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Dynamics of the annual cycle changes in the bioavailable phosphorus forms share in excess sludge

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ABSTRACT

The objective of the research study was to define the changes in the phosphorus forms share in excess sludge, depending on the sludge temperature during the year. The share of phosphorus speciation forms in activated sludge was determined using the phosphorus sequential extraction scheme according to Golterman. Excess sludge was collected at six wastewater treatment plants. The results analysis of the annual cycle of phosphorus speciation in excessive sludge shows that during summer, when the average temperature of the sewage sludge is 20°C, the bioavailable fractions (Ca-EDTA and Na-EDTA) were dominant, whereas in winter in December and January when sludge temperature drops to 5°C, that is, the cardinal temperature for phosphorus bacteria, the number of bioavailable forms falls dramatically. Statistically significant effect of temperature on the shares of phosphorus speciation forms was demonstrated.

Keywords: Mobility forms; Phosphorus; Wastewater; Temperature

1. Introduction

Sewage sludge, being a waste generated in the process of wastewater treatment, is a source of numerous macro- and micro-elements [1,2]. The nitrogen content in the sludge ranges from 2.5% to 4.0% DW, phosphorus content (P_2O_5) from 2.2% to 4.7% DW, potassium content (K_2O) from 0.2% to 0.4% DW, calcium content (CaO) from 2.0% to 5.0% DW, magnesium content (MgO) from 0.5% to 1.0% DW [3,4]. Thus, municipal sewage sludge contains large amounts (with the exception of potassium) of nutrients necessary for plants. Sludge should be perceived as a recyclable, rich in biogenes feedstock for the production of bio-fertilizers. Using sewage sludge as a fertilizer is reasonable, since it is the simplest and least costly solution to the problem of how to dispose of such waste. It can also be successfully used for the reclamation of degraded soils [5]. Therefore, small, mechanical-biological waste treatment plants generating waste with potentially low levels of heavy metals should aim to implement measures for biological utilization of sewage sludge [6]. One of sewage sludge utilization methods involves using it for agricultural purposes. According to Gawdzik et al. [7] heavy metal content in sewage sludge is associated, that is, with the type of industry in the area in which the sewage treatment plant operates.

In Poland, sewage sludge may be used for natural purposes, that is, when its heavy metal content is low. The permissible contents of heavy metals in sludge are determined by the Regulation of the Minister of the Environment of February 6, 2015 on municipal sewage sludge (Table 1) [8].

According to forecasts by the International Fertilizer Manufacturers Association (IFA) reserves of natural phosphate deposits can come to an end within 60–240 y [9]. This estimation may be affected by a value of birth rate since the increasing number of the world's population will generate a growth in the crop production and consequently an increase in the demand for fertilizers. Therefore, the use of sludge for biological purposes (from an economic point of view) is an alternative solution to reduce the use of phosphorous

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Table 1
Maximum amount of heavy metals in sewage sludge for various purposes [8]

No	Metal	Heavy metal content in the sludge (mg/kg d.m.) not more than in applying municipal sewage sludge		
		Agriculture and land reclamation for agricultural purposes	Land reclamation for non-agricultural purposes	Adaptations of the land[a]
1	Cd	20	25	50
2	Cu	1,000	1,200	2,000
3	Ni	300	400	500
4	Pb	750	1,000	1,500
5	Zn	2,500	3,500	5,000
6	Hg	16	20	25
7	Cr	500	1,000	2,500

[a]Adaptation to the specific needs of waste management plans, zoning plans, or land development decision, plants to produce compost, plants for non-food or non-feed purposes.

mineral fertilizers. The main problem is to obtain the sludge of appropriate quality [10]. Sludge should be stable and conform to the standards regarding heavy metal content and hygienic sanitary conditions. The final form of sludge formed in the technological process at the wastewater treatment plant is an excess sludge and this particular sludge can be used for biological purposes provided the sanitary requirements are met. The content of phosphorus – an important biogene – in the excess sludge is also an important facet with regard to its utilization. Detailed information on the potential possibility of this element being assimilated by plants is provided by speciation analysis [11]. It consists in the application of procedures permitting qualitative and quantitative identification of the phosphorus forms in the examined sample through the usage of increasingly stronger reagents in the sequential extraction [12]. There are many methods of speciation analysis of phosphorus in soils and sediments [13]. One of them – the Golterman method [14] – has been adapted by the authors to determine the phosphorus forms in sewage sludge [15]. The Golterman method was also used to assess the content of the bioavailable fraction of phosphorus in sewage sludge, among others by Wang et al. [16]. This speciation method is innovative due to the usage of chelate reagents in the analysis. The use of these reagents can shorten the time of fractionation and stop a change in pH, and thus prevent phosphate hydrolysis and dissolution.

The paper discusses the changes in the bioavailable forms share of phosphorus in excess sludge, depending on the sludge temperature, which may vary considerably during the year. Sewage sludge temperature is directly affected by air temperature and indirectly by the size of the wastewater treatment plant [17]. The lower temperature in smaller sewage treatment plants may be caused by small cubic capacities of open bioreactors. The temperature of sludge is important for the biochemical processes occurring therein. Increased sludge temperature enhances the decomposition of organic compounds [18]. The decrease in the sludge temperature is observed to be accompanied by the inhibition of the sewage purification process, which is associated with a reduced microbial activity and even the death of organisms present in the sludge. According to Chen et al. [19] bacterial community structure is significantly correlated with temperature of sewage sludge. They demonstrated that at a low temperature (15°C), in sewage sludge proliferated species of microorganism different than at a high temperature (25°C). They also showed the effect of temperature on the removal of phosphorus. The increase in temperature by 5°C (from 20°C to 25°C) resulted in the decrease in phosphorus removal efficiency from 89.31% ± 1.86% to 63.11% ± 3.86% ($p < 0.01$). Then the temperature drop by 5°C (from 20°C to 15°C) led to the increase in phosphorus removal efficiency from 89.17% ± 2.63% to 90.22% ± 6.21% ($p < 0.01$). Chen et al. [19] explained this phenomenon by the temperature effect on changes in the composition of bacteria belonging to PAOs (polyphosphate-accumulating organisms) and GAOs (glycogen accumulating organisms). Low temperatures then favoured the dominance of phosphorus accumulating bacteria (PAOs). Lopez-Vazquez et al. [20] studied the effect of various carbon sources (variable ratios of acetate to propionate), temperature and pH on competition between polyphosphate and glycogen accumulating organisms (PAOs and GAOs, respectively). They also observed that at lower temperature (10°C) PAOs were the dominant microorganisms, regardless of the applied source of the influencing carbon or pH. Then at 30°C microorganisms from the GAOs group were the dominant ones. According to literature reports, a temperature higher than 20°C already deteriorates the process of increased biological dephosphatation. This deterioration is associated with the dominance of GAOs [21,22]. In lake sediments the same direction of temperature effect on phosphorus release was also noted. Jensen and Andersen [23] showed that an increase in temperature significantly affects the release of phosphorus from lake sediments. Studying four lakes whose temperature was about 7°C in January and 21°C in July they found that at 21°C the concentration of the released phosphorus was from 5 to 13 times higher than at 7°C. Since the effect of the sewage sludge temperature on the dephosphatation processes is very important, the article attempts to provide a speciation analysis of phosphorus in excess sludge, in which the sewage sludge temperature may range from 5°C to 20°C.

2. Object of investigation

The study focussed on the excess sludge from six wastewater treatment plants (Table 2).

All the analyzed sewage sludge samples were taken from sewage treatment plants located in the Świętokrzyskie Province (in Poland). The distances between sewage treatment plants ranged from 20 to 40 km. These plants did not agree to reveal the names of the facilities, therefore in this paper they are identified by a letter of alphabet.

3. Methodology used

The samples of the excess sludge were collected at monthly intervals. Each designation was performed time times. The content of different phosphorus fractions was determined in the collected samples using the Golterman fractionation scheme [14]. This method is a sequential extraction scheme, wherein after each extraction step the sample is filtered and treated with another extractant. All the extractions were performed at room temperature. In the first step a 15 cm^3, sludge sample is subjected to the extraction with a Ca-EDTA solution for 4 h. In the second stage, the residue left after the first stage is subjected to the extraction with a solution of Na-EDTA for 18 h. The next step involved the extraction of the sample with a H_2SO_4 solution for 2 h. The last, fourth step of the sequential extraction lasted for 2 h and involved the use of the NaOH solution for the extraction (Table 3).

According to Golterman, the fractions of Ca-EDTA and Na-EDTA, that is, phosphorus adsorbed on the surface of sludge particles are mobile forms (of the highest bioavailability, which can be directly assimilated by the plants).

The determination of total phosphorus in the extracts (obtained according to Golterman method) was performed by spectrophotometric method using a UV-Vis Perkin Elmer spectrophotometer. The measurement was performed in accordance with the procedure for determining orthophosphates with the use of phosphate-molybdenum blue and for determining general phosphorus after prior oxidization of the sample with potassium peroxodisulfate (VI) [24].

Table 2
Characteristics of sewage treatment plants

Facility	SRT (day)	Organic matter in excess sludge (% d.w.)	Nominal capacity (m^3/d)	Biological purification	Chemical purification	Sewage system
A	11	72.5	900	Three-phase activated sludge method	–	Combined system
B	12	69.1	1,200	Three-phase activated sludge method	–	Combined system
C	10	64.8	300	Three-phase activated sludge method	–	Combined system
D	11	69.7	500	Combination of a three-phase activated sludge method and the swirl biofiltration	–	Combined system
E	10	62.3	500	Three-phase activated sludge method	lime	Separate system
F	20	60.4	72,000	Involves a three-phase activated sludge method	PIX and PAX	Separate system

Table 3
Extraction scheme according to Golterman [12]

Stage	Type of extractant and conditions of extraction	Fraction
1	0.05 M Ca-EDTA, 4 h	Ca-EDTA-P Phosphorus associated with oxides and hydroxioxides of iron, aluminum and manganese
2	0.1 M Na-EDTA, 18 h	Na-EDTA-P Phosphorus associated with carbonates
3	0.5 M H_2SO_4, 2 h	Phosphorus found in soluble combinations with organic matter
4	2 M NaOH, 2 h	Remaining phosphorus, including the one combined with aluminosilicates and contained in the organic matter in the form of combinations that are not subject to the sulfuric acid activity in step 3

4. Results and discussion

Phosphorus speciation analysis in excess sludge from wastewater treatment plants illustrates the change in the share of mobile forms of phosphorus per year (Fig. 1, Table 3). Mobile forms of phosphorus are the sum of phosphorus contained in the Ca-EDTA and Na-EDTA fractions. Based on these results it can be concluded that the temperature of the sludge is an important parameter influencing the speciation forms shares of this element. The temperature of sewage sludge from the wastewater treatment plants *A*, *B*, *C*, *D*, and *E* was significantly lower in winter than the temperature of the sludge from a wastewater treatment plant *F*. Sludge temperature may be affected by many factors, including wastewater treatment technology, the type of sewage system, the volume of reactors and, above all, air temperature [25,26]. The lowest sludge temperature was recorded in January, when it averaged at 5.5°C in the small wastewater treatment plants, while the temperature of the sludge in the large wastewater treatment plants was 10.5°C.

In all the examined excess sludge the bioavailable fractions (Ca-EDTA and Na-EDTA) were dominant in the summer (in August the average share of the mobile forms amounted to 70%–85%).

A similar direction of changes in the phosphorus fraction shares was observed by Jensen and Andersen [23], who, using the Hieltjes–Lijklema sequential extraction method, observed an increase in the exchangeable phosphorus

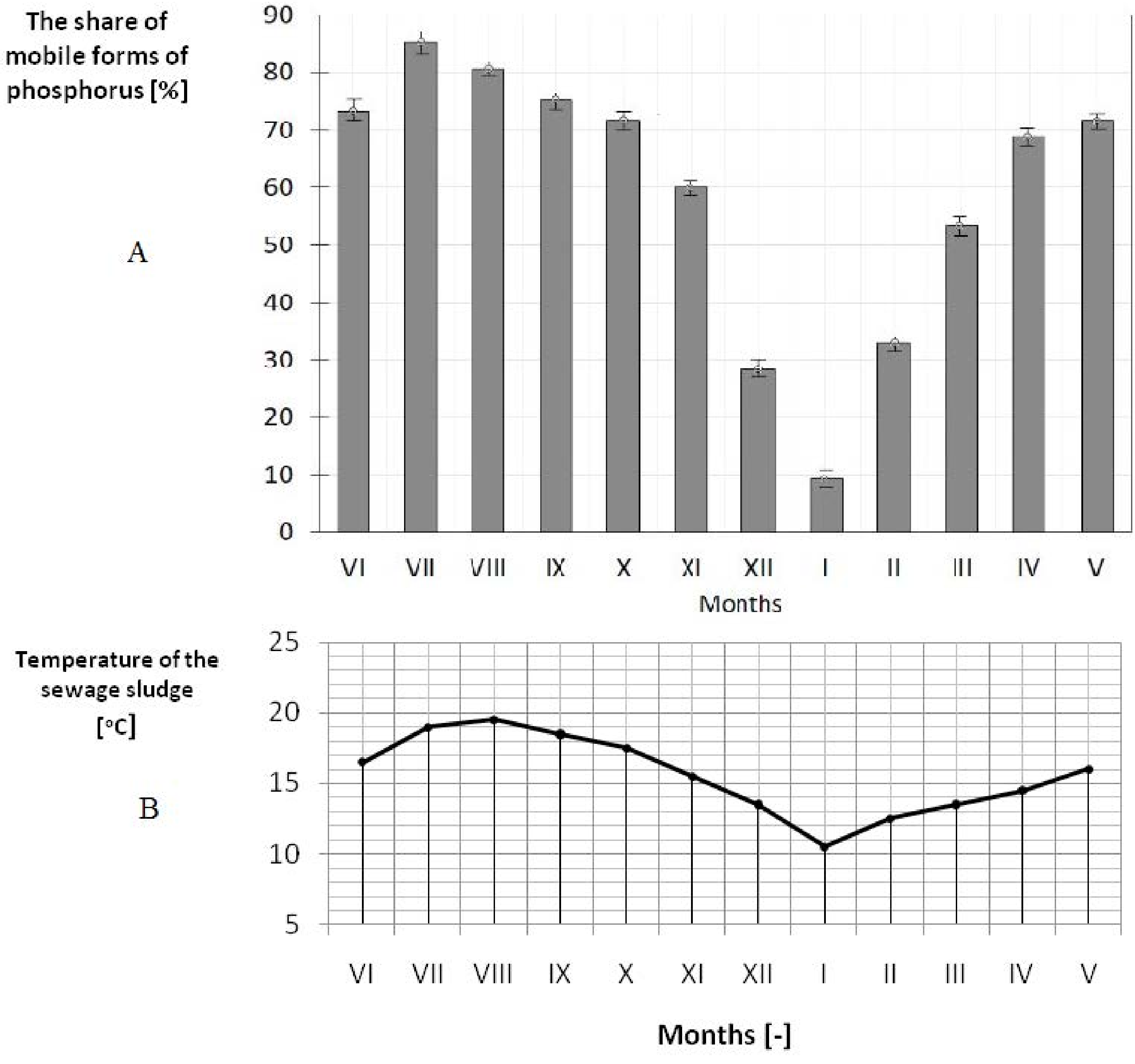

Fig. 1. Changes in the parameters of the excess sludge from the wastewater treatment plant *F* in the annual cycle ((a) changes in mobile forms shares and (b) changes in the sludge temperature).

fraction with an increase in temperature. The fraction of exchangeable phosphorus can be fully identified with the bioavailable fraction. Jensen's research concerned lake sediments. Analogous results concerning the increase in the share of bioavailable fractions in the summer, in the case of the study of the balance of phosphorus release from lake sediments, were obtained by Liu et al. [27] and Gomez et al. [28]. In the autumn and winter, along with a decrease in ambient temperature, the shares of these bioavailable fractions decreased (in January the average shares of mobile forms were only 9%–32%).

The dominant fractions of phosphorus in the autumn and winter were therefore fractions of H_2SO_4 and NaOH or hard available phosphorus fractions (Fig. 2). The H_2SO_4 and NaOH fractions are organic phosphorus or aluminosilicate fractions [14]. Organic phosphorus in sewage sludge can be accumulated in microorganism cells or contained in organic matter, which can account for 75% to 85% of d.w. of raw sludge [29]. According to literature reports, 10°C is the temperature at which PAOs bacteria [20,30], characterized by increased phosphorus accumulation, become dominant. This could explain the predominance of organic phosphorus forms (H_2SO_4 and NaOH)) identified, that is, with phosphorus accumulated in bacterial cells. A significant predominance of the organic phosphorus fraction in winter may also be attributable to reduced decomposition of organic matter at low temperature [30]. The wastewater that flows into the treatment plants contains significant amount of phosphorus present in organic matter [31]. Zhang et al. [32] studied the share of different phosphorus fractions in primary sludge, both activated and digested. The organic fraction of this element accounted for 70% of the phosphorus contained in the primary sludge. A separate analysis of research results [33] showed that, despite temperature changes, the dominant fractions were those of hard-to-access phosphorus (H_2SO_4 and NaOH), which is also identified with organic phosphorus. This pool of organic matter in primary sludge is subjected to biological treatment. This process involves microorganisms included in the activated sludge, producing enzymes that catalyze various chemical reactions [34]. These reactions consist in the breakdown of multi-molecular compounds such as

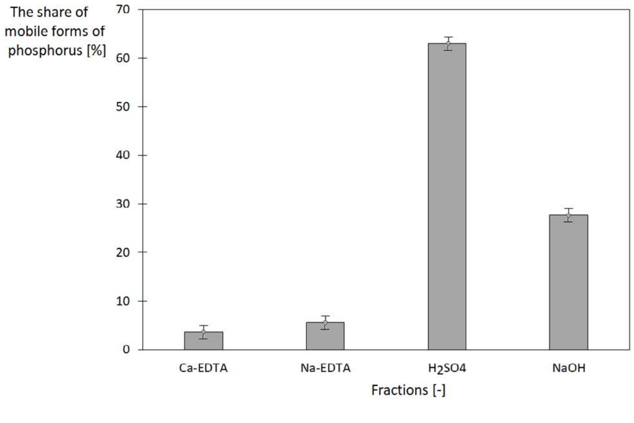

Fig. 2. Phosphorus speciation forms share in the excess sludge collected in January from the wastewater treatment plant *F*.

proteins, carbohydrates, fats to final inorganic products, that is, CO_2, H_2O, NO_3^-, PO_4^{3-}, SO_2^{2-}. Simultaneously, some compounds are used to synthesize microorganism biomass [35]. In the process of organic compound breakdown the enzymatic reactions are of particular importance. Zhang et al. [32] performed phosphorus analysis by ^{31}P NMR, which shows that organic phosphorus forms such as phosphate mono and diesters predominated in the primary sludge and amounted to 78% of total phosphorus. The splitting of these esters is determined by the activity of phosphatase enzymes [36]. In turn, the rate of enzymatically catalysed reactions – according to the van't Hoff rule – rises 2–3 times with temperature increase by 10°C [37]. In winter low sludge temperatures (Table 4) may cause a decrease in the rate of enzymatic reactions (both catalyzing the breakdown of phosphate esters and multi-molecular compounds). This phenomenon may be accountable for reduced phosphorus release from sludge in winter [23,27,28], which is confirmed by the negligible share of phosphorus bioavailable forms (Ca-EDTA and Na-EDTA fractions) in January (Table 4). To sum up, many factors may be responsible for the dominance of hardly soluble phosphorus fractions in winter, that is, increased accumulation of this element in the cells of the PAOs bacteria. Another likely factor may be a decrease in the rate of enzymatic reactions, which are important in the mineralization of organic substances.

Thus, with the reduction of the sludge temperature, the endogenous decomposition rate of organic compounds is reduced, causing the organic matter in the sludge to increase. In the winter, in the month of January when the sludge temperature drops to an average of 5.5°C, that is, the cardinal temperature for most bacteria, the number of bioavailable forms decreases dramatically. Although in January the temperature of the sludge from a large wastewater treatment plant *F* does not fall below 10°C (Fig. 2) the mobile forms share in the sludge is the lowest (9%). This may be connected with the dosing of coagulants, which are conducive to sedimentation. In the case of the *F* treatment plant, PIX and PAX coagulant were dosed. Liu et al. [27] studied the release of phosphorus from coprecipitants formed during the removal of orthophosphate using Fe (III) coagulation. They showed, that is, that the phosphorus release rate increased together with the rise in temperature, however, at 10°C the maximum release rate of this element was low at 1.4%. The low phosphorus release rate at this temperature may be accountable for the lower content of the bioavailable phosphorus fraction in the sludge from the *F* sewage treatment plant in January (Fig. 2) compared to the sludge from other treatment plants (Table 4).

In order to assess the impact of the wastewater treatment technology, wastewater treatment plant capacity, the dynamics of biochemical processes in the bioreactor on the share of mobile forms of phosphorus in sludge, a cluster analysis was performed. The final result is a dendrogram, a tree diagram illustrating the arrangement of clusters, permitting an easy graphical depiction of the analyses results. In order to depict the proximity of the analyzed objects, a specific distance measure is used. In most cases the conducted analyzes took advantage of the metric called the Euclidean distance which, in the case of the comparable water treatment plants, modeled by the *p*-string of two real normalized variables

Table 4
Parameters of excess sludge from selected wastewater treatment plants *A–F* (m.f.s.-share of mobile forms of phosphorus, *T* – temperature)

Months	Sewage treatment plants											
	A		*B*		*C*		*D*		*E*		*F*	
	m.f.s. (%)	*T* (°C)	m.f.s. (%)	*T* (°C)	m.f.s. (%)	*T* (°C)	m.f.s. (%)	*T* (°C)	m.f.s. (%)	*T* (°C)	m.f.s. (%)	*T* (°C)
I	32	6	22	5	28	5.5	19	5	25	5.5	9	10.5
II	42	8	33	8	38	9	33	8	41	7.5	33	12.5
III	46	12	50	11.5	48	12	43	11.5	52	10.5	53	13.5
IV	59	13.5	62	13	77	13	63	13	62	12.5	69	14.5
V	72	16.5	65	16	70	16.5	68	16.5	66	14	72	16
VI	61	16	72	17.5	68	17	70	16.5	68	16.5	73	16.5
VII	68	18.5	80	19	80	18.5	76	18.5	71	18	85	19
VIII	71	19.5	83	19.5	84	19	80	19.5	75	18.5	81	19.5
IX	64	16	62	15.5	71	16.5	68	16.5	69	16	75	18.5
X	61	15	57	14.5	61	14	64	14	62	13	72	17.5
XI	59	12	56	11.5	54	12.5	46	12	43	11	60	15.5
XII	45	8	37	7.5	33	7	31	7	30	7	29	13.5

(sludge temperature and mobile forms share) is described by the formula [38,39]:

$$d(x,y)=\sqrt{\sum_{i=1}^{p}(x_i-y_i)^2} \quad (1)$$

in which *p* represents the duration of the research period in months, *x*, *y* are the share of mobile forms of phosphorus in the WWTP.

In order to determine the distance between the emerging clusters, the popular single bond method was applied. The results of the conducted calculations are shown in Fig. 3. The presented dendrogram (Fig. 3) shows that the examined wastewater treatment plants differed from each other. The mechanical-biological wastewater treatment plants *A*, *B*, *C*, and *D* had a similar sludge temperature and mobile forms shares in the analyzed period.

In winter (November, December) the mechanical-biological-chemical wastewater treatment plant *E* had a lower mobile forms share in the sludge than the mechanical-biological plants *A*, *B*, *C*, and *D* whereas the sludge temperature in plant *E* was similar to that in mechanical-biological plants. The similar temperatures of the sludge from *A*, *B*, *C*, *D*, and *E* may confirm that the sludge temperature depends on the cubic capacity of the reactors, since the nominal capacity of these plants does not exceed 1,200 m³/d. Therefore, the wastewater treatment plants *A*, *B*, *C*, *D*, and *E* form cluster I. Dissimilar values of the mobile forms shares in plant *E*, on the other hand, may indicate the impact of the precipitating agent (lime), which is used in this plant alone. In the case of the mechanical-biological-chemical treatment plant *F*, the sludge temperatures were higher than in other objects during the examination period. Higher temperatures of the excess sludge that even in the winter did not fall below 10°C and the nominal capacity of the wastewater treatment plant

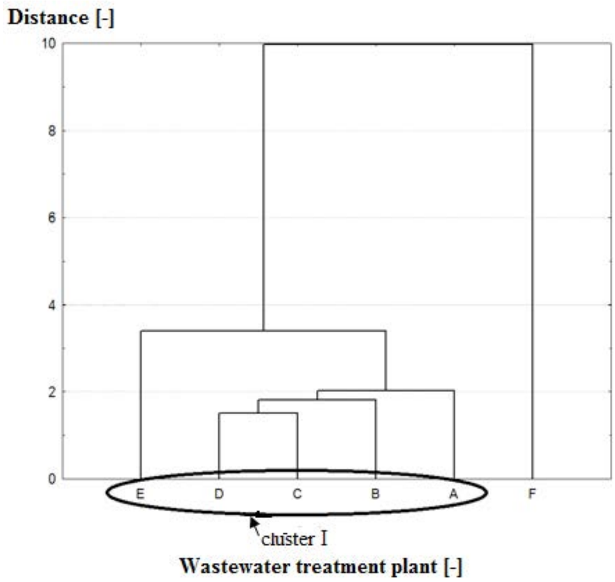

Fig. 3. Dendrogram for the analyzed wastewater treatment plants.

amounting to 72,000 m³/d may indicate the impact of the reactors' capacity on their thermal stability. Thus, a larger reactor's capacity is more favorable due to the thermal and biological stability of the sludge.

Moreover, from June to November, the mobile forms share in the sludge was higher than in the other objects, whereas in January and February it was lower. It may be directly connected with the application coagulants PIX and PAX in this plant alone.

The next stage involved an attempt to develop a mathematical model illustrating the relations between the mobile

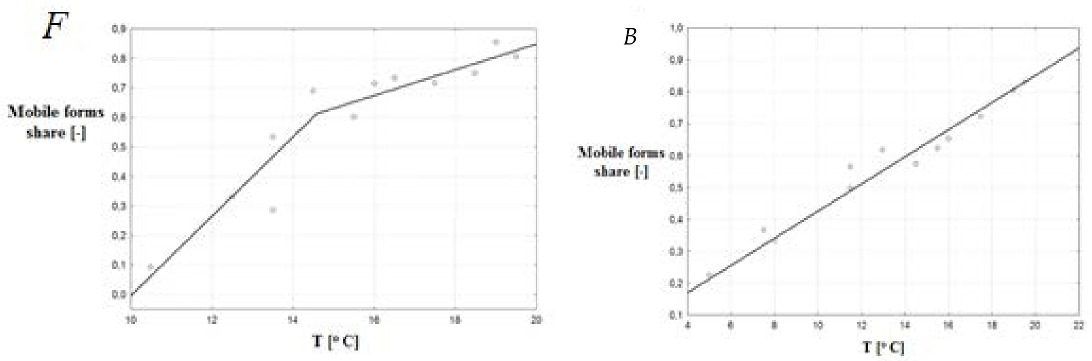

Fig. 4. Relation m.f.s = *f*(*T*) for the wastewater treatment plant *F* and *B*.

Table 5
Values of the parameters (α_0, α_1, α_2, T_{gr}) of the equation m.f.s = *f*(*T*) for the wastewater treatment plants *F* and *E*

Sewage treatment plants	Parameters				R^2
	α_0	α_1	α_2	T_{gr}	
F	–1.353 (±0.3570)	0.135 (±0.0270)	–0.091 (±0.0350)	14.573	0.953
E	0.016 (±0.0001)	0.045 (±0.0040)	–0.034 (±0.0140)	14.832	0.975

forms shares (m.s.f) and the sludge temperature (*T*). Taking into account the recorded observations (Fig. 4), this relation was described using the piecewise regression [40]:

$$\text{m.f.s.} = \begin{cases} \alpha_0 + \alpha_1 \cdot T \quad dla \quad T < T_{gr} \\ \alpha_0 - \alpha_2 \cdot T_{gr} + (\alpha_1 + \alpha_2) \cdot T \quad dla \quad T > T_{gr} \end{cases} \tag{2}$$

where α_0, α_1, α_2 are the model's empirical parameters estimated by Levenberg–Marquardt method, T_{gr} is the border temperature corresponding to the change of the relation m.f.s = *f*(*T*).

The performed calculations show that the dependency m.f.s = *f*(*T*) is described by the Eq. (1) in the case of biological-chemical treatment plants *E* and *F* (Fig. 4) and the values of the determined parameters α_i as well as the standard deviations and probabilities are presented in Table 5. In other cases, the relation m.f.s = *f*(*T*) was linear and was described by Eq. (1a), in which it was adopted that $\alpha_0 = 0$, the results of the calculations are presented in Table 6. Moreover, Fig. 4 include the exemplary results of the measurements and calculations m.f.s = *f*(*T*) for the wastewater treatment plants *F* and *B*.

As demonstrated above (Tables 5 and 6), the values of the α_i parameter differ considerably in the two analyzed treatment plants. It is worth noting that T_{gr} values are similar and change within the scope 14.573°C – 14.832°C, which means that with regard to practicality below app. 14.7°C further decline in temperature entails such a dramatic decrease in the mobile forms share. Therefore, with regard to the changes in bioavailable phosphorus forms share, as far as the potential usage of excess sludge for the biological purposes is concerned, one should not allow the temperature to drop below 14.5°C in the examined mechanical-biological-chemical wastewater treatment plants.

Table 6
Values of parameter α_1 in the equation m.f.s = *f*(*T*) for the wastewater treatment plants in cluster I

Sewage treatment plant	Parameter	Coeffecient of determination
	α_1	R^2
A	0.041 (±0.015)	0.985
B	0.043 (±0.008)	0.990
D	0.043 (±0.001)	0.998
C	0.042 (±0.001)	0.995

Based on the results presented in Tables 5 and 6, it can be concluded that in small mechanical-biological wastewater treatment plants (*A*, *B*, *C*, *D*, *E*) located in Świętokrzyskie Province (Poland) the value of the α parameter ranged within 0.041 – 0.043. Moreover, the calculations reveal that as the sludge temperature grew by 1°C the mobile forms share contained in the sludge increased on average by 0.042.

5. Conclusions

The research paper presents the results of the studies concerning bioavailable phosphorus fractions share in the excess sludge from six wastewater treatment plants.

The results of the studies permit the following conclusions:

- temperature is the factor which has a statistically significant effect on the changes in the mobile forms shares in the sewage sludge. The higher the excess sludge temperature the higher the mobile phosphorus forms share.

- As the temperature rises, the share of phosphorus mobile fractions (Ca-EDTA and Na-EDTA) increases and the share of hard-to-access fractions (H_2SO_4 and NaOH), which are identified, that is, with phosphorus contained in organic matter, decreases. The temperature increase probably causes the acceleration of metabolic activity of phosphorus bacteria and therefore increases the intensity of the enzymatic hydrolysis process. In summer higher sludge temperatures (up to 20°C) may cause an increase in the rate of enzymatic reactions (both catalyzing the decomposition of organic substances containing, that is, phosphorus), which may be one of the reasons for an increased phosphorus release from sludge in the summer [23,27,28].
- This hypothesis is confirmed by insignificant shares of hard-to-access phosphorus forms in winter.
- depending on the existing technological conditions, the different examined sewage sludges are characterized by different shares of the particular phosphorus speciation forms, which may indicate that each sludge has an individual chemical composition depending on the applied wastewater treatment technology. However, one can observe the similarities in the case of small mechanical-biological treatment plants. During the examination period the excess sludge from those treatment plants were characterized by both, a similar sludge temperature and the mobile forms share. The research paper examined also phosphorus speciations from two biological and chemical wastewater treatment plants.
- The excess sludge from two mechanical-biological-chemical wastewater treatment plants had different phosphorus mobile forms shares depending on the applied precipitating agent (PIX and PAX or lime).
- Considering that the examined excess sludge came from merely two biological-chemical sewage treatment plants, the results obtained from treatment plants *E* and *F* should be treated as the results of preliminary tests which need to be continued with more sludge samples from other treatment plants using similar treatment methods.

The knowledge on the quantitative shares of mobile phosphorus fractions in different types of sewage sludge is essential for the application of the particular excess sludge for biological purposes. Therefore, bearing in mind the changes of bioavailable phosphorus forms shares during the year, with regard to the potential use of the excess sludge for fertilization purposes, it is possible to define the temperature the reduction of which would significantly reduce the bioavailable forms share of the analyzed element. Thus, the regression analysis allows determining the optimum temperature of the wastewater treatment process at which one can obtain a relatively high share of mobile phosphorus forms while maintaining a relatively low cost of operating the plant.

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