0.5–1 mL. The digested solutions were then diluted to 50 mL with double deionised water. Prior to the ICP-MS measurement, an additional dilution of 1 mL to 10 mL was performed.

The analysis of the samples was carried out using a PerkinElmer SCIEX ELAN DRC- ICP-MS (MDS Inc., Concord, ON, Canada) system with a cross-flow nebuliser. The spectrometer was optimised to provide minimal values of the ratios CeO^+/Ce^+ and Ba^{2+}/Ba^+ and optimal intensity of the analytes. Determination of phosphorus was performed in cell-based mode by optimising and applying a dynamic bandpass tuning parameter (RPa) for m/z 31, as described by Lyubomirova et al., 2020. The calibration standard solutions were prepared in the concentration range of 0.001–10 mg/L from a stock standard solution (Fluka, Steinheim, Switzerland) with an initial concentration of 1000 mg/L. External calibration was performed, yielding a coefficient of determination (R^2) of at least 0.999.

The accuracy was checked by analysis of two sewage sludge certified reference materials: CRM 029 (Trace Metals—Sewage Sludge 2—Sigma-Aldrich, Laramie, WY 82070, USA) and ERM-CC144 (Sewage Sludge, elements, European Commission—Joint Research Centre Directorate F—Health, Consumers and Reference Materials, Geel, Belgium). The comparison of the results showed a good agreement between the experimental and certified values.

Phosphorus content in the sludge dewatering liquor

The PO_4^{3-} and the PO_4^{3-} -P concentrations of the sludge dewatering liquor were determined with HACH Lange cuvette tests (LCK series that are ISO 15705 approved). The samples were decomposed in LT200 dry thermostat and analysed spectrophotometrically with a DR3900 spectrophotometer (Hach Lange). If the concentration of the sample exceeded the maximum range of the test, preliminary dilutions were performed, and the measured concentration was multiplied by the respective dilution factors.

Phosphorus content in the sludge ash

The P content of the sludge ash was calculated based on the analytically determined P content in the dewatered sludge and the proportion of the dry mass of the dewatered sludge and the sludge ash.

RESULTS

Characterisation of the wastewater strength

The data from the studied WWTPs show that all plants receive influent volumes greater than the volumes billed for domestic, commercial, and industrial wastewater (Figure 1). This indicates substantial dilution of the incoming wastewater.

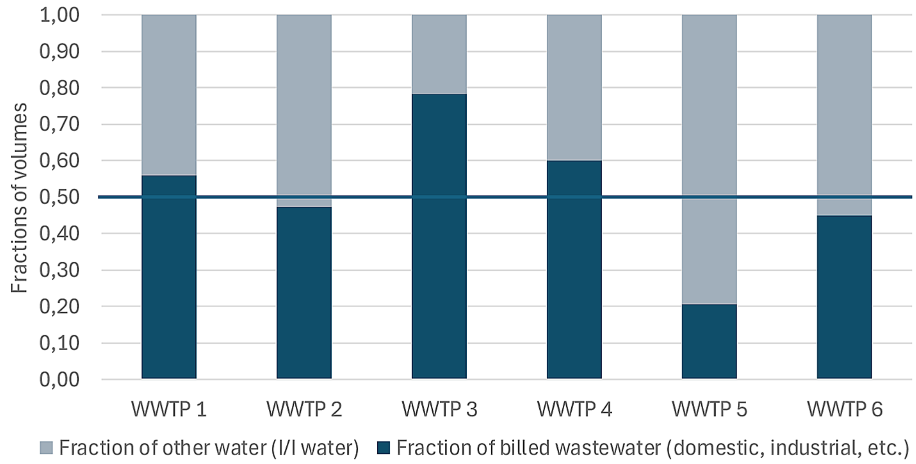

Figure 1. Fractions of billed wastewater (domestic, industrial, etc.) and other water (I/I water) at WWTP inlet (average for the three-year period 2020–2022) (Borisov et al., 2026)

The results presented in Figure 1 show that only three WWTPs (WWTP1, WWTP3, and WWTP4) exhibited a ratio of billed wastewater volume to total influent volume slightly greater than 0.5.

The observed dilution of wastewater by infiltration water (Figure 1) as well as the exfiltration from the sewerage network lowers phosphorus concentrations and can consequently limit the feasibility and efficiency of the phosphorus recovery processes. To assess the phosphorus recovery potential of the studied WWTPs, the phosphorus content/concentration was evaluated in three streams and materials:

- sludge dewatering liquor,
- sludge ash,
- dewatered sludge.

The selection of the first two streams was guided by the phosphorus recovery pathways supported by currently available recovery technologies, whereas the selection of the third stream was based on existing legislative requirements for phosphorus recovery.

Phosphorus content in the sludge dewatering liquor

Given that sludge dewatering liquor is the primary target stream for most established phosphorus recovery technologies, the concentration of PO_4^{3-}-P in this stream was analysed. The average values for each of the examined plants are presented in Table 3.

The results presented in Table 3 reveal that WWTPs 1, 3, and 4, which employ both biological and chemical phosphorus removal processes (Table 1) and have less diluted influents (Figure 1), exhibit higher phosphorus concentrations in the sludge dewatering liquor than the remaining WWTPs.

Phosphorus content in sludge ash

Table 4 summarises the sludge ash data obtained in the present study. To enable a more objective comparison, the samples were classified into two categories based on the sludge treatment method prior to incineration: ash derived from mechanically dewatered sludge and ash derived from sludge dried on drying beds. Among the studied facilities, WWTP1 and WWTP4 showed the highest phosphorus concentrations in the ash derived from both mechanically dewatered sludge and sludge dried on drying beds.

Phosphorus content in sludge

The studied WWTPs were grouped according to the capacity thresholds established in the legislation of European countries regarding phosphorus recovery, above 50,000 p.e., above 20,000 p.e., and above 1.000 p.e, respectively. The phosphorus content of the dewatered sludge in WWTPs belonging to these three capacity categories is presented in Figure 2.

Figure 2 shows that the average phosphorus content in the dewatered sludge of the studied WWTPs ranges from 12.3 to 26.7 g P/kg DM. Furthermore, the figure indicates no apparent correlation between WWTP size and phosphorus content in the sludge, which is consistent with expectations. To further explore this relationship,

Table 3. Average P concentration in the sludge dewatering liquor

Parameter	WWTP1	WWTP2	WWTP3	WWTP4	WWTP5	WWTP6
P concentration, mg/L	148	48	75	107	20	30

Table 4. Measured phosphorus content in the sludge ash

WWTP	For incinerated mechanically dewatered sludge, t P/t ash				For incinerated sludge from drying beds, t P/t ash			
	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average
WWTP1	0.07	0.04	0.06	0.06	0.04	0.04	0.08	0.05
WWTP2	0.05	0.03	0.03	0.04	0.04	0.04	0.03	0.04
WWTP3	0.05	0.03	0.03	0.03	0.06	0.05	0.02	0.04
WWTP4	0.08	0.06	0.06	0.07	0.08	0.07	0.07	0.07
WWTP5	0.06	0.03	0.03	0.04	No data	No data	No data	No data
WWTP6	0.06	0.02	No data	0.04	0.06	0.04	0.02	0.04

Table 5. Percentage of influent phosphorus accumulated in the dewatered sludge

WWTP No	Size	Inlet P load	DM of dewatered sludge	Average P content in the dewatered sludge	Average P in the dewatered sludge per year	% of inlet P in the dewatered sludge
	p.e.	t/year	t/year	kg P/t DM	t/year	%
WWTP1	1 126 694	520.7	17656.4	26.7	471.9	90.6%
WWTP2	131 769	41.2	816	12.3	10.1	24.4%
WWTP3	112 415	35.8	1624	19.5	31.7	88.7%
WWTP4	48 578	20.2	256.25	23.4	6.0	29.7%
WWTP5	36 633	14.4	206.75	15.2	3.1	21.8%
WWTP6	5 413	2.9	91.52	18.1	1.7	57.0%

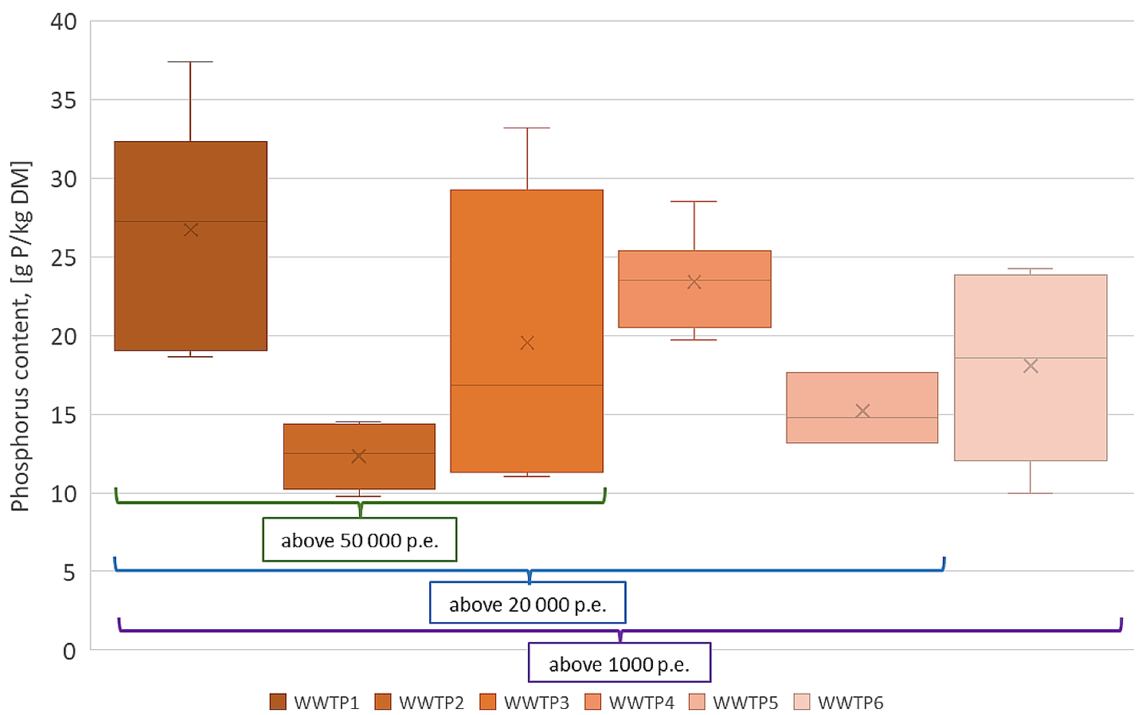

Figure 2. Phosphorus content in the dewatered sludge

the percentage of influent phosphorus accumulated in the dewatered sludge was calculated as an annual average based on data provided by the Water Operators for the period 2020–2022.

Table 5 confirms that no relationship was observed between WWTP size and phosphorus content in the dewatered sludge. Two of the studied plants (WWTP1 and WWTP3) retain approximately 90% of the influent phosphorus in the sludge. Both facilities employ combined biological and chemical phosphorus removal processes (Table 1) and have less diluted influents (Figure 1). Although WWTP4 applies the same treatment approach, only about 30% of the influent phosphorus is accumulated in the sludge. From the remaining three WWTPs, which rely solely on chemical phosphorus precipitation, the retained P in WWTP6 was slightly below 60%, while in the other two plants – WWTP2 and WWTP5, the P in the dewatered sludge was approximately 20–25% of the influent P load.

These results illustrate that factors other than plant size, such as wastewater strength, treatment technology and operational conditions, have a significant influence on phosphorus retention in sewage sludge. For example, a logical correlation was observed in the study, whereby a higher phosphorus load at the WWTP influent corresponds to a higher phosphorus content in the dewatered sludge, as shown in Figure 3. Furthermore, the WWTPs with the highest average phosphorus content in the dewatered sludge are also those characterised by lower wastewater dilution (Figure 1), underscoring the importance of influent characterisation when assessing the phosphorus recovery potential.

DISCUSSION

Phosphorus recovery potential in relation to available recovery technologies

The technologies with a Technology Readiness Level (TRL) of 9 (i.e. available on the market) can be broadly classified into two categories: liquid-phase and solid-phase targeted, as depicted in Figure 4. With regard to phosphorus recovery from liquid streams, most commercially available full-scale technologies require a minimum phosphorus concentration of 50 mg P/L in the reactor influent to achieve efficient phosphorus recovery (Di Capua et al., 2022; Vu et al. 2023). Three of the six studied WWTPs (WWTP1, WWTP3, and WWTP4) exhibited average phosphorus concentrations above this threshold (Table 3).

WWTP2 and WWTP6 showed PO_4^{3-}–P concentrations of 48 mg/L and 30 mg/L, respectively (Table 3). Consequently, the only currently available technology that could potentially be applied for phosphorus recovery from their sludge dewatering liquor is the Crystalactor process, which can operate at influent concentrations as low as 25 mg P/L (Di Capua et al., 2022; Vu et al. 2023).

The remaining facility, WWTP5, exhibited a mean PO_4^{3-}–P concentration of 20 mg/L (Table 3), making it unsuitable for phosphorus recovery using any of the currently available full-scale technologies considered in this study. This WWTP has the highest dilution with infiltration water (Figure 1).

With regard to phosphorus recovery from ash, the minimum reactor inlet P content of the ash

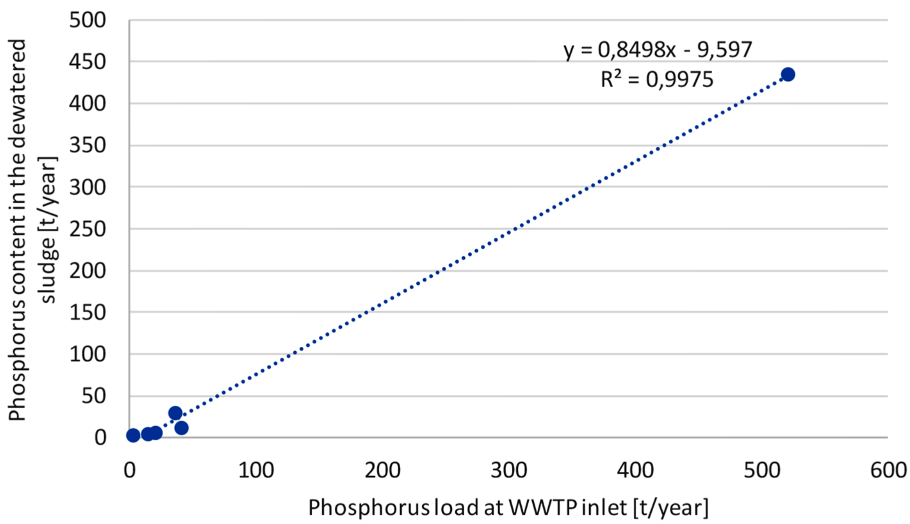

Figure 3. Correlation between WWTP influent phosphorus load and phosphorus content in the dewatered sludge

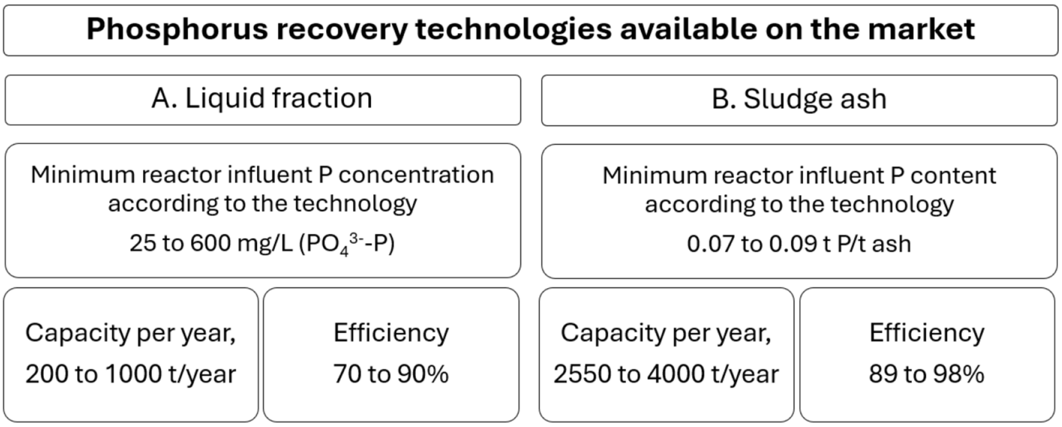

Figure 4. Market available technologies and minimum phosphorus requirements (Desmidt et al., 2014; Chrispim et al., 2019; Vu et al., 2023; ESPP 102, 2025 ; Abdolrezayi et al., 2025)

should be 0.07 to 0.09 t P/t ash (Figure 4). The results in Table 4 show that most of the samples were below these limiting values, regardless of the preliminary dewatering method. Additionally, none of the WWTPs showed consistent results above 7–9% P content. Only individual samples from WWTP1 and WWTP4 were above 0.07. Furthermore, the only mean values that are on the border of this threshold are the ones from WWTP4. Hence, it is not realistic to expect that phosphorus recovery from ash can occur in the studied WWTPs with low strength influents.

Phosphorus recovery potential in relation to legislative requirements in other countries

As mentioned in the introduction, three European countries have already integrated the P recovery requirements and criteria in their national legislation. They are summarised in Table 6.

Considering the current P recovery criteria in Germany, none of the analysed samples from the examined plants had a consistent phosphorus content exceeding 20 g/kg DM, except for WWTP4 (Figure 2). However, its capacity is slightly below the stated threshold of 50 000 p.e., which excludes it formally from the legislative requirements (Table 6). Notably, only WWTP1 covers both criteria, being the largest (>50 000 p.e.), and having an average phosphorus content above 20 g/kg DM (26.7 g/kg DM). Consequently, none of the investigated WWTPs with low strength influents (except WWTP 1) would be needed to implement phosphorus recovery if the newly implemented German regulations were applied in Bulgaria.

Among the national phosphorus recovery requirements considered, the Swiss criteria are the most stringent, as they apply to all WWTPs with a capacity exceeding 1.000 p.e. and require a relatively high phosphorus recovery (at least 16

Table 6. Legislative phosphorus recovery requirements from WWTPs in European countries

Country	Year of application of the P recovery requirement	Municipal WWTP capacities required to recover P	P recovery criteria	Reference document
Germany	2029 for WWTPs >100 000 p.e.; 2032 for WWTPs >50 000 p.e.	>100,000 p.e. from 2029; >50,000 p.e. from 2032.	Recovery is obligatory If the sludge contains ≥20 g P/kg DM. For sludge: either ≥50% P recovery or reduction below 20 g P/kg DM. For sludge ash: ≥80% of ash-P.	AbfKlärV, 2017
Switzerland	From 2026	≥1.000 p.e.	P concentration/content is not specified. Recovery: at least 16 kg P/t sludge DM should be recovered.	Phosphorreiche Abfälle, 2020; Phosphorrecycling, 2024
Austria	From 2033	≥20,000 p.e.	For sludge: ≥60% of influent P recovered. For sludge ash: ≥80% of ash-P or the entire ash must be used for fertiliser.	AVV, 2024

g P/kg DM). All WWTPs included in the present study exceed this capacity threshold, however, only half of them (WWTP1, WWTP3, and WWTP4) exhibit phosphorus contents above 16 g P/kg DM (Table 5). These are the facilities that employ both biological and chemical phosphorus removal (Table 1). These findings indicate that the direct transfer of Swiss phosphorus recovery requirements to Bulgaria may not be appropriate without careful consideration of local wastewater characteristics and treatment practices.

The current Austrian phosphorus recovery requirements represent a combination of the Swiss and German approaches. They include both a WWTP capacity threshold and a phosphorus recovery performance criterion, however, instead of a fixed phosphorus content requirement, compliance is assessed based on the proportion of influent phosphorus recovered (Table 6). Five of the WWTPs analysed in this study exceed the Austrian capacity threshold of 20,000 p.e. However, only two of these facilities (WWTP1 and WWTP3) meet the Austrian phosphorus recovery criterion, as approximately 90% of the influent phosphorus is retained in the sludge (Table 5). In contrast, the remaining plants retain only 21.8%, 29.7%, and 57.0% of the influent phosphorus load in the sludge and therefore fall well below the required recovery threshold of 60% (Table 5). These findings suggest that the direct adoption of the Austrian phosphorus recovery requirements into Bulgarian legislation may be challenging, as compliance would be difficult to achieve for a substantial proportion of WWTPs with capacities above 20,000 p.e. under current operating conditions and low strength influents.

Regarding the current regulatory requirements for phosphorus recovery from sludge ash, only Germany and Austria explicitly specify it, with both frameworks requiring recovery of at least 80% of the phosphorus contained in the ash (Table 6). The German criteria appear unlikely to be met by the WWTPs included in this study, as all plants with capacities above 50 000 p.e. consistently exhibited ash phosphorus contents below 0.07 t P/t ash, the threshold considered necessary for the efficient application of currently available recovery technologies (apart from only two samples from WWTP1). Under the Austrian framework, only WWTP4 both exceeds the 20 000 p.e. capacity threshold and achieves an ash phosphorus content compatible with the requirements of available full-scale technologies.

Phosphorus recovery potential in relation to other valuable elements in sludge

The present study focused on the phosphorus recovery potential and did not address the quality of the recovered products. Nevertheless, phosphorus should not be considered in isolation from the overall composition of sewage sludge. Valchev et al. (2024) provided a detailed characterisation of the elemental composition of sludge from the same WWTPs, showing that sewage sludge contains not only phosphorus but also several other valuable elements that could contribute to resource recovery. In addition to the nutrient contents, the sludge was found to contain substantial amounts of aluminium (average 19.3 g kg^{-1} DW), magnesium (6.7 g kg^{-1} DW), titanium (1.73 g kg^{-1} DW) and manganese (0.69 g kg^{-1} DW), highlighting the broader resource recovery potential of sewage sludge. Several other critical and precious elements, including gallium, silver and gold, were also detected, but only at relatively low concentrations, suggesting that their recovery would require a case-specific assessment of technical feasibility and economic viability. These findings demonstrate that the complete elemental composition, including trace elements, should also be considered when selecting recovery technologies and defining the most appropriate end use of the recovered products. Such an integrated approach supports both resource efficiency and compliance with environmental and agricultural quality requirements. Consequently, the phosphorus recovery potential identified in the present study should be interpreted within the broader context of integrated resource recovery from sewage sludge, taking into account both valuable and trace elements to support the selection of sustainable recovery technologies and circular economy solutions.

CONCLUSIONS

This study demonstrated that the phosphorus recovery potential of WWTPs treating low-strength wastewater is strongly influenced by wastewater strength, the phosphorus removal technology employed, and the distribution of phosphorus among dewatered sludge, sludge ash, and sludge dewatering liquor. Higher influent phosphorus loads and the presence of biological phosphorus removal generally resulted in higher phosphorus contents in dewatered sludge, whereas lower wastewater strength and the exclusive use of chemical phosphorus removal reduced the proportion of influent phosphorus retained in the sludge line.

Among the recovery pathways assessed, phosphorus recovery from sludge dewatering liquor appears to be the most viable option. Most of the studied WWTPs exhibited PO_4^{3-}–P concentrations compatible with currently available liquid-phase recovery technologies. These findings indicate favourable conditions for targeted phosphorus recovery from sludge dewatering liquor in WWTPs treating low-strength wastewater. Nevertheless, phosphorus concentration alone should not be considered a decisive factor. A comprehensive feasibility assessment remains essential prior to the selection and implementation of a recovery technology.

In contrast, phosphorus recovery from sludge ash is unlikely to be feasible for most of the investigated plants, as the phosphorus content in the ash was generally below the levels required for the efficient application of currently available full-scale recovery technologies.

The results further indicate that the direct adoption of existing European phosphorus recovery requirements would be challenging for the studied Bulgarian WWTPs, primarily due to highly diluted influent wastewater and the resulting relatively low phosphorus content in sludge and sludge ash. Consequently, the phosphorus recovery strategies in Bulgaria should not rely solely on the regulatory thresholds adopted from other countries. Instead, they should be developed with due consideration of wastewater strength, plant-specific phosphorus mass balances, and the actual availability of recoverable phosphorus streams.

Although this study is based on Bulgarian WWTPs, the findings are expected to be applicable to other countries with similar wastewater characteristics, treatment technologies, and operational conditions. In particular, WWTPs treating highly diluted, low-strength municipal wastewater are likely to face comparable limitations regarding phosphorus accumulation in sludge and sludge ash, while phosphorus recovery from sludge dewatering liquor may represent the most promising recovery pathway. Nevertheless, local wastewater characteristics, treatment configurations, and national regulatory frameworks should be taken into account when transferring these findings to other regions.

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