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Application of Activated Sludge Model for phosphorus recovery potential simulation

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ABSTRACT

The study investigates phosphorus (P) recovery potential from sewage sludge in the most prevalent activated sludge (AS) systems obtained with an Activated Sludge Model (ASM) simulation using BioWin software by EnviroSim Associates Ltd., (Hamilton, Ontario, Canada). The simulation study includes 10 various wastewater treatment systems. The analyzed systems were based on the following technologies: conventional activated sludge, anoxic-oxic, 3-Stage Bardenpho, 5-Stage Bardenpho, Johannesburg (JHB), modified Johannesburg system (MJHB), University of Cape Town, modified University of Cape Town system, oxic-anoxic (OA) and anaerobic-oxic. The ASM-based simulation allowed to develop P flows diagrams for 10 analyzed AS systems considering the effluent P load discharged to wastewater receiver and P recovery potential estimated on the base of total phosphorus content (TP) and inorganic phosphorus (IP) content in the sewage sludge. The range of the P recovery potential based on TP content in the sewage sludge reached from 1.33% in the JHB and MJHB systems to 1.01% in the OA system. The study covered the P bioavailability context by analyzing the simulation results of the IP content in the sewage sludge which varied from 0.19% in JHB and MJHB systems to 0.05% in the OA system.

Keywords: Activated Sludge Model; Sewage sludge; Wastewater treatment; Phosphorus recovery; Phosphorus flow

1. Introduction

Phosphorus (P) content in the discharged wastewater remains a global concern due to its key role in accelerating aquatic vegetation growth leading to eutrophication of surface waters [1,2]. The most emerging concern of high P content in the discharged wastewater is related to the fact that P is considered a main limiting factor of eutrophication, especially in freshwaters ecosystems (lakes, rivers and reservoirs) and some marine waters, which quality is dependent on riverine nutrient loads, discharges [3–6]. Moreover, municipal effluents are characterized by a high share of inorganic P compounds which are especially dangerous to the aquatic environment due to their high bioavailability resulting in a high eutrophication potential of discharged wastewater [7].

In the past decades many legal and technical measures have been taken in the European Union (EU) Member States to limit the P loads discharged to wastewater receivers including the implementation of the Urban Wastewater Treatment Directive 91/271/EEC (UWWTD) [8], Water Framework Directive 2000/60/EC (WFD) [9] and other important regulations at national and regional levels [10].

An apparent trend has recently been noticed in changing views on advanced nutrients removal from wastewater for their recovery in order to, for example, obtain valuable nitrogen (N) or P-based fertilizers [11]. This tendency could be explained by the depletion of limited P resources which resulted in including P in the critical raw materials list for

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the European Economy by the European Commission (EC) [12,13]. P is a non-renewable key element necessary for all living beings that cannot be substituted by any other element due to its biological functions (a component of DNA and RNA, responsible for energy metabolism) [14]. In response to the growing demand for P in the light of limited phosphate rock resources, some countries such as Germany and Switzerland have introduced legal requirements with established transition periods for the introduction of an obligatory P recovery from municipal wastewater [15]. Other countries such as Austria and Sweden are developing similar national regulations [16].

While primary extraction of phosphate rock in the EU takes place currently only in Finland [17], the great majority of P-based raw materials is imported from non-EU countries such as Morocco (35.1%), Russia (31.6%), Algeria (12.3%) and Israel (7.5%) and the total amount of phosphate rock and its derived products imported to the EU Member States in 2017 reached 5.5 million Mg which constitutes nearly 90% of the EU's phosphate rock market share [18].

On the contrary to primary P sources, its secondary sources are present in almost every country around the globe [19]. P recovery is possible from different waste streams such as municipal and industrial wastewater, sewage sludge, sewage sludge ash, municipal and industrial waste, pig slurry, meat and bone meal, etc. [20–24]. It was estimated by Koppelaar and Weikard [25] that the total extraction of primary sources of phosphate rock is 21.1 million Mg while about 15%–20% can be replaced by P recovered from wastewater.

Furthermore, P recovery from wastewater is definitely in line with the circular economy model [26] in which the value of products, materials and resources is maintained in the economy for as long as possible [27].

The current study is an attempt to investigate P flows in the most widely used activated sludge (AS) systems in order to indicate which technologies are able to provide the highest load of valuable P compounds which can be extracted afterward from sewage sludge. The study focuses on the flows of total phosphorus (TP) and inorganic phosphorus (IP), mainly as soluble orthophosphates ($P–PO_4$), wherein the content of IP is of special importance for the value of recovered material due to its high biological bioavailability [28].

AS technologies have been firstly applied over 100 y ago in Davyhulme WWTP in Manchester, United Kingdom [29]. Since then, the AS process was constantly being modified in order to achieve an optimal quality of various types of wastewater discharged into the water environment [30]. Many developed AS modifications have resulted in the optimization of treatment processes and their increased efficiency [31]. The AS process primarily uses bacteria, some protozoa, and other microorganisms in the form of biomass suspension to remove organic substances, including nutrients: carbon (C), N and P compounds [32]. Currently, the AS technology is the most widely used biological method of wastewater treatment, especially of nutrient-reach municipal effluents. Industrial effluents, in turn, contain relatively low P loads. However, wastewater discharges from food and beverage, textile and paper industries usually contain the largest share of industrial P load introduced to surface waters [33–35]. Furthermore, some industrial facilities discharge wastewater into municipal sewage system which transports industrial wastewater into municipal wastewater treatment plants (WWTPs) that leads to an increase in nutrient loads [36].

Therefore, an Activated Sludge Model (ASM) simulation was used in order to identify which wastewater treatment technologies provide the highest P recovery potential. The results can have high importance for current and future decisions regarding the selection of efficient wastewater treatment systems which besides high nutrient removal rates would allow for efficient P recovery from sewage sludge.

2. Material and methods

The research methodology included an ASM-based simulation carried out by EnviroSim Associates Ltd., (Hamilton, Ontario, Canada) software – BioWin. The aim of the simulation was to assess the P recovery potential in AS technological systems used in the majority of full-scale municipal WWTPs [37].

The ASM-based models are or can be incorporated in most of the applied simulation software, such as ASIM, AQUASIM, GPS-X, WEST and BioWin [38]. However, the initial concept of the development of ASM-based software was to create a useful modeling tool for optimizing wastewater treatment processes with particular emphasis on nutrient removal efficiency in order to reduce the discharged N and P loads [39].

Mathematical models implemented in ASM-based software are useful for a quantitative evaluation of wastewater treatment processes [40]. In the BioWin an original ASM Hybrid model was implemented by EnviroSim, which enclose different valuable features of various ASMs including ASM1, ASM2d and ASM3 [32,41]. In addition, it contains the module for modeling the sewage sludge quantity and quality parameters that enable to investigate P flow in the WWTPs and P recovery potential [42,43].

The simulation study was performed using the input data set from the municipal WWTP "Krakow-Kujawy" in Poland (373,000 of designed population equivalent). The Krakow-Kujawy WWTP was designed as an enhanced biological nutrient removal (EBNR) plant, based on the AS technology. There are 4 bioreactors installed in the plant after the primary settling tanks with 3 types of chambers able to ensure anaerobic, anoxic and oxic conditions for efficient nutrient removal. The maximum wastewater flow in the bioreactors is approx. 70,000 m^3/d, while the average flow is 55,000 m^3/d, so the total capacity of 4 operating bioreactors is 64,000 m^3. A facultative chamber, which was designed to provide oxic or anoxic conditions depending on the inflowing wastewater parameters is located between the anaerobic and oxic chamber. The predenitrifcation of recirculated sludge takes place in a separate predenitrification chamber with a depth of 3.4 m and a capacity of 620 m^3, located within the external line of recirculation from the secondary settling tanks with an average depth of 3 and 42 m diameter [44].

The P recovery potential simulation was conducted for one of the operating bioreactors using wastewater quality data based on the two-week average and the adopted simulation period of 60 d. The input data set to the model is shown in Table 1.

The simulation was carried on according to the developed algorithm presented in Fig. 1.

Table 1
Set of the input wastewater parameters from the Krakow-Kujawy WWTP [own table based on the Krakow Waterworks materials]

Krakow-Kujawy WWTP		BOD_5 mg/L	COD mg/L	TP mg/L	IP mg/L	TN mg/L	N–NH_4 mg/L	N–NO_3 mg/L	N-NO_2 mg/L
Raw wastewater	Mean	259.86	569.66	6.60	3.71	67.65	47.26	0.13	0.02
	Min.	102.00	320.00	6.21	3.49	46.90	34.10	0.07	0.01
	Max.	335.00	628.50	6.86	3.89	79.25	54.75	0.16	0.03
	SD	92.76	197.97	0.24	0.18	11.74	7.44	0.03	0.01
Wastewater after primary settling tank	Mean	260.34	502.48	8.68	6.33	81.93	60.63	0.14	0.02
	Min.	188.00	388.00	7.88	5.69	67.60	55.30	0.12	0.01
	Max.	220.00	424.00	8.99	6.46	90.50	64.25	0.15	0.02
	SD	92.09	152.59	0.39	0.33	8.39	3.42	0.01	0.00
Biologically treated wastewater	Mean	4.11	29.15	0.37	0.20	17.52	10.80	5.29	0.77
	Min.	1.50	18.00	0.23	0.08	13.60	2.71	1.28	0.14
	Max.	4.40	35.00	0.62	0.43	20.75	16.45	10.40	1.21
	SD	2.49	10.95	0.14	0.13	2.73	4.86	2.92	0.38

BOD_5 – biochemical oxygen demand; COD – chemical oxygen demand; TP – total phosphorus; IP – inorganic phosphorus; TN – total nitrogen; N–NH_4 – ammonium nitrogen; N–NO_3 – nitrate–nitrogen; N–NO_2 – nitrite–nitrogen; SD – standard deviation.

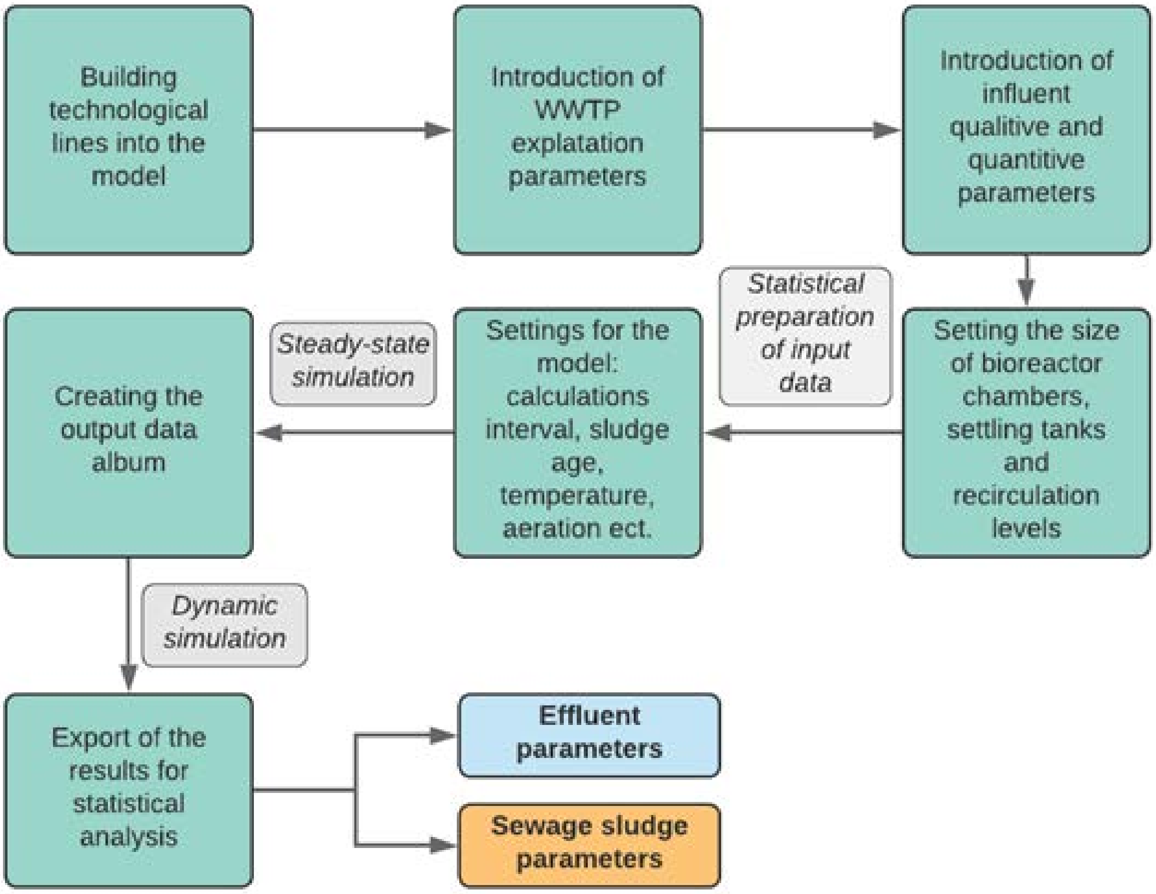

Fig. 1. Algorithm of the simulation in BioWin.

The model set-up began with creating technological lines according to real dimensions of the Krakow-Kujawy WWTP, with introduced operation parameters as well as influent quantitative and qualitative data. The schemes of the bioreactor sections and recirculation regimes were set following the guidelines of the German ATV Standards [45] for various wastewater treatment systems such as conventional activated sludge (CAS), anoxic-oxic (AO), 3-Stage Bardenpho, 5-Stage Bardenpho, Johannesburg (JHB), modified Johannesburg system (MJHB), University of Cape Town (UCT), modified University of Cape Town system (MUCT), oxic-anoxic (OA) and anaerobic-oxic (A/O). The model settings included: interval of calculations, sludge age, temperature, aeration efficiency, etc.

All of the above actions led to the steady-state and dynamic simulation which have resulted in obtaining treated wastewater and sewage sludge parameters concerning the most relevant in terms of P recovery (e.g., TP and IP content).

The ASM simulation results were used to assess the P recovery potential of 10 AS systems variants according to the following criteria: (1) the TP content in sewage sludge, (2) the IP content in sewage sludge.

3. Bioavailability context of P compounds in wastewater

The bioavailability of P compounds is often discussed regarding the eutrophication potential of treated wastewater [46]. It is a well-known fact that IP is the most essential bioavailable element responsible for the excessive growth of aquatic vegetation and acceleration of surface waters eutrophication [47]. The share of bioavailable and non-bioavailable P compounds in treated wastewater and sewage sludge is varied and to a large degree depends on the applied wastewater treatment technology [48].

Detergents are the main source of IP in municipal wastewater which during the wastewater flow within the sewage system are easily hydrolyzed to orthophosphates [49]. The share of IP in TP content of municipal wastewater depends on the type of discharged wastewater. Effluents from industries such as mineral fertilizers and synthetic cleaning agents production along with the surface flow from agricultural areas within the municipal catchment areas have a high impact on the IP content in municipal wastewater.

It is estimated that from 5% to 50% of P in wastewater treated in EBNR systems is not available for aquatic vegetation [50]. Organic phosphorus fraction is less bioavailable than IP while mineral P compounds can be directly absorbed by plants [51]. Considerations about the eutrophication potential are inversely proportionally linked with the P recovery potential. The greater the bioavailable P share in the TP load removed from wastewater, the greater the amount of valuable P accumulating in the sewage sludge [52]. The bioavailability of P in the sewage sludge strongly depends on the addition of iron or aluminum salts during wastewater treatment in AS systems supported by chemical P precipitation. Chemical support is often used at EBNR plants to meet the strict final effluent quality requirements.

The most common methods for P recovery from digested sewage sludge or the liquors from sludge dewatering are based on struvite (MAP) or calcium phosphate (Ca-P) precipitation [53]. Both precipitation products quality of P recovery is very sensitive to metal salts addition whereas the bioavailability of soluble P compounds in the sludge is reduced by the metal ions and the further P recovery loses its economic viability [54].

Concerning the struvite chemical formula ($NH_4MgPO_4 \cdot 6H_2O$), avoiding or limiting the amount of added precipitation agents is crucial to correctly maintain the struvite crystallization process since magnesium can be replaced by iron or aluminum compounds and form unwanted structures.

Furthermore, within chemical P precipitation toxic ions including arsenic and fluoride may occur in the final P recovery product. Moreover, high aluminum content in secondary fertilizers might be toxic for plants grown in low pH soils [55,56]. Therefore, the bioavailability context was included in the assessment of P recovery potential by the consideration of IP content in the sewage sludge.

4. Results and discussion

The ASM-based simulation generated a number of important results concerning P flow in WWTPs operating in various technologies. However, regarding the aim of the study which was to identify AS systems with the highest P recovery potential, mainly the content of TP and IP were analyzed. The simulation results in terms of TP content in sewage sludge are presented in Fig. 2.

The highest average TP load was obtained in the sewage sludge produced in JHB system (108.07 ± 8.76 kg/d) and MJHB system (108.02 ± 8.78 kg/d). The lower TP loads were contained in the sewage sludge from MUCT (101.23 ± 10.39 kg/d), UCT (99.44 ± 10.60 kg/d) and A/O (98.95 ± 8.21 kg/d), 3-Stage Bardenpho (91.46 ± 9.75 kg/d), 5-Stage Bardenpho (87.02 ± 8.62 kg/d) systems. The lowest TP load was obtained within CAS (82.08 ± 7.32 kg/d), AO (81.79 ± 7.32 kg/d) and OA (79.52 ± 7.01 kg/d) systems. The simulation results concerning TP loads in sewage sludge showed that more advanced wastewater treatment systems, such as JHB and MJHB, are characterized by higher P recovery potential than conventional systems. However, the TP load does not fully represent the useful properties of obtained sewage sludge while the greatest value is represented by bioavailable IP content [57].

Therefore, the ASM simulation of the amount of the IP in the sewage sludge has been proceeded. The results presenting the IP load in sewage sludge in the investigated AS systems are shown in Fig. 3.

Due to the high share of bioavailable P in wastewater treated in the analyzed AS systems, without chemical P precipitation, the IP load in the sewage sludge was low and varied on average from 3.98 to 15.83 kg/d. The highest potential of IP recovery was obtained in JHB (15.83 ± 1.28 kg/d) and MJHB (15.78 ± 1.28 kg/d) technologies. A lower IP load was obtained in MUCT (10.38 ± 1.06 kg/d), A/O (9.90 ± 0.82 kg/d), and UCT systems (9.58 ± 1.02 kg/d). A very low IP load was observed in the 3-Stage Bardenpho (6.94 ± 0.74 kg/d), 5-Stage Bardenpho (5.64 ± 0.56 kg/d), CAS (4.48 ± 0.40 kg/d), AO (4.44 ± 0.40 kg/d) and the least in OA system (3.98 ± 0.35 kg/d).

In the analysis of the P recovery potential, one of the critical parameters would be the share of bioavailable P load in TP loads which will determine the utility of sewage sludge for fertilizer production. In case of the simulation results

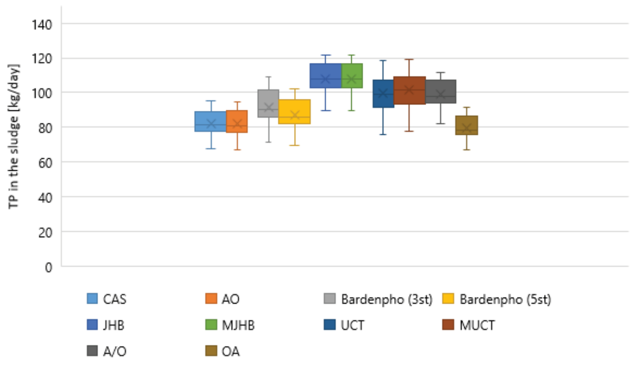

Fig. 2. TP load in the sewage sludge produced in analyzed AS systems.

the share of bioavailable P in TP was the following: JHB (14.64%), MJHB (14.61%), MUCT (10.25%), A/O (10.00%), UCT (9.63%), 3-Stage Bardenpho (7.58%), 5-Stage Bardenpho (6.49%), CAS (5.46%), AO (5.43%) and OA (5.00%).

The simulation results allowed to present P flows in the analyzed wastewater treatment systems with constant

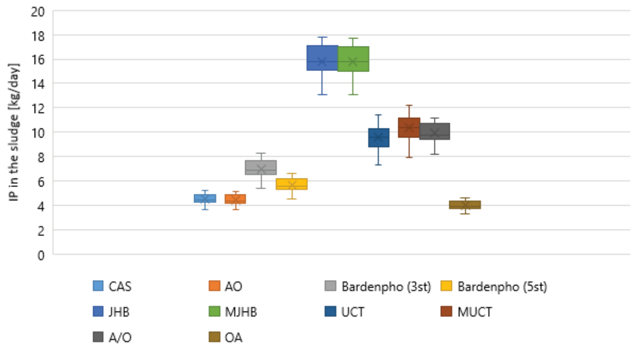

Fig. 3. IP load in the sewage sludge from the analyzed AS systems.

input raw wastewater parameters. The P flows were simulated for obtaining 2 outputs: effluent being discharged to wastewater receiver and sewage sludge which can be further processed to recover valuable raw materials. The simulated P flows are shown in Fig. 4.

The obtained P flows within the ASM simulation allowed for the assessment of P recovery potential according to the

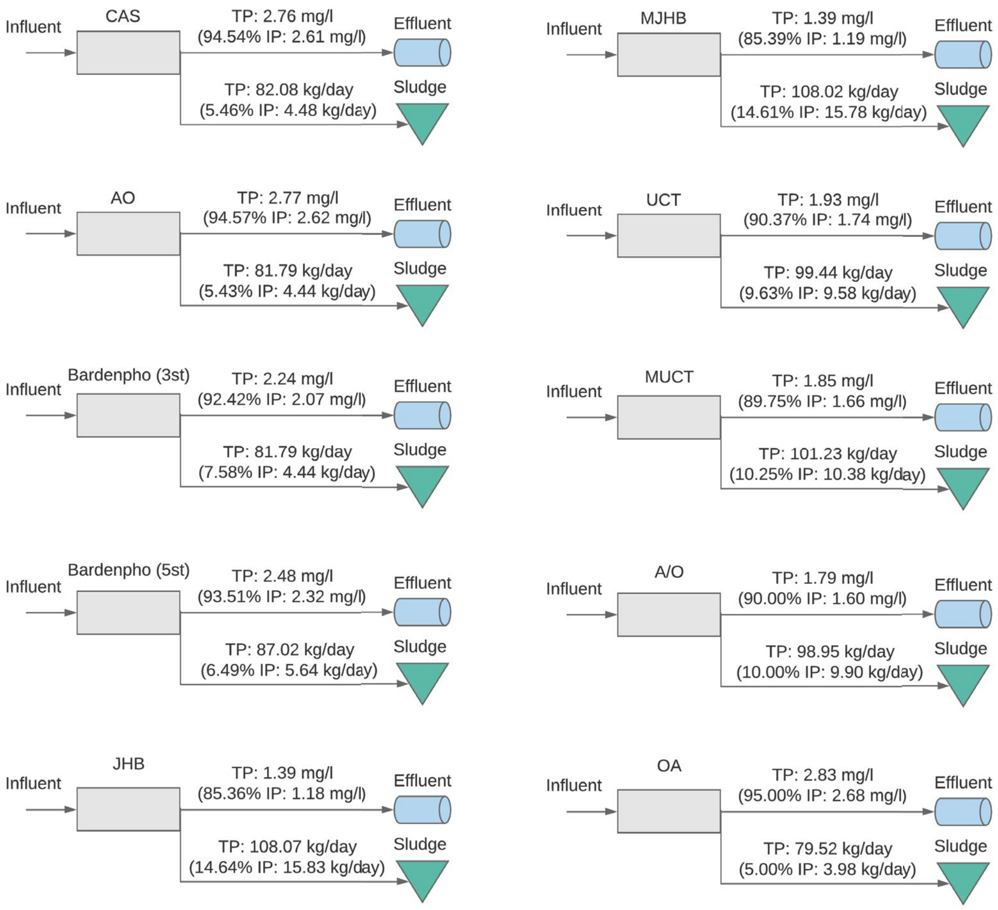

Fig. 4. Simulated P flows in the analyzed wastewater systems.

adopted criteria which were the following: (1) the TP load in sewage sludge, (2) the IP load in sewage sludge. The assessment results are presented in Fig. 5.

The JHB and MJHB systems were characterized by the highest P recovery potential containing 1.33% of TP and 0.19% of IP in the sludge. MUCT, UCT and A/O systems showed high TP content (1.26%, 1.23%, 1.21% respectively), but the IP content was lower (0.13%, 0.12%, 0.12% respectively). The P recovery potential of 3-Stage Bardenpho, 5-Stage Bardenpho, CAS, AO and OA technologies was lower and in terms of TP it amounted to 1.11%, 1.08%, 1.05%, 1.05%, 1.01% respectively and to 0.08%, 0.07%, 0.06%, 0.06%, 0.05% respectively in terms of IP.

Ideally, a WWTP should ensure maximum P removal efficiency from wastewater through its accumulation in the sewage sludge and its further recovery as a raw material or ready-to-use products [58]. However, even with the use of advanced WWTP technologies, the efficiencies of P removal and recovery are limited [59,60]. The ASM-based simulation confirms that EBNR technologies are able to ensure low TP content of treated wastewater. A high P removal rate achieved by the most advanced systems such as JHB and MJHB corresponded with the highest P recovery potential. On the other hand, less advanced systems such as CAS, AO and OA which due to the lack of a designated anaerobic chamber for biological P removal can discharge large loads of P to the receiver. So their use without technological and operational modifications in order to intensify the P removal (e.g., installation of biological filters or membranes systems [61,62]) or additional precipitation for P recovery) is not recommended [63].

It needs to be underlined that the analyzed systems could achieve much higher P recovery potential if supported by chemical P precipitation using aluminum or iron-based coagulants. However, due to its possible negative side effects such as leading to the formation of residues with limited bioavailability and contaminants in the final product of P recovery from sewage sludge or its dewatering liquors chemical P precipitation was not considered in this study [52,64,65].

The current legal regulation aimed at eutrophication mitigation in different countries dictates the necessity of the application of efficient nutrient removal technologies ensuring high efficiency of their removal [66]. In many cases, even advanced EBNR systems are not able to ensure such high levels of nutrients elimination. For water bodies sensitive to eutrophication, for example, the Baltic Sea, the Helsinki Convention signatory countries are obligate to limit effluent TP concentration to a maximum of 0.5 mg/L for direct treated wastewater discharge to the Baltic Sea [67]. To achieve such a low level of TP, AS technologies are regularly supported with aluminum or iron salts [68], and other chemical substances for P precipitation [69]. Such a solution is used on a wide scale in Finland and other Nordic and Baltic countries due to restrictive P limits [70]. A study from Norway including effluent parameters from 60 WWTP [71] shows that the P removal efficiency for conventional biological treatment was 2.93 ± 1.68 mg/L, for biological-chemical treatment it was 0.52 ± 0.51 mg/L while chemical treatment allowed the achieving of 0.42 ± 0.42 mg/L. Besides additional costs of chemical reagents, P precipitation leads to arising of various undesired complexes in the effluent and the sewage sludge [72,73]. To maintain effluent TP content below 0.5 mg/L a 2–3 time overdose of metal salts is required [74]. This makes P recovery from sewage sludge difficult and therefore, limits the P recovery methods to technologies based on thermochemical sewage sludge processing and P recovery from sewage sludge ashes [75,76]. Unfortunately, in many counties, this method of processing sewage sludge is not common due to economic, environmental, social or political reasons [77].

However, in recent years, an innovative technology called RAVITA was developed and applied at a small pilot plant in Helsinki Viikinmaki WWTP in Finland to respond to P recovery needs in chemically supported small and medium WWTPs. RAVITA enables P recovery as phosphoric acid (H_3PO_4), which can be used as a raw material in the fertilizer industry. Moreover, P recovery can be combined with N–NH_4 recovery by an air washer unit to obtain the final product in the form of a valuable fertilizer – ammonium phosphate ($(NH_4)_3PO_4$) [78]. Therefore, more research is needed

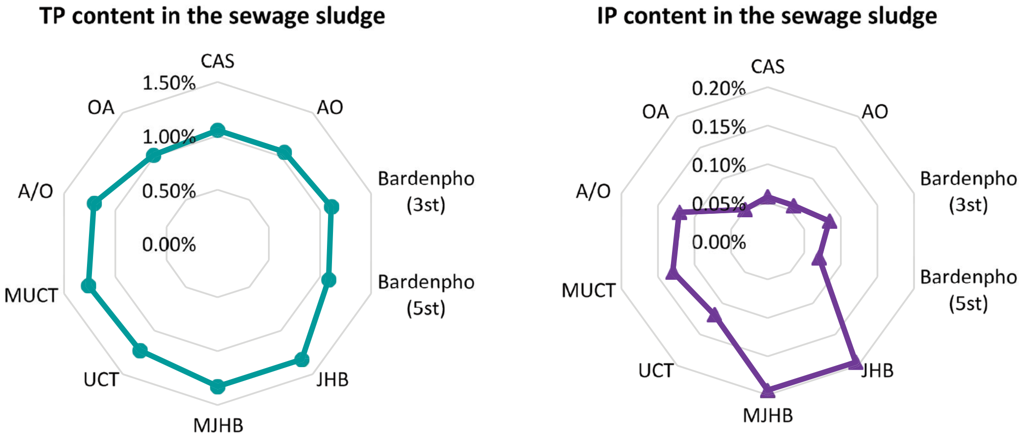

Fig. 5. P recovery potential based on (a) TP and (b) IP content in the sewage sludge.

to combine strict legal effluent limits (<0.5 mg TP/L) with the high bioavailability of nutrients in the sludge.

5. Conclusions

Regarding the limited P resources, the importance of sustainable P management focused on efficient P recovery from various waste streams including sewage sludge, seems to be one of the most prevalent global issues present in many counties. The current and future policy is foreseen to support P recovery methods, such as P recovery from wastewater and other waste streams by introducing strict legal regulations based on P discharge limits in WWTP effluents. In order to be prepared for the incoming P recovery-oriented approach, it is essential to assess its recovery potential. The ASM-based simulation allowed to investigate the P recovery potential of 10 different wastewater treatment systems based on AS technology. The recommended directions for P recovery from sewage sludge is to use efficient EBNR technologies such as JHB-based and UCT-based systems, which ensure low effluent P content, high TP content in the sewage sludge (from 1.33% of TP in JHB and MJHB systems and 1.26%–1.23% in MUCT and UCT systems) with the highest share of bioavailable P (from 0.19% of IP in JHB and MJHB systems and 0.13%–0.12% in MUCT and UCT systems). Other, less advanced AS systems can be considered with additional chemical P precipitation only when P recovery will be performed after mono-incineration of sewage sludge.

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