Auto - abstract about achievements in scientific-research, didactic and organizational activity

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1. Full Name

Agnieszka Elwira Tuszyńska

2. Diplomas and academic degrees

2001 - obtaining a master's degree in environmental engineering with the specialization in sanitary engineering at the Faculty of Hydraulic Engineering and Environmental Engineering at the Gdańsk University of Technology (currently: Faculty of Civil and Environmental Engineering), master's thesis "Project of a sewage treatment plant for the village of Bryzgiel about PE = 1000 lying in the Wigry National Park "

2005 - obtaining a doctor’s degree of technical sciences in the field of environmental engineering with the specialization in water and wastewater technology at the Faculty of Civil and Environmental Engineering at the Gdańsk University of Technology, title of the doctoral dissertation "The influence of organic matter on oxygenation and efficiency of removing pollutants in hydrofit beds"

3. The course of employment in scientific units

2001 - 2005 - PhD student's position of the PhD Study "Geotechnics and Environmental Engineering" at the Faculty of Hydraulic Engineering and Environmental Engineering (currently the Faculty of Civil and Environmental Engineering) of the Gdańsk University of Technology

2006. - 2008. - assistant position at the Department of Water and Wastewater Technology at the Faculty of Civil and Environmental Engineering at the Gdańsk University of Technology

2006. - 2008. – adjunct position at the Department of Heating and Ventilation at the Faculty of Civil and Environmental Engineering of the University of Technology and Agriculture (currently: Faculty of Civil and Environmental Engineering and Achitecture, University of Technology and Life Sciences in Bydgoszcz)

2008. - 2012 - adjunct position at the Department of Water and Wastewater Technology at the Faculty of Civil and Environmental Engineering at the Gdańsk University of Technology

2011 - 2017. - position of an academic teacher at the Engineering Faculty of the College of Environmental Management in Tuchola

2012 - currently - adjunct position at the Department of Sanitary Engineering at the Faculty of Civil and Environmental Engineering at the Gdańsk University of Technology

4. Identification of an achievement resulting from article 16, section 2 of the act on academic degrees and titles and about degrees and titles in the field of fine arts of march 14, 2003 (Journal of Laws January 19, 2018, item 261).

a) Title of achievement

Analysis of the possibility of using digestate as a source of bioavailable phosphorus

b) Publications included in the achievement

Monograph:
Tuszyńska A. (2019) Analysis of the possibility of using digestate as a source of bioavailable phosphorus. Monographs of the Committee of Environmental Engineering of the Polish Academy of Sciences, no. 153, Warsaw 2019, 201s., ISBN: 978-83-63714-52-9

c) Discussion of the scientific purpose of the a.n. work and the results achieved together with presentation of their possible use

Biogas production technology is seen as one of the most forward-looking solutions in the waste management sector and alternative renewable energy production. In 2016, the number of biogas plants in Europe was over 17 thousand (with a total installed capacity of approximately 8,300 MWe), the majority of which are agricultural biogas plants. The developed countries are responsible for 80% of biogas production in Europe: Germany, Italy, France and Great Britain (Scarlat et al., 2018). In Poland, biogas plants are mainly associated with sewage treatment plants using anaerobic stabilization of sewage sludge. Currently, as in other EU countries, there is a significant increase in the number of agricultural biogas plants using organic substrates, mainly animal-farming and agri-food production waste. According to data from 2018, approximately 400 million m3 of agricultural biogas was produced in Polish agricultural biogas plants, and the total capacity of the installation was 100.6 MWe (National Center for Agricultural Support, KOWR, 2018). This amount will grow systematically due to the development of agricultural production and intensification of agri-food production and processing. The growing number of agricultural biogas plants not only in Europe but also in the world means at the same time an increase in the load of side products of the fermentation process in the form of digestate pulp (called digestate). The side products of the fermentation process in agricultural biogas plants are a greater problem for the natural environment than municipal biogas plants (usually located in the sewage treatment plant and waste treatment plants). Municipal facilities were imposed the obligation to develop and digest digestate primarily through dewatering, drying and thermal combustion. While agricultural biogas plants face both the problem of overproduction of digestate and its improper utilization (Svoboda et al., 2013). In practice, this usually means its excessive infiltration

in soils leading to excessive loading of biogenic compounds and sometimes their undesirable infiltration into groundwater.

Due to the need to increase the share of renewable energy in the energy balance and reduce the use of fossil fuels, it is necessary to carry out research on not only increasing the efficiency of the process or the use of different types of substrates, but also research to reduce the potential negative impact of facilities processing different types of waste. According to the principles of a circular economy, energy production should be associated with minimizing the negative impact of side products of the fermentation process. Further investments related to the development of biogas plants require searching for solutions to the digestate problem.

The paper analyzes the possibility of using digestate as a source of phosphorus. Limiting the availability of this element from non-renewable sources encourages the search for alternative sources of phosphorus, e.g. from sewage, municipal and industrial sludge as well as from digestate. This is in accordance with the principles of clean production, where the waste is processed into a product, or it is possible to recover valuable raw materials from it. Due to the depletion of natural sources of phosphorus (which is accompanied by an increase in the prices of phosphorous raw materials) issues related to the search for alternative sources of phosphorus are very important.

Previous research results have been limited to the recovery of phosphorus from the digestate or the post-fermentation effluents produced during the fermentation of sewage sludge or municipal waste in municipal biogas plants. In the case of agricultural biogas plants, literature reports describing the recovery of biogenic compounds concerned a narrow group of agricultural waste. The most commonly studied group of wastes was animal faeces or dairy waste. The use of digestate for the recovery of phosphorus resulting from the fermentation of other substrates of agricultural and food origin is not fully recognized.

The aim of the work was to recognize the mobility of phosphorus compounds and the possibility of their recovery in a bioavailable form from digestate. The implementation of the work objective required testing of substrates - the so-called batch components (including animal waste, agricultural waste and food waste) and side products obtained as a result of their fermentation. Research was conducted on the effect of the fermentation process on the transformation and mobility of phosphorus compounds in the solid fraction, followed by assessment of the quality of leachate in terms of the possibility of phosphorus precipitation in the bioavailable form (struvite) as well as the evaluation of the fertilization potential of the digestate fraction.

Achieving the work objective required the following tasks:

1) assessment of the impact of batch components on the quality of fermentation side products (solid fraction of digestables and post-fermentation leachates);

2) speciation analysis of phosphorus compounds in raw materials and side products of the fermentation process;

3) quality assessment of leachate in the aspect of the possibility of precipitation of the bioavailable form of phosphorus;
4) definition of fertilization values of post-fermentation fractions.

I conducted the tests in two facilities on a technical scale (agricultural biogas plant Kożanówka and agricultural biogas plant Przypisówka, located in the Lublin province) and pilot plant (in the fermentation chamber at the Institute of Chemistry and Nuclear Technique, ICHTJ in Warsaw). I have tested selected agri-food waste, including beet pulp, apple pomace, cow's slurry, distillery, maize silage and mixtures of individual substrates introduced into fermenters and digestate obtained from the fermentation of individual monosubtrates and batch components. The post-fermentation samples were then subjected to mechanical separation into a solid fraction and a liquid fraction (post-fermentation effluents).

Ad. 1. The impact of batch components on the quality of fermentation side products

In order to assess the batch components for the quality of fermentation side products, I made the following physico-chemical tests:
a) in batch components and solid fraction of digestables - dry matter content and total organic mass, Kiejdahl nitrogen, magnesium ions, calcium, potassium, iron and pH;
b) in post-fermentation leachates - a total suspension and an organic suspension, chemical oxygen demand (COD), nitrogen compounds (NH4-N, Nog), Mg, Ca, K, Fe ions and pH.

The content of dry matter in the analyzed samples of substrates varied within a wide range: from about 3% to over 30% d.m. I observed the lowest content of dry matter in samples of distillery and cow’s slurry. While samples of maize silage and substrate mixtures with the predominant share of this raw material were characterized by a several times higher content of dry matter. In addition, the substrates were characterized by both high content of organic matter in the dry matter as well as its similar share. The average content of organic matter in the substrates was nearly 80.0%, and the remaining approx. 20.0% were mineral substances. Regarding the solid fraction obtained from the fermentation of substrates, the highest share of organic matter in the dry matter was found in the fermentation of agricultural waste (about 70.0 - 80%), and the lowest (55.0 - 65%) from the fermentation of food waste, i.e. from raw materials showing high biodegradability (fruits and vegetables). It is widely believed that the solid fraction of digestate contains high concentrations of organic matter, while post-fermentation effluents constitute a rich source of nitrogen compounds and other nutrients (Tambone and Adani, 2017). Nevertheless, I showed that the post-fermentation effluents also contained high concentrations of organic matter and suspension. The dry matter content in the liquid fraction of digestables varied from 4.0 to approx. 10.0%, while the content of organic matter from 20.0 to more than 40.0%, and the value of the proportion of organic matter to dry matter from 60% to over 70.0%. The concentration of organic matter expressed in COD in the post-

fermentation effluents varied within a wide range (from 3.5 to almost 16 gO_2/L), with COD concentrations being related to the origin of the digestate. The highest values of COD concentrations were recorded in the effluents from the fermentation of distillery or animal faeces, and the lowest in the leachates from the fermentation of fruit and vegetable waste and lignocellulosic agricultural waste. I also observed that the co-fermentation of animal faeces with agri-food waste contributed to the increase in the concentration of COD in the effluents. The proportion of elements such as P, Mg, Ca, K and Fe was from 3 to 9 times higher in the solid fraction of digestate than in the post-fermentation leachate. While the most mobile element turned out to be N, whose share in the solid fraction of digestables was on average 20.0%. Definition of the content of total nitrogen and ammonium ions in the analyzed digestate fractions was important from the point of view of observing the maximum nitrogen doses during fertilization of agricultural land (150-250 kgN/ha·year, Directive 91/676 / EEC). The highest nitrogen content was recorded in samples of solid fraction of digestate from distillery, and the lowest values in samples from fermentation of waste with a predominance of fruit and vegetables. The dominant form of nitrogen in post-fermentation leachates was ammonium nitrogen formed during the hydrolysis of proteins and urea (feedstock components) during the fermentation process. A wide range of NH_4^+ ion concentration values in the liquid fraction of analyzed digestates was associated with the origin of raw materials subjected to fermentation. Feedstock materials, such as distillery and cow's slurry, were characterized by the highest nitrogen content of all raw materials analyzed. Therefore, I observed the highest values of NH_4^+ concentration in the effluents from fermentation of these wastes, and the lowest values were obtained for leachates from the fermentation of fruit and vegetable waste and lignocellulosic agricultural waste. I also observed that the co-fermentation of animal faeces or distillery with agri-food waste contributed to the increase in the concentration of ammonium ions in the effluents. Definition of concentrations of other macroelements (including potassium, magnesium, calcium and iron) in digestate effluents (which would be used for fertilization of green crops) is also important due to the avoidance of the existence of high fertilization with these elements of agricultural land (eg recommended values for potassium) to 100 kg/ha·year, Rollett et al., 2015). Potassium was characterized by the highest concentrations in post-fermentation leachates. The highest concentrations of Mg, Ca and Fe were observed in the leachates from the fermentation of cow's slurry (the values were respectively: 0.15 g/L, 0.27 g/L and 0.03 g/L). However, the values of Mg, Ca and Fe concentrations both in the leachates from fermentation of green fibrous waste (maize silage) as well as in the effluents from the fermentation of waste from the food industry (apple pomace and beet pulp) were several times lower. Determination of the nitrogen to phosphorus (N:P) value in the solid and liquid fraction of digestables was also important because of avoiding too high fertilization of agricultural land with phosphorus compounds (e.g. recommended values for phosphorus is 60 kg/ha·year, Rollett et al., 2015). The calculated N:P ratios were significantly lower in the solid fraction of digestables (values varied from 0.1 to 1.2) compared to post-fermentation

leachates (from about 2 to almost 6). Post-fermentation fractions were characterized by lower values of organic matter to nitrogen (MO:N) ratio as compared to the ratios for feedstock materials. The feedstock materials were characterized by MO:N values from about 12 to 30. The MO:N values in the solid and liquid fraction of digestables varied accordingly: from about 10 to 26 and from 3 to 6 and were close to the values presented in the literature (Tambone et al., 2017).

Ad. 2. Speciation analysis of phosphorus compounds in raw materials and side products of the fermentation process

The indicator that allows to assess the role of side products of the fermentation process as a secondary source of nutrients is the content of biologically available phosphorus. The literature review shows that the digestate fraction (solid fraction of digestate and post-fermentation effluents) from agricultural biogas plants constitute a phosphorus-rich fertilizer. Unfortunately, the research results are usually limited to the general phosphorus content in side products of fermentation, and there is very little data on the proportion of phosphorus compounds in the labile and bioavailable form for plants in individual digestate fractions.

The basis for the determination of individual combinations of phosphorus in substrates and solid fraction of digestates was the phosphorus fractionation scheme described in the Standards in Measurements and Testing (SMT) Program Extraction Protocol. In recent years, the most commonly used method of specifying phosphorus compounds (in wastes, sewage sludge, soil samples or bottom sediments of water reservoirs) is the harmonized SMT protocol (Standards in Measurements and Testing (SMT) Program extraction protocol), which has been approved by the European Commission as a postulated method for extracting specific forms of phosphorus (Pokhrel et al., 2018). Therefore, I have adopted this method of phosphorus speciation in feedstock materials and solid fraction of digestables. In this extraction method, phosphorus was divided into so-called organic phosphorus (OP fraction) and inorganic phosphorus, specifying its forms in combinations with Al, Fe, Mg and Mn oxides and hydroxides (as the NAIP fraction) and in combinations with Ca (as the AP fraction). The NAIP fraction represented unstable and highly soluble forms of phosphorus, such as struvite ($MgNH_4PO_4 \cdot 6H_2O$) and hydrated aluminum phosphate ($AlPO_4 \cdot 2H_2O$), and the OP fraction - a combination of phosphorus and organic matter, phospholipids, DNA, simple phosphate monoesters. The AP fraction represented forms of phosphorus with moderate to low solubility, i.e. dicalcium phosphate dihydrate ($CaHPO_4 \cdot 2H_2O$), poorly soluble hydroxyapatite ($Ca_5(PO_4)_2OH$), phytic acid salts and calcium phosphate (Ajiboye and Akrinremi, 2007; Turner and Leytem, 2004). However, in the analyzed digestate leachates, I determined the forms of organic and inorganic phosphorus in suspension and in dissolved form using the generally accepted method of determining phosphorus using vanadomolybdic acid. This method is used to determine the phosphorus fraction in sewage and water samples to assess the potential bioavailability of phosphorus and the risk of eutrophication (Li

and Brett, 2015). Using this analytical method, I distinguished between general phosphorus (TP), general dissolved phosphorus (TDP) and reactive and unreactive molybdate phosphorus in dissolved and suspended form (respectively: SRP and SNRP and PRP and PNRP fractions). Reactive molybdate phosphate in dissolved form is often equated with orthophosphate ions. In contrast, organic and the most condensed phosphorus compounds have been classified as unreactive molybdate phosphate (both in dissolved and suspended form) (Li and Brett, 2015).

On the basis of the conducted research, I proved that animal faeces and a distillery was the source of the highest total phosphorus content (sum of OP, NAIP and AP fractions) in comparison with other analyzed raw materials. In these wastes, the content of phosphorus was over 10 times higher than in the case of lignocellulosic waste (which is classified as agricultural waste) and with fruit and vegetable waste. I found the presence of phosphorus in both organic (OP) and inorganic (IP) forms in feedstock materials. In all analyzed waste groups, I observed the highest phosphorus content in the IP fraction, while the lowest in the OP fraction. Animal faeces were characterized by the content of inorganic phosphorus: about 25 mg/gd.m., and fruit and vegetable waste: about 2 mg/gd.m. Also phosphorus in the digestate fractions was mainly inorganic phosphorus and its content determined the feedstock biomass. Obtained results of the phosphorus speciation analysis in the digestate fractions were significantly different from the phosphorus content in other fertilizer supplements. For comparison, in sewage sludge, phosphorus usually occurred in the organic fraction and the NAIP fraction (the proportion of these bioavailable forms of phosphorus was about 80.0% relative to the total phosphorus content) (Xie et al., 2011).

In the case of analyzing the effect of fermentation on the phosphorus bioavailability, the sentences are very divided. Some authors argue that there is a higher content of phosphorus that is bioavailable to plants in the digestate compared to the feedstock materials (Möller and Müller, 2012). While other authors are of the opposite opinion (Hjorth et al., 2010, Khalid et al., 2011). Based on the obtained results, I found that the share of the bioavailable phosphorus, i.e. with the high mobility potential (sum of the NAIP and OP fractions) in the fermentation side products decreased significantly compared to the raw materials used, and its content in the individual digestate fractions determined the batch biomass. The content of phosphorus forms with high mobility potential in the solid fraction of digestates was reduced from approx. 8.0 to 20.0% in comparison with feedstock materials. The highest content of bioavailable phosphorus was observed in samples of solid fraction of digestate from cows slurry and distillery (respectively 9.1 and 6.5 mg/gd.m) and its shares in these fractions amounted to 29.0% and 39.0% respectively with reference to total phosphorus. While the content and share of the bioavailable phosphorus in these feedstock materials were respectively: 14.3 and 9.9 mg/gd.m. and 44.0 and 42.0%. The lowest content of bioavailable phosphorus was found in samples of solid fraction of digested food waste (fruit and vegetables) (0.7 mg/gd.m.) and their share in relation to feedstock materials decreased by 8.0%.

Based on the results of the research, I showed a certain relationship between the effectiveness of separation of the digestate and the content of organic and inorganic phosphorus (in suspension) in the post-fermentation leachates. Effective separation into digestate fractions from the fermentation of cow's slurry or distillery resulted in a lower share of the PRP and PNRP fraction (phosphorus in suspension) in the post-fermentation effluents, as compared to the leachates from the fermentation of lignocellulosic plant waste. In post-fermentation effluents from distillery or fermentation of cow's slurry, the proportion of phosphorus in the suspension accounted for 1.5 and 2.0%, respectively, whereas in the fermented cosubstrate effluent with the predominance of silage, the total share of PRP and PNRP fraction was more than twice as high. I also observed that in all analyzed post-fermentation leachates the form of reactive dissolved phosphorus dominated (SRP fraction). High concentrations of orthophosphates in the effluents resulted mainly from the release of phosphate ions from the OP fraction due to the hydrolysis of organic matter during the fermentation process.

Ad 3. Quality assessment of post-fermentation leachate in the aspect of the possibility of precipitation of the bioavailable form of phosphorus

The liquid fraction of digestate directly applied on farmlands (fertigation), due to the high content of nutrients may cause too much fertilization of soils. Nutrients such as N and P in effluents from animal faeces fermentation may occur in N:P ratios from 1:1 to 2.5:1, while the N:P ratio for crops is from 3:1 to 15:1 (Rollett et al., 2015). For this reason, when post-fermentation effluents are used for fertilizing arable land, there is a high risk of too high fertilization with phosphorus. The calculated values of the N:P ratio in my research varied from 2.7 to 5.7, i.e. the relations were not very favorable (due to too high concentrations of phosphorus) in relation to fertigation of farmlands. Therefore, I attempted to precipitate struvite from the analyzed post-fermentation leachates to improve the N:P ratio in the leachate and at the same time to recover nutrient elements in the form of struvite ($MgNH_4PO_4 \cdot 6H_2O$). The analyzed effluents were characterized by high concentrations of PO_4^{3-} and NH_4^+ ions, which from the point of view of recovery of these elements constitute a valuable product. The range of concentrations varied from 0.23 to 0.65 g/L for $PO_4^{3-}$and from 1.73 to 2.11 g/L for NH_4^+, although the highest concentrations of these ions were found in the leachates from the fermentation of animal waste and distillery, and the lowest from the fermentation of lignocellulosic waste. Analyzed post-fermentation effluents were characterized by high values of magnesium concentrations (from 0.01 to 0.22 g/L), which is important from the economic point of view related to struvite production, because there is no need for high doses of magnesium (which reduces operating costs). However, concentrations of Mg^{2+} in the leachate were not sufficient to precipitate struvite. The conducted research showed that the Mg:P ratio changed from 0.08:1 to 0.31:1. The necessary molar ratio Mg:P is 1:1, while in the technical scale it should be higher and maintained at a level of 1 , 1:1 to 1.6:1, while the ratio P:N must be at least 1:1 (Cieślik and Konieczka, 2017). The analyzed effluents were

characterized by a pH of 8.2 to 9.0 and a temperature of 20 to 25 ^{o}C and according to literature reports, optimal pH and temperature ranges in which struvite crystals were more effectively precipitated were within the range of: 8.0-9.0 and 20-35 ^{o}C respectively (Tansel et al., 2018; Ye et al., 2014; Moulessehoul et al., 2017). The post-fermentation effluents were characterized by concentrations of biogenic compounds close to the ranges that occur in the effluents from fermentation of sewage sludge in municipal wastewater treatment plants. This is important because the precipitation of struvite from leachate in municipal facilities is already carried out on a technical scale. However, few literature references refer to the removal or recovery of phosphorus from waste generated in agricultural biogas plants. While the recovery of phosphorus in the form of struvite from raw animal faeces or waste from the dairy industry has already been the subject of research, only few works concerned the subject of the recovery of phosphorus from the liquid fraction of digestables. Based on the literature review, I also found that most of the published works concerned the results of research carried out on synthetic sewage (similar to the composition of leachates from the fermentation of animal faeces or dairy waste). Conducting research on real leachate was a deliberate action, because, for example, synthetic effluents do not fully reflect the quality of real leachate. The dynamics of precipitation and crystallization of struvite in synthetic effluents may differ from the results of tests with the use of real leachates. The precipitation of struvite in real effluents can be hindered by the presence of a suspension or the presence of elements such as calcium, iron or potassium (Le Corre et al., 2005). Therefore, in this study (based on the recommendations given in the available literature), I took into account the presence of calcium ions when determining the optimal magnesium dose for struvite precipitation. Accordingly, the doses of magnesium salts were selected so that at the same time the molar ratios of magnesium to dissolved phosphorus would be at the level of 1.15:1 to 1.2:1 and the molar ratio Ca:Mg below 1. I observed that the concentrations of ammonium in " purified " (i.e. after precipitation of struvite from leachates) post-fermentation effluent were reduced, but still showed a high variability: from 0.97 to 1.61 g/L, the efficiency of ammonium ions removal in the analyzed effluents was similar and amounted to approx. 20.0%. I have not found that the type of dosed magnesium source had an effect on the increase or decrease in the efficiency of ammonium ions removal from post-fermentation effluents. Regardless of the nature of the origin of fermentation leachates and the type of external magnesium compounds used (for the tests I chose $MgCl_2$, $MgSO_4$ and MgO), I observed high efficiency of removing orthophosphates (SRP fraction) from leachates (which varied from about 95.0 to 99.0%). This meant that PO_4^{3-} ions reacted with Mg^{2+} and NH_4^{+} ions and precipitated in the form of struvite from the effluents. However, by analyzing the fraction of dissolved organic phosphorus (SNRP fraction), I found that the effectiveness of its removal from the leachate was negligible (5.0 - 7.0%). In contrast, concentrations of phosphorus fraction in suspension (PRP fraction and PNRP fraction) in "purified" post-fermentation effluents were reduced, but still showed a high variability, respectively: from about 0.1 to 0.7 g/L for the PRP fraction and from

approx. 0.05 to 0.15 g/L for the PNRP fraction. The presence of magnesium chloride in the effluents contributed to the removal of phosphorus in the PRP and PNRP fractions by an average of 20.0%. I observed the similar effectiveness of phosphorus removal in the suspension in the effluents after adding magnesium sulfate, and the lowest using magnesium oxide (about 15.0%). The removal of the PRP fraction and PNRP fraction correlated with the efficiency of the suspension removal, and the type of magnesium source used determined this efficiency. The presence of magnesium chloride in the leachate contributed to the most effective suspension removal (on average by 22.0%). A similar value was observed in the effluents with the addition of magnesium sulphate, while the lowest efficiency was obtained with the use of magnesium oxide. Precipitation of struvite in the effluents contributed to the removal of total phosphorus from approx. 75.0 to almost 90.0%. The highest efficiency of phosphorus precipitation was observed during the dosing of $MgSO_4$, and the lowest efficiency with the use of magnesium oxide. In the effluents that previously precipitated the struvite, the phosphorus fraction in the suspension and the dissolved organic phosphorus predominated, the percentage of which in terms of total phosphorus varied from approx. 50.0 to more than 70.0% and from approx. 30.0 to 50.0%. Iron concentrations in "purified" post-fermentation leachate (after precipitation of struvite) were at a similar level as in the initial samples of post-fermentation leachates and were reduced to a maximum of 6.0% in relation to the concentrations in the output samples. I observed a similar situation with regard to calcium ion concentrations. This was particularly important because it indicates that the phosphate ions were precipitated in the form of struvite and not e.g. hydroxyapatite. The potassium concentration was also slightly reduced in the "purified" post-fermentation leachate (up to 12.0% with respect to the concentration in the output samples). I therefore assumed that there was a low tendency of salt precipitation in the effluents, e.g. as $MgKPO_4 \cdot 6H_2O$.

The particle size of the precipitated struvite suspension is of great importance in the aspect of the design of struvite recovery technology. For example, in this way, the separation of struvite from liquids can be determined. On the basis of the granulometric analysis, I received information about the size of the precipitated particles of struvite. I observed that the crystals were of different sizes, and their maximum sizes, depending on the origin of the effluents in which they precipitated, varied from 54 to 85 μm. The obtained test results confirmed the assumption that the presence of interfering agents (suspensions) may affect the dynamics of struvite precipitation and crystallization. In spite of maintaining similar parameters of struvite precipitation (values of Mg:P and Ca:Mg ratios, pH, temperature, reaction time and mixing intensity), researchers who conducted work only on synthetic effluents observed higher sizes of struvite crystals, which confirms that synthetic effluents do not reflect in full quality of real leachate, and the dynamics of precipitation and crystallization of struvite in the analyzed real leachates may significantly differ from the results of studies using synthetic leachates.

Ad. 4. Evaluation of fertilization values of post-fermentation fractions

The greatest importance of nitrogen and phosphorus in nature is due to their bioavailability. Nitrogen mineralization is caused by specific processes leading to the formation of ammonia or ammonium nitrogen. This applies to transformations related to oxidation-reducing processes and the occurrence of nitrogen at various levels of oxidation. The majority of nitrogen transformations are determined by the activity of soil microflora. This is essential for plants, because ammonium nitrogen is a form directly absorbed by their root system, and is also easily converted into nitrates, which are even more easily used by plants. While the amount of phosphorus taken up by plants depends on the balance between the many compounds containing phosphorus. Plant roots, fungi and bacteria that inhabit the soil, produce acid and alkaline phosphatase, which hydrolyses the organic forms of phosphorus to its inorganic soluble forms (H_3PO_4, $H_2PO_4^-$, HPO_4^{2-}, PO_4^{3-}) directly absorbed by the plants. It should be emphasized that the intensity of these processes depends to a large extent on the pH of the soil. In Poland, over 50.0% of agricultural soils are acidic soils (5.0 <pH <6.0) and very acidic (pH <5.0), slightly acidic soils (6.1 <pH <6.7) and neutral (6.8 <pH <7.4) account for 42.0%, and only 8.0% of agricultural soils are alkaline soils (pH> 7.4) (Gonet et al., 2015).

Analysis of the quantitative content of phosphorus forms in the solid fraction of digestables provided important information on its different bioavailability. When assessing the role of a solid fraction of digestate as a potential source of phosphorus for soil fertilization, its biological availability is more important than the total content of this element. According to Psenner et al. (1984) form of phosphorus with the highest bioavailability in soil is phosphorus occurring in organic compounds and in combinations with Al, Fe, Mg and Mn oxides and hydroxides, wherein its greatest mobility occurs in soils with a pH in the range 5 - 7. Such a pH range most of the land is domestic arable land (their share is 92.0% in relation to the total arable land area). The share of these forms of phosphorus in the analyzed solid fractions of digestates was from about 30.0 to 50.0% in relation to total phosphorus, which means that the solid fractions from the obtained digestate were characterized by a moderate content of bioavailable phosphorus. The highest content of bioavailable phosphorus was found in fermentation samples of animal faeces (about 10.0 mg/gd.m.) and the lowest in fermentation samples of the substrate mixture with a predominance of beet pulp content (about 1.0 mg/gd.m.). For comparison, in animal manure the phosphorus content is on average 3.9 mg/gd.m. (Niemiec, 1995). On the other hand, the percentage of the least mobile form of phosphorus, i.e. in combinations with calcium, ranged from about 50.0 to 70.0%. Although this form of phosphorus was not bioavailable, its share in solid digestate fractions was an important element in the fertilization of soils due to its high calcium content. Liming is an agricultural way to control the acid reaction of arable soils. Currently, low consumption of calcium fertilizers contributes to the increased acidity of soils. The solution to this problem may be the application of solid digestate fractions on agricultural lands. Its alkaline pH (due to the high content of calcium ions) can contribute to the reduction of soil acidification. The content of

organic matter in the dry mass of solids ranged from about 50.0 to almost 80.0%. The post-fermentation effluents also contained high concentrations of organic matter (20.0 - 40.0%). The post-fermentation effluents from which struvite was previously precipitated were indicated as suitable for replacing nitrogen fertilizers, due to the high concentrations of ammonium ions (values varied from 0.97 to 1.61 g/L) and the high value of the N:P ratio (from 14.3 to 20.1). Referring to Polish and European recommendations regarding limit values of heavy metal concentrations in side products of fermentation, which can be used in agriculture, I found that none of the tested samples of the solid fraction of digestables exceeded the value of maximum concentrations. The conducted research confirmed the possibility of agricultural use of digestate fraction in accordance with the principles of the circular economy.

The most important achievements resulting from the conducted research:

1. For the first time, comprehensive studies of phosphorus fractions in batch components and side products of the fermentation process generated in agricultural biogas plants were carried out. Raw materials representing agricultural waste, food waste and animal waste were selected for the study.
2. Analysis of the quantitative content of phosphorus forms in the solid and liquid fraction of digestables provided important information on its different bioavailability.
3. It was shown that fermentation contributed to the mobility of phosphorus compounds. The share of phosphorus with high mobility potential in digestate fractions decreased by 8.0 - 20.0% in comparison to the share in the raw materials used and ranged from approx. 30.0 to 50.0% in relation to total phosphorus.
4. It was shown that the highest content of bioavailable phosphate was characterized by the solid fraction of digestate from fermentation of animal manure (the average value was about 10 mg/gd.m.), And a 10-fold lower fraction from the fermentation of fruit and vegetable waste.
5. It was also shown that the post-fermentation effluents were characterized by high concentrations of PO_4^{3-} and NH_4^+ ions. The highest concentrations of these ions were found in the effluents from the fermentation of animal manure and distillery, and the lowest from the fermentation of lignocellulosic waste.
6. The developed procedure of struvite precipitation confirmed the possibility of precipitation of the bioavailable form of phosphorus (struvite) from post-fermentation effluents. On the basis of the obtained results, regardless of the type of external source of magnesium (MgO, $MgCl_2$ and $MgSO_4$), high efficiency of orthophosphate removal from post-fermentation effluents

(from 95.0 to 99.0%) was found, and the removal efficiency of ammonium ions was about 20.0%.

7. The conducted research confirmed the possibility of agricultural use of post-fermentation fractions in accordance with the principles of the circular economy.

The possibility of using the results:

1. The possibility of using post-fermentation leachates from agricultural biogas plants for the production of struvite was demonstrated. The effluents were characterized by concentrations of biogenic compounds close to the ranges that occur in the effluents from the fermentation of sewage sludge in municipal wastewater treatment plants and may constitute an alternative source of phosphorus recovery.
2. Post-fermentation effluents from which struvite was previously precipitated were indicated as suitable for replacing nitrogen fertilizers, due to high concentrations of ammonium ions (values varied from 0.97 to 1.61 g / L) and high value of the N: P ratio (from 14.3 to 20.1).
3. The possibility of using the solid digestate fraction as a source of bioavailable phosphorus for fertilizing agricultural land has been demonstrated.

5. Discussion of other scientific-research achievements

a) Before obtaining a doctoral degree

In 1996, I started studies at the Gdańsk University of Technology at the Faculty of Environmental Engineering (currently: Faculty of Civil and Environmental Engineering). After five years of study, I obtained a master's degree in environmental engineering with a specialization in sanitary engineering. Diploma thesis "Project of a sewage treatment plant type SBR for the village of Bryzgiel lying in the Wigry National Park", which I made under the supervision of Prof. Bernard Quant, I defended on 25. June 2001 with a very good result.

Immediately after graduating from university, I started doctoral studies in the field of geotechnics and environmental engineering under the supervision of Prof. Hanna Obarska-Pempkowiak, who interested me in the problem of wastewater treatment using the hydrophyte method. In 2003, the proposed scope of research obtained co-financing in the form of a supervisory research project of the Ministry of Science and Informatics entitled "Determination of respiratory abilities of wetlands and filters in household wastewater treatment plants during their operation" (No. 3T09604926).

Doctoral dissertation titled "The impact of organic matter on oxygenation and the efficiency of removing contaminants in hydrophyte beds" I defended on 14. December 2005 at the Faculty of Civil and Environmental Engineering at the Gdansk University of Technology obtaining the title of doctor of technical sciences in the field of environmental engineering with the specialization of water and wastewater technology.. The work was mainly experimental and I carried out research in three wet buildings. The aim of the experiment was to recognize the dynamics of decomposition and accumulation of organic matter in hydrophyte beds irrigated with wastewater, as well as to determine the conditions precluding its accumulation in the ground. I published my research results related to the subject of my doctoral thesis before obtaining the doctoral degree in 16 reviewed works (Annex 4: item II.A. item 9, item II.E.2 item 8 and 9, item II.E.3 item 16 - 19, item II.E.4 item 40 - 42, item II.E.5 item 47, item II.E.6 item 61 - 65.)

During the doctoral studies I have completed numerous internships abrod at German research centers (Technische Universität München, Frauenhofer Gesellschaft Stuttgart) and state (Bayerisches Staatsministerium für Umwelt, Gesundheit und Verbraucherschutz; Wasserwirtschaftamt Hof; Wasserwirtschaftamt Nürnberg; Wasserwirtschaftamt München). I also participated in professional courses in design and executive companies in Munich and Berlin (Fa. AKUT GmbH; Fa. Schlegel GmbH & Co. KG). In 2003, as part of a scientific internship in Bavarian water management offices, I was able to learn about modern environmental engineering technologies, the basics of water law of the European Union, Germany and Bavaria and integrated water management in accordance with Agenda

21. Two years later I became a DAAD scholarship holder (Deutsche Akademische Austauschdienst) and completed a six-month scientific internship at the Department of Water Protection and Waste Management (Lehrstuhl und Laboratorien für Wassergüte und Abfallwirtschaft) at the Munich University of Technology (Technische Universität München), where under the supervision of Prof. Peter Wilderer, I conducted research related to my doctoral thesis.

During my stay in Germany, I also participated in courses and seminars raising my academic qualifications. They concerned the microbiological analysis of the activated sludge (course conducted by ATV-DVWK in Augsburg), while at the invitation of the Bavarian Ministry of Environmental Protection, I participated twice in seminars devoted to the subject of integrated water resources management.

In parallel with my scientific work, I also gained professional experience. As a designer assistant, I have completed internships in German companies that carry out design, advisory and executive work in the field of sanitary engineering. I was responsible, among others for preparing the concept and design and technical documentation for municipal wastewater treatment plants. In addition, I participated in the design and implementation process of water supply and sanitary sewage systems. The completed projects of these facilities have allowed me to gain, so important at work at a technical university, professional experience. Among others In the period between 2004 and 2005, as part of the partner project bfz GmbH and SINAENCO, I was the designer and coordinator of the construction of a constructed wetlands treatment plant, which is the biological degree of wastewater treatment from the textile industry for Toritama in Brazil. During my stay in Brazil, at the invitation of the University of Recife, I gave a lecture on natural methods of wastewater treatment (Annex 4: point II.L, item 17). Scentific-research internships in Germany have developed my research and organizational skills. I got to know new experimental techniques, I also made numerous contacts with scientists from Germany. The initiated cooperation is continued to this day. Since 2004, I have been a member of the International Project for Transfer of Water Technologies (Project Technologietransfer Wasser - TTW) based in the Bavarian Ministry of Environmental Protection.

b) After obtaining a doctoral degree

After obtaining the doctoral degree, my academic achievements cover the following thematic areas:

1) Removal of pollutants from sewage in municipal facilities;

2) Sewage-sediment economy oriented at increasing the production of renewable energy in municipal facilities;

3) Innovative solutions for the removal and recovery of biogenic compounds from wastewater in the municipal economy.

Ad. 1.

The aim of the research was to determine the effectiveness of removing pollutants from wastewater in: a) ecological treatment systems and b) conventional wastewater treatment plants.

Removal of pollutants from wastewater in ecological treatment systems

Scientific interests regarding the removal of pollutants from sewage in ecological treatment systems are presented in the publications: point II.A. Pos. 3 - 8; point II.E.1. Pos. 4; point II.E.2. Pos. 6 and 7, point II.E.3. Pos. 13, 14; point II.E.4. Pos. 29-34, 36, 38; point II.E.5. Pos. 44; point II.E.6. Pos. 56, 58-60 (Annex 4).

Ecological Treatment Systems (ETS) are modeled on systems known as "constructed wetlands" implemented in Western Europe and North America, whose work simulates the hydraulic and habitat conditions of natural swamp ecosystems. The ground-plant method of wastewater treatment is a biological process involving heterotrophic microorganisms and water-loving plants existing in well-designed systems with subsurface sewage flow (Vegetated Submerged Beds - VSB) or with surface sewage flow (Free Water Surface - FWS). Due to specific conditions enabling plant development, oxidation and reduction processes are intensified, which - supported by sorption, sedimentation and assimilation processes - make it possible to remove a significant part of pollutants from wastewater. Ecological treatment systems are used to remove pollutants from point sources (constructed wetlands) and area sources (buffer plant zones) and to drain and neutralize sewage sludge. The ability of ETS facilities to remove pollutants from wastewater depends on many environmental factors, which include, among others: variable oxygen conditions, temperature, as well as the pH of sewage and the load of organic matter.

Initially, the above-mentioned topic was a continuation of the issues taken in the doctoral dissertation. Tests carried out in VSB systems showed that the organic substance present in the suspension susceptible to decomposition and hardly biodegradable significantly affected the ability of wastewater to biodegrade them and determines high efficiency of pollutants removal in the analyzed objects. It was found that the load of the organic suspension of hydrophyte beds with subsurface vertical sewage flow below 4.0 g/ m^2day ensured proper exploitation of the deposits with the elimination of excessive accumulation. However, for deposits with subsurface horizontal sewage flow, the permissible organic suspension load was $\leq$ 14.0 g/m^2day. It was shown that in the deposits where the load values were below the admissible values, the efficiency of removal of pollutants was on average 70.0% for BOD_5 and approximately 60.0% for COD and total suspension. After receiving funding from the MNiSW and WFOŚiGW in Gdańsk as part of the implementation of three research projects (with the implementation of two projects running under my direction) (Annex 4: point II, J. items 6 and 7 and point III.F.) in 2009 - 2012 I was conducting research in three FWS systems - in

Kartuzy, Swarzewo and Żarnowiec located in the Pomeranian province. The analyzed objects effectively removed from the sewage a suspension with a particle size above 100 μm. In addition, these facilities were characterized by high efficiency of removing the total suspended solids from sewage exceeding 80,0%. The effectiveness of organic substance removal (expressed in BOD_5) was also significant, ranging from 60.0 to 75.0%. Ecological treatment systems with surface sewage flow also ensured efficient removal of the phosphorus suspension fraction from the sewage at the level of 40.0%. However, along with the suspension removal from the sewage, a secondary phenomenon of sewage pollution with phosphorus from the slurry deposited in bottom sediments was observed. It was observed that depending on the changing physico-chemical conditions occurring in ecological treatment systems, the share of phosphorus speciation forms in sediments varied, and thus the phosphorus balance conditions between wastewater and sludge varied, which affected the efficiency of phosphorus removal in these facilities. The nature of the chemical bonds in which this element occurred was decisive for the stability of depositing or the rate of phosphorus release from the sediments. The studies of the occurrence of mobile forms of phosphorus in bottom sediments of FWS facilities were of key importance in assessing the amount of phosphorus that was released as a result of chemical dissolution of mineral compounds and microbial decomposition of organic matter and re-integrated into the biological cycle, resulting in an increase in primary production. On the basis of the conducted research, it was shown that phosphorus was highly mobile in connections with iron and organic matter. The decrease in the share of these forms of phosphorus along the vertical profile of sediments taken from the analyzed objects indicated intensive release of the element from sediments. Due to the periodic anaerobic conditions in the systems, Fe^{3+} was reduced to Fe^{2+} and hence the dissolution of Fe-P complexes and the re-release of phosphate ions to wastewater. I also found a significant correlation ($r = 0.79$) between the content of organic matter in sediments and the content of phosphorus in organic matter. The obtained results allowed me to conclude that the majority of phosphorus accumulated in the analyzed sediments occurred in the connection with the suspension fraction that is hardly degradable and susceptible to biological decomposition. In Swarzewo and Kartuzy, the fraction of this phosphorus decreased with the depth of the sediment profiles from 70.0% in the surface layer to 40.0% at a depth of 30 cm. The decrease in the share of this phosphorous fraction along the vertical profiles of the sediments indicated the intensive release of the element from the sediments. I have observed, for example, that under good aerobic conditions, the release of phosphorus associated with organic matter was much more prevalent than depositing it in sediments. The phosphorus forms associated with calcium and magnesium were less mobile than the forms of phosphorus previously discussed by me, as their share increased with the depth in the vertical profiles of sediments. The availability of these forms of phosphorus was related to the pH of sewage flowing through the ETS systems. At pH values from 7.2 to 8.5, precipitation of phosphate ions in the form of calcium phosphate took place. The analyzed sewage was characterized by similar pH values, which

led to the formation of water-insoluble phosphorus and calcium compounds and accumulation of the element in sediments.

In conclusion, the obtained results are important in terms of ensuring the correct operation and exploitation of ecological treatment systems. This information may be helpful especially during designing ETS facilities for treating wastewater of unfavorable composition or when very efficient removal of phosphorus compounds and organic matter is required to protect surface waters against eutrophication.

Removal of pollutants from wastewater in conventional wastewater treatment plants

Scientific interests about pollutants removal from wastewater in conventional wastewater treatment plants are presented in the publications: point II.A. Pos. 1 and 2; point II.E.2 pos. 5; point II.E.3. Pos. 12; point II.E.4. Pos. 21 and 27 (Annex 4). The results obtained were also presented at international scientific conferences - point II.E.6. Pos. 49, 53 and 55 (Annex 4).

Proper operation of biological wastewater treatment plants with increased biogenic compounds removal depends largely on the availability of sufficient quantities of suitable (biodegradable) organic compounds (carbon sources). These compounds should satisfy the needs of three groups of microorganisms, including denitrification bacteria, dephosphatative microorganisms and denitrifying bacteria accumulating polyphosphates. Due to the limited amount of biodegradable organic compounds in incoming sewage, three groups of microorganisms must compete for the same substrates, which in turn may lead to disturbances in the proper operation of the treatment plant. In practice, external sources of organic carbon are used for this purpose. The first group includes commercial products (methanol, ethanol, acetic acid, sodium acetate or glucose). Despite their proven effectiveness, economic barriers are a major obstacle to their use in sewage treatment plants. Due to the high costs of commercial compounds, side products or waste materials have recently gained more attention as "alternative" external carbon sources. Alternative carbon sources include, for example, waste from distilleries - fusel oils. The effect of the addition of fusel oils has been studied in terms of the metabolic properties of denitrifying bacteria accumulating polyphosphates. I analyzed the ability of an activated, non-acclimated sludge after accumulation of fusel oils to remove biogenic compounds from wastewater. The results of the research were published in the international journal *Bioprocess and Biosystems Engineering* (IF = 2.139) and presented in the form of an oral presentation at the IWA Specialist Conference, *"Nutrient removal and recovery: moving innovation into practice"*, which took place in Gdańsk in 2015. The obtained results allowed me to formulate conclusions that for non-acclimated biomass, the phosphate release and uptake rate (PRR / PUR) and nitrate utilization rate (NUR) were low and close to the rate obtained in the reference test. For acclimated biomass, PUR and NUR increased significantly, i.e. 3.5 and 2.7 times, respectively. Based on model simulations, it was

estimated that the activity of DPAO bacteria and denitrifying heterotrophic organisms was approximately 20.0% and 80.0% of total NUR, respectively.

In cooperation with the Department of Chemistry and Commodity Industry of the Maritime University of Gdynia and the municipal company - Water and Sewage Company in Swarzewo, I also participated in the implementation of research related to the assessment of the impact of surfactants in sewage on the effectiveness of pollution removal in municipal sewage treatment plants.

One of the pollutants going to municipal wastewater treatment plants together with sewage is surfactants. These compounds are widely used in the textile, paper, cosmetics and pharmaceutical industries. They are also used in the production of food and fertilizers, paints and varnishes. Due to the wide use of surfactants in household cleaning products, significant amounts are transferred to municipal wastewater. Therefore, it seemed important to undertake research on the following issues: a) determine the changes in the structure of activated sludge under the influence of surfactant and b) the influence of LAS anionic surfactant on the mobility of phosphorus fractions in activated sludge under changing physico-chemical conditions. The laser diffraction analyzer Mastersizer 2000 was used to determine the granulometric composition of the activated sludge and to determine the changes under the influence of the presence of anionic surfactant in the effluents. The tests were carried out for various concentrations of anionic surfactant, both typical for municipal wastewater and those found in industrial wastewater. To carry out the analyzes, samples of activated sludge were taken directly from the aeration chamber of the municipal sewage treatment plant in Swarzewo. The background of the measurements was an oxygenated active sludge. As an anionic surfactant, linear sodium dodecylbenzenesulfonate (LAS) was used. My task was to analyze the effect of the surfactant additive on the change in the size of activated sludge flocs. The conducted research allowed to state that the tested surfactant doses significantly influenced the quality of the activated sludge. The presence of anionic surfactant contributed to the change in the distribution of floc sizes. The LAS concentration below 200 mg/L in the sludge caused a significant fragmentation of its flocks, while the higher concentration of their agglomeration. The largest and the fastest changes in the size distribution of sludge flocs were observed after addition of surfactant at a concentration of 100 mg/L. Another research topic concerned the influence of the presence of anionic surfactant on the mobility of phosphorus forms in activated sludge in sewage. The conducted research on the quantitative relations of the phosphorus fractions provided important information on the cumulative stability and rate of release of this element from the activated sludge to sewage. The research material were samples of municipal sewage and activated sludge taken from the municipal sewage treatment plant in Swarzewo. Work was carried out on a laboratory scale in a sequencing batch reactor (SBR). Phosphorus speciation was conducted for six measurement series differing in the conditions under which the activated sludge was kept. The activated sludge under anaerobic conditions with the addition of surfactant in concentrations of 10 and 100 mg/L and the sludge without surfactant were kept. The next

three series of tests were performed in activated sludge after aeration with and without the addition of surfactant in the same concentrations. Obtained results of the study allowed to conclude that during the aerobic phase, the presence of LAS surfactant in the sediment made it difficult to accumulate phosphorus in it. The ability to collect and store of phosphorus compounds by bacteria in the oxygenated activated sludge with the addition of LAS decreased compared to the precipitate without surfactant. This phenomenon intensified with increasing concentration of the added surfactant. The results of the research have been published in, among others in peer-reviewed scientific journals *Ecological Chemistry and Engineering* and *Marine Engineering and Geotechnics*.

Ad. 2.

In 2013 - 2017, I conducted research work by participating in a scientific team led by Prof. Jacek Mąkinia, as part of an international scientific - research project co-financed from the funds of the Norwegian funds „Integrated technology for improved energy balance and reduced greenhouse gas emissions at municipal wastewater treatment plants". The aim of the project was the practical application of the principles of sustainable sewage and sediment management in municipal wastewater treatment plants, taking into account technological, energy and economic aspects as well as greenhouse gas emissions. As part of the task named „Increasing primary sludge production by coagulation and flocculation process in a primary clarifier" I took part in the research on the analysis of the impact of the addition of organic polymers and coagulants to wastewater on: a) the efficiency of removing organic compounds from wastewater; b) the rate of biological processes in the biological part of the municipal sewage treatment plant; (c) recovery of the easily biodegradable fraction of organic matter from the generated primary sludge, and (d) the efficiency of biogas production in the anaerobic digester based on the increased primary sludge production.

The research material were samples of raw sewage and activated sludge, which were collected from two municipal sewage treatment plants located in Gdańsk and Gdynia. Three commercial organic polymers were used in the research and, as a reference point, the $ZnSO_4$ coagulant. The experiments were carried out with raw wastewater subjected to a two-hour sedimentation without and with the addition of analyzed reagents. Laboratory scale tests in a specially constructed laboratory device for measuring biochemical rates of wastewater treatment processes using activated sludge. In the analyzed samples of sewage and sediments, measurements of concentrations were carried out, among others fraction of organic matter, nitrogen and phosphorus compounds. In order to determine the relationship between increased production of primary sludge and methane production, the mathematical model - Anaerobic Digestion Model 1 (ADM1) was used for calculations. Based on the results obtained during the laboratory tests, it was found that the average efficiency of organic matter removal from raw sewage undergoing two-hour sedimentation without addition of reagents remained at 30.0%. However, after the addition of organic polymers to wastewater, this efficiency has

improved significantly and almost doubled. During this time, the coagulation of zinc sulfate caused over 70.0% reduction of the organic suspension and colloidal fraction from wastewater. The research results showed that the tested organic polymers also influenced the increased production of primary sludge. The average volume of precipitate sediment from one liter of raw sewage ranged from approx. 15 to 40 cm^3. Increased precipitation of organic compounds from wastewater with the aid of the analyzed polymers did not cause disturbances of biological processes: phosphate release and uptake rates (PRR/PUR) and the nitrate uptake rate (NUR). On the other hand, the removal of a significant amount of organic matter present in the colloidal fraction and suspension after the addition of zinc sulfate resulted in a reduction of the rate of biological removal of phosphates and nitrates from sewage by 30.0% during two-phase experiments and by 20.0% during single-phase experiments. Mathematical simulations performed using the ADM1 software allowed to formulate the conclusion that the initial chemical precipitation of organic compounds from raw sewage may contribute to acceleration of anaerobic processes and improvement of biogas production. Mathematical analysis has shown that the use of organic polymers can contribute to increased efficiency of biogas production. After a series of tests on a laboratory scale, technical tests were carried out at the sewage treatment plant in Słupsk. The addition of organic polymers contributed to the increased removal of the suspension from raw sewage (at the level of approx. 70.0%) and did not disturb the work of the biological part of the treatment plant. The research results were presented at three science and technology seminars in 2014, 2015 and 2016 in Gdańsk, Gliwice and Poznań (organized as part of the above project) and four international conferences (in 2014 at the 2nd IWA Specialized International Conference ecoSTP2014 in Verona in Italy, in 2015 at the IWA Specialist Conference - Nutrient Removal and Recovery: moving innovation into practice in Gdańsk; in 2015 at the 12th IWA Leading Edge Conference on Water and Wastewater Technologies in Hong Kong in China; in 2017 at IWA Specialist Conference Sustainable Wastewater Treatment and Resource Recovery: Research, Planning, Design and Operation in Chongqing, China) and met with great interest, among others exploiters of the treatment plant and representatives of offices interested in environmental protection issues. Currently, manuscript named „Effect of enhanced primary treatment on recovery of biodegradable COD from primary sludge and biological processes in the activated sludge system" is under preparation to the JCR journal.

Ad 3.

Issues related to the topic "Innovative solutions for the removal and recovery of nutrients from wastewater in the municipal economy" are presented in the following publications: point II.E.1. Pos. 1 - 3; point II.E.4. Pos. 24 - 25, 28, 35, 37 - 39, point II.E.6. Pos. 48, 50 (Annex 4).

The aim of the academic activity was to present the possibilities of innovative solutions for the removal and recovery of phosphorus and nitrogen in: a) areas with scattered development and b) in municipal facilities.

In Poland, approximately 40.0% of the population lives in rural areas. In the case of smaller pollution emitters, there is a paradox - although individual emitters are small, however, the high total load of biogenic compounds, coming from small emitters, has adverse environmental consequences. Although the amount of rural wastewater is smaller compared to urbanized areas, they have higher concentrations of pollutants. Currently, only about 2,000 wastewater treatment plants with a combined sewerage system operate in rural areas in Poland, servicing 5.0% of villages (approximately 20.0% of the entire rural population). The main reason for such a small number of treatment plants is the spatial development of the Polish village, which clearly does not favor the construction of area sewage systems. Due to the unfavorable specificity of the development of the Polish village, long-term negligence in the construction of sewage system, and hence for huge needs, the introduction of only "urban sewerage systems" to rural areas is unjustified for economic reasons. In most rural locations, the construction of such systems is also irrational due to technological, economic and environmental needs. It is also estimated that for a total of about 3 million farms as much as 75.0% gets rid of domestic waste without treatment. In order to improve the quality of life combined with environmental protection, especially in rural areas, I promote innovative solutions for the simultaneous management and recycling of domestic wastewater while at the same time removing and recovery of biogenic compounds from them. In recent years, I have established cooperation with the Swedish community within the framework of the international EQUAL Program on the general strategy of sustainable development and ecological sanitation. In particular, this applies to an alternative solution for sewage management in a rinsed biotoilette by separation of urine and processing of other waste into compost. Properly separated urine allows to reuse at least 70.0% of phosphorus and 50.0% of nitrogen present in human feces in the natural cycle. At the same time, the technologies with the use of separating toilets completely solve the problem of sewage-sediment management, while ensuring the natural use of final products. I have concluded experience gained during participation in the EQUAL Program in two monographs and in numerous scientific and technical articles on a national and international scale. In the works I presented the results of research and practical tips, supported by experience gained from the analysis of the work of existing facilities. These works devoted to this subject may serve to popularize information on alternative ways of managing wastewater in rural areas in Poland among designers, installers and investors.

In the case of municipal sewage treatment plants, in a conventional approach, the digestates are separated into two solid and liquid fractions (effluents) prior to their final management. After dehydration of the sediments, most often the effluents are directed to the beginning of the sewage treatment system. Increasingly, however, lateral nitrogen removal lines are used in sewage treatment plants, and the latest trend is the use of technologies for the recovery of nitrogen and phosphorus compounds due to their high concentrations in the effluents. Measurable benefits of such solutions include reduction of loads of biogenic compounds in the effluents recycled for re-biological treatment; minimizing the use of chemicals for phosphorus precipitation contributing to lower costs; limiting the formation of struvite in the fermentation chambers up to 90,0%. The solutions applied in the Netherlands, Germany, Switzerland, Japan and Austria, their development and proven economic efficiency, currently set the rules for the management of phosphorus compounds for municipal facilities, and the need to adapt to the requirements of EU Directives 91/271 (The Urban Wastewater Treatment) justifies development of phosphorus recovery technology. On 1 January 2016, Switzerland became the first country in the world where the recovery and recycling of phosphorus from sewage sludge has become mandatory. On 3 October 2017, a new regulation on sewage sludge entered into force in Germany, which says that sewage treatment plants with a size of more than 50,000 PE have, as in Switzerland, an obligation to recover phosphorus from sewage sludge. It refers to the cessation of the use of sludge as a fertilizer and the beginning of the development of the most effective recovery of phosphorus and other nutrients process. Wastewater treatment plants, in which the content of phosphorus in the dry matter of the sludge is above 2.0%, are required to recover phosphorus from sediments or from ashes (as a final product after combustion of sludge). Currently, the requirements for the recovery of elements in Germany are 50.0% from the sediment and 80.0% from the ashes. Looking to the future, it is also likely that the recovery of biogenic compounds, from waste products generated in sewage treatment plants, will take effect in other European countries, the more so now that agricultural use of sewage sludge is no longer permitted in the Netherlands, Denmark and some Austrian Länder. Following this research topic, I had the opportunity to conduct research related to the recovery of biogenic compounds (in the form of precipitated struvite) in effluents from municipal facilities as part of the implementation of two international projects - a research project entitled "Regional Sustainable Biogas Solutions" under the European Territorial Cooperation program and the European Neighborhood Instrument (Interreg South Baltic Project) and a research project entitled "Pomeranian Biogas Model" co-financed from the funds of the Norwegian funds, as part of the Polish-Norwegian Research Cooperation Program. The obtained research results were presented, among others at the 12th international conference "Sewage sludge management methods" organized by ABRYS in 2018 in Poznań and a nationwide conference entitled "Pomeranian Biogas", which took place in 2016 in Gdańsk. Since 2017, I have been extending research activities in the above-mentioned area to research related to the influence of cosubstrates on the quality of generated digestate effluents

in municipal biogas plants in the aspect of recovering phosphorus compounds from them. Currently, I am carrying out research under the following acronyms: DEZMETAN (Project: “Development of technology for the preparation of substrates used in methane cofestation by disintegration methods” co-financed by the European Regional Development Fund) and MODEON (Project: “Model sedimentary management in a sewage treatment plant oriented towards increasing the production of renewable energy and recovery of biogenic compounds” co-financed by the Regional Fund for Environmental Protection and Water Management in Gdańsk). An important remark is that on the basis of the results obtained so far in the laboratory scale, the concept of integrated two-stage technology for post-digestion leachate treatment and nutrient recovery in the pilot scale was developed, while the DEZMETAN project will build an installation for precipitating struvite from leachate. In 2019, pilot scale tests are planned. Currently, there are two manuscripts in preparation: “The influence of various physico-chemical process parameters on simultaneous deamonification and struvite crystallization - review” and “Influence of disintegration of sediments and cosubstrates subjected to the fermentation process on the removal and recovery of nutrients from digestate”. There is also a paper on "Dissolved organic phosphorus and nitrogen in digester liquors from agricultural biogas plants", which will be presented this year at the 10th IWA International Symposium on Waste Management Problems in Agro-Industries in Rhodes, Greece.

6. Information on didactic and organizational activities, scientific cooperation and popularization of science

Didactic activity

I started teaching during the Doctoral Studies at the Faculty of Civil and Environmental Engineering (WILiŚ) of the Gdańsk University of Technology (PG). In the years 2005 - 2006 as part of the DAAD scholarship I conducted a series of lectures in German on topics related to the treatment of water and sewage at the Department of Water Protection and Waste Management at the Munich University of Technology. In the years 2006 - 2008 I conducted classes at the Faculty of Civil and Environmental Engineering and Achitecture of the University of Technology and Life Sciences in Bydgoszcz (WBAiIŚ, UTP) (major: environmental engineering, 1st and 2nd degree studies, full-time and part-time). In 2011-2017 I taught at the Faculty of Engineering (WI) of the College of Environmental Management in Tuchola (WSZŚ in Tuchola) (field of study: environmental engineering, 1st degree studies, part-time). Currently I run classes at the Faculty of Civil and Environmental Engineering at the Gdańsk University of Technology (major: environmental engineering, 1st and 2nd degree studies, full-time and part-time). The classes I was conducting included the following subjects:

- *lectures: environmental toxicology (WBAiIŚ UTP in Bydgoszcz), water and sewage technology (WI WSZŚ in Tuchola), fluid mechanics (WI WSZŚ in Tuchola);*
- *seminars: diploma seminar (WI WSZ in Tuchola, WILiŚ PG);*
- *auditorium classes: plumbing (WBAiIŚ UTP in Bydgoszcz), fluid mechanics (WI WSZŚ in Tuchola), water and sewage technology (WI WSZŚ in Tuchola), general chemistry (WILiŚ PG), air protection (WILiŚ PG), construction installations (WILiŚ PG);*
- *laboratory exercises: water and wastewater technology (WBAiIŚ UTP in Bydgoszcz, WI WSZ in Tuchola, WILiŚ PG), general chemistry (WILiŚ PG);*
- *design exercises: water and wastewater technology (WI WSZŚ in Tuchola), natural methods of wastewater treatment (WILiŚ PG), sanitary installations (WILiŚ PG), waterworks (WILiŚ PG).*

I have developed my own program of classes - lectures on environmental toxicology. I also collaborated in the preparation of a design and auditorium exercises program on natural wastewater treatment methods and air protection.

In 2012 it was published by the Seidel-Przywecki Publishing House with the seat in Warsaw, an academic textbook "Sewers. Design, implementation, operation ", of which I am a co-author (Annex 4: point II E.1 item 1). This is the first textbook of this type on the Polish market, in which it presents, among others, characteristic requirements of new technical solutions - in the design, implementation and operation phase. In addition to the dominant computational aspects, formal problems were raised as well as legal and administrative aspects. It is worth noting that the existing comprehensive literature

comes mainly from around 40-50 years ago and basically concerns older technologies. The manual presents the outdated generally accepted standards for sewage systems design. Until now, its recipients - apart from students and academics - have become employees of design offices and representatives of territorial authorities (including employees of starosties, municipal offices and city offices). In 2013, I received an award for the didactic achievements of the Rector of the Gdańsk University of Technology for co-authorship of this academic textbook (Annex 4: item III D. item 2).

The first MA thesis was made under my direction in 2006, since then I have been the supervisor of over 100 diploma theses, including 54 MA theses, I have been entrusted with numerous reviews of the works. Among others the results of two theses, the first - related to the recovery of biogenic compounds from domestic wastewater, the second - concerning ecological sanitation in scattered areas, carried out under my supervision, were published in 2013 and 2014 in the industry magazine "Wodociągi-Kanalizacja" (Annex 4 : point II E.4 items: 24, 25, 28).

I have been the organizer and protector of student didactic trips both in the country and abroad. Among others In 2003 and 2005 I took care of a group of young scientists as part of the ongoing "Young Scientists Program" organized by the German side (ATV-DVWK, Deutsche Vereinigung für Wasserwirtschaft, Abwasser and Abfall eV), which was carried out in Berlin (2003) and Munich (2005). In 2014, I was the academic supervisor of a group of students from universities (Gdańsk University of Technology, Koszalin Technical University, Cracow University of Technology and WSZŚ in Tuchola) participating in the scientific camp organized by the College of Environmental Management in Tuchola (Annex 4: point III Q.). The aim of the camp was to get acquainted with the methodology of carrying out research and analyzes allowing for the development of a plan for the protection of the environment and the state of pollution of a given town. The task faced by students during their stay was to identify sources of pollutants of water, soil and air in Tleń (Kujawsko-Pomorskie province). The solution was presented by students under my direction at the 5th International Scientific and Technical Conference on "Heating and ventilation in industry and agriculture" in 2014.

In addition, in the course of my work and doctoral studies, apart from universities, I undertook activities for the benefit of local governments in the field of consultancy and training on issues related to the protection and treatment of water and sewage as well as waste management. I participated in vocational training addressed to representatives of local governments in Poland (City Hall in Gdańsk, City Hall in Gdynia) and abroad (Germany, Brazil) as part of cooperation with the Ministry of Environmental Protection of Bavaria (Bayerisches Staatsministerium für Umwelt, Gesundheit und Verbraucherschutz and SINAENCO). This activity was manifested by giving lectures on water and sewage issues (Annex 4: point II L., items: 6, 12, 17).

In 2007, I was a supervisor of full-time students in the field of construction at the Faculty of Civil and Environmental Engineering at the Gdańsk University of Technology.

In 2011 and 2012, I was a member of the Program Committee at the Faculty of Civil and Environmental Engineering at the Gdańsk University of Technology. For five years, since 2012, I was a member of the Consultancy and Program Board of the Environmental Engineering at the College of Environmental Management in Tuchola. Since 2016, I have been a member of the Faculty Committee for Evaluation of Parametric and Categorization (WKOPiK) of the Faculty of Civil and Environmental Engineering at the Gdańsk University of Technology.

Organizational activity, academic cooperation and popularization of science

In the years 2005 - 2017 I participated fourteen times in the organization of international and national scientific conferences, seminars and workshops (Annex 4: point III C.). Together with teams from the Department of Water and Sewage Technology and the Department of Sanitary Engineering, Faculty of Civil and Environmental Engineering, Gdansk University of Technology, among others in 2015 and 2016, I took part in the organization of two international conferences (IWA Specialist Conference - Nutrient Removal and Recovery, and the 8th Eastern European Young Water Professionals Conference, IWA YWP) as well as in 2005 and 2009 in nationwide conferences. I was also twice the secretary of scientific conferences periodically organized by the College of Environmental Management in Tuchola, which took place in 2013 - 2014. As part of the Polish-Norwegian scientific - research project I participated in the preparation of six workshops and three seminars that took place in Gdańsk, Poznań, Gliwice and Oslo (Norway). I am currently participating in the preparation of a nationwide scientific conference entitled: "*Innovation in Environmental Engineering*", which will take place in June this year in Gdańsk.

As a manager and contractor, I participated in seven research projects, including three international projects, among others within the framework of "Polish-Norwegian Research Cooperation" and the European Territorial Cooperation and European Neighborhood Instrument program (Interreg South Baltic Project) (Annex 4: points: II J. and III F.). The remaining projects were financed by the Ministry of Science and Higher Education and WFOŚiGW in Gdańsk. Currently, I participate in the implementation of two research projects: MODEON - co-financed by the Regional Fund for Environmental Protection and Water Management in Gdańsk and DEZMETAN - co-financed from the European Regional Development Fund (Annex 4: point II J. items: 1, 2). Among others from funds that were obtained from research projects, measuring equipment for laboratories was purchased, i.e. a muffle furnace, scales, Oxi-Top oxygen measurement in the ground and a thermostatic cabinet. The obtained funds from the Regional Fund for Environmental Protection and Water Management in Gdańsk purchased a laser granulometer manufactured by Malvern Instruments Ltd 2000. From the funds received as part of the MODEON project, the concept of integrated two-stage technology for post-digestion effluent treatment and nutrient recovery in the pilot scale was developed; as part of the DEZMETAN project, an installation for precipitating struvite from leachate will be built.

I was also the author and co-author of a total of 9 studies and documentation of research works (Annex 4: point II F.) and 7 scientific expert opinions (Annex 4: point III M.).

I broadened my professional competences (scientific, didactic) thanks to participation in numerous courses, trainings, domestic and foreign internships (Annex 4: point III L.). Since 2002, I have completed a total of fifteen internships and trainings, including thirteen at foreign institutes, including in Germany, Portugal and Brazil.

In recent years, I have also established closer cooperation with the Swedish community, including within the EQUAL program (Let's build together) as part of the overall strategy for sustainable development and ecological sanitation. In particular, this applies to an alternative solution for sewage management in a rinsed biotoilette by separation of urine and processing of other waste into compost. These systems are realistic solutions, consistent with the modern objectives of the EU Water Framework Directive and Sustainable Development. Therefore, in order to improve the quality of life combined with environmental protection, especially in rural areas, I promote innovative solutions for the recycling of domestic sewage. The articles I am co-author of can contribute to the dissemination of information on alternative methods of domestic waste water management among students, designers, installers and investors. Cooperation with the Swedish side has also resulted in the publication of two monographs (Annex 4: point II E.1, items: 2, 3). As a member of the International Water Technology Transfer Project (Project Technologietransfer Wasser - TTW) based in the Bavarian Ministry of Environmental Protection, I participated in seminars and projects devoted to Integrated Water Ressource Management. Cooperation with the German side also resulted in the publication of a number of scientific publications (Annex 4: point II E.2, item: 6, item II E.4, items: 22, 23, 36, 40, 42, point II E.6., item 64).

As part of international cooperation, I participated in a number of conferences and international seminars (seventeen times). I am also taking an active part in national thematic conferences (from sixteen since 2002). The papers delivered at conferences have been published, among others in the form of chapters in monographs and as articles reviewed in a collective work in a language of international and national scope.

At the request of editorial offices of international and national journals, I have edited fifteen reviews of articles, including Ecological Engineering, Environmental Technology, Desalination, Journal of Environmental Management, African Journal of Biotechnology, Life Science Journal, Environment Protection Engineering, Bioprocess and Biosystems Engineering, Geoderma, Chemical Engineering Journal.

My activity for scientific cooperation and popularization of science has been recognized by three awards of the Rector of Gdańsk University of Technology for outstanding organizational work and for outstanding research and development activities.

7. Summary of academic achievements

Before obtaining a doctoral degree

In 2001-2005, I published a total of 16 scientific papers. I was, among others co-author of a work published in a journal with IF, two articles reviewed in a collective work in an international language, four articles constituting chapters in national monographs, three articles in peer-reviewed journals (including one in German) and five articles in conference materials (including two in international language).

In the years 2003 - 2005 I was the main contractor of the supervisor's grant entitled "Determination of respiratory abilities of wetlands and filters in household wastewater treatment plants during their operation".

I presented the results of my research at conferences in the form of eight lectures.

In addition, I was a co-author of two expert reports related to the use of the hydrophyte method for the treatment of municipal wastewater and the neutralization of sewage sludge.

In the years 2002 - 2005 I completed ten foreign courses and scientific internships in German research centers and in design and executive companies. For me, a scientific stay in Germany was of great value as part of the DAAD six-month scholarship.

After obtaining a doctoral degree

In the years 2006-2019, I published a total of 58 scientific papers, including, among others, eight papers in journals distinguished by the Journal Citation Reports database (in the following journals: Bioresource Technology, Ecological Engineering, Water Science and Technology, Bioprocess and Biosystems Engineering, Biochemical Engineering Journal, Chemical Industry, Year of Environmental Protection, Polish Journal of Environmental Studies,), three monographs and one national academic textbook, three articles constituting chapters in international monographs, six articles constituting chapters in national monographs, twenty papers in peer-reviewed journals and other permanent publications as well as thirteen publications in conference materials.

The above works were created as part of research projects. In 2009-2012, I managed two grants funded by the MNiSW and the WFOŚiGW in Gdańsk. I was a contractor in one national project funded by WFOŚiGW in Gdańsk and three international projects under the "Polish-Norwegian Research Cooperation" program implemented by the National Center for Research and Development and the European Territorial Cooperation and European Neighborhood Instrument program. Currently, I am involved (as a contractor) in two research projects co-financed by the European Regional Development Fund and from the funds of the WFOŚiGW in Gdańsk.

I participated in the implementation of thirteen reports, collective studies and expert opinions (including one in Germany) thematically related to water protection and wastewater treatment.

In 2007, I participated in a scientific internship in Portugal. In 2008 - 2013 I took three specialized scientific courses in Poland. In 2018 I completed a professional internship at a German design office.

Also, it was extremely valuable for me to participate in eleven international conferences, twelve national conferences and seminars and the opportunity to deliver nine papers and presentations of four posters.

The cognitive and application values of my research work have been recognized by five awards of the Rector of the Gdańsk University of Technology, including: for scientific achievements; for the distinctive research and development activity; for outstanding organizational work and for didactic achievements.

Statistics of scientific papers

The total impact factor for all published scientific papers in accordance with the Journal Citation Reports (JCR) list is IF = 15.97. The total value of the Ministry of Science and Higher Education (PM) scores is PM = 535.0. However, the number of points including own contribution (before and after doctorate) is 280,1. The number of citations of scientific papers according to the Web of Science database (WoS) is 64 (without self-citations - 61), while the h-index is equal to 4.

Table 1 summarizes the scientific achievements before and after obtaining a doctoral degree.

Table 1. List of scientific achievements before and after obtaining a doctoral degree

No.	Type of achievement	Number	
		before obtaining a doctoral degree	**after obtaining a doctoral degree**
1	**Publications, including:**	**16**	**58**
	in journals from the JCR list	1	8
	monographs and textbooks	0	4
	chapters in monographs and articles reviewed in a collective work of international scope	2	3
	chapters in monographs and articles reviewed in a collective work of national scope	4	6
	in peer-reviewed journals and other periodicals	3	20
	in collective publishing and conference materials	5	13
	electronic publications	1	4
2	**Participation in research projects, including:**	**1**	**7**
	international	0	3
	national	1	4
3	**Design, construction and technological achievements**	**1**	**3**
4	**Participation in organizational / scientific committees of conferences, seminars, workshops**	**1**	**14**
5	**Presentation of papers (R) and presentation of posters (P) at conferences**	**8 (R)**	**9 (R)** **4 (P)**
6	**Creative professional work, including:**	**3**	**13**
	collective studies, documentation of research works	2	7
	expert opinions and opinions	1	6
7	**Domestic and foreign internships**	**10**	**5**
8	**Promoter of diploma theses, including:**	**0**	**115**
	engineering	0	61
	master	0	54
9	**Citations (without self-citations)**	**0**	**64 (61)**
10	**Hirsch index**	**0**	**4**
11	**Impact Factor**	**1,19**	**14,78**
12	**Points according to MNiSW**	**54,0**	**481,0**
	including own contribution	19,9	260,2

References

1. Ajiboye B., Akrinremi O.O. (2007) Phosphorus speciation of sequential extracts of organic amendments using nuclear magnetic resonance and x-ray absorption near-edge structure spectroscopies. J. Environ. Qual. 36: 1563 - 1576.
2. Cieślik B., Konieczka P. (2017) A review of phosphorus recovery methods at various steps of wastewater treatment and sewage sludge management. The concept of "no solid waste generation" and analytical methods. J. Clean. Prod. 142: 1728 - 1740.
3. Dyrektywa Rady z dnia 12 grudnia 1991 r. dotycząca ochrony wód przed zanieczyszczeniami powodowanymi przez azotany pochodzenia rolniczego (91/676/EWG).
4. Gonet S., Smal H., Chojnicki J. (2015) Właściwości chemiczne gleb. W: Andrzej Mocek (red.): Gleboznawstwo, Wydawnictwo Naukowe PWN, ISBN 978-83-01-17944-6: 201 - 205.
5. Hjorth M., Christensen K. V., Christensen M. L., Sommer S. G. (2010) Solid–liquid separation of animal slurry in theory and practice : A review. Agron. Sustain. Dev. 30: 153 - 180.
6. Khalid A., Arshad M., Anjum M., Mahmood T., Dawson L. (2011) The anaerobic digestion of solid organic waste. Waste Manage., 31: 1737 - 1744.
7. Le Corre K. S., Valsami-Jones E., Hobbs P., Parsons S. A. (2005) Impact of calcium on struvite crystals size, shape and purity. J. Cryst. Growth 283: 514 - 522.
8. Li B., Brett M. T. (2015) The relationship between operational and bioavailable phosphorus fractions in effluents from advanced nutrient removal systems. Int. J. Environ. Sci. Technol. 12: 3317 - 3328.
9. Möller K., Müller T. (2012) Effects of anaerobic digestion on digestate nutrient availability and crop growth : A review. Eng. Life Sci. 12(3): 242 - 257.
10. Moulessehoul A., Gallart-Mateu D., Harrache D., Djaroud S., de la Guardia M., Kameche M. (2017) Conductimetric study of struvite crystallization in water as a function of pH. Journal of Crystal Growth 471: 42 - 52.
11. Niemiec W. (1995) Ekologiczne utylizacje odchodów zwierzęcych w gospodarstwach górskich. Wojewódzki Inspektorat Ochrony Środowiska, Kraków: 1 - 66.
12. Pokhrel S. P., Milke M.W., Bello-Mendoza R., Buitrón G., Thiele J. (2018) Use of solid phosphorus fractionation data to evaluate phosphorus release from waste activated sludge. Waste Manage. 76: 90 - 97.
13. Psenner R., Puckso R., Sager M. (1984) Die Fraktionierung organischer und anorganischer Phosphorverbindungen von Sedimenten. Arch. Hydrobiol./Suppl. 70: 111 - 155.
14. Rollett A., Taylor M., Chambers B., Litterick A. (2015) Guidance on Suitable Organic Material Applications for Land Restoration and Improvement: Final Report.
15. Scarlat N., Dallemand J. F., Fahl F. (2018) Biogas: Developments and perspectives in Europe. Renevable Energy 129: 457 - 472.
16. Svoboda N., Taube F., Wienforth B., Kluss C., Kage H., Herrmann A. (2013) Nitrogen leaching losses after biogas residue application to maize. Soil Tillage Res. 130: 69 - 80.
17. Tambone F., Adani F. (2017) Nitrogen mineralization from digestate in comparison to sewage sludge, compost and urea in a laboratory incubated soil experiment. J. Plant Nutr. Soil Sci.: 1 - 11.
18. Tambone F., Orzi V., D'Imporzano G., Adani F. (2017) Solid and liquid fractionation of digestate: mass balance, chemical characterization, and agronomic and environmental value. Bioresour. Technol. 243: 1251 - 1256.
19. Tansel B., Lunn G., Monje O. (2018) Struvite formation and decomposition characteristics for ammonia and phosphorus recovery: A review of magnesium-ammonia phosphate interactions. Chemosphere 194: 504 - 514.
20. Turner B. L., Leytem A. B. (2004) Phosphorus compounds in sequential extracts of animal manures: chemical speciation and a novel fractionation procedure. Environ. Sci. Technol. 38: 6101 - 6108.
21. Xie C., Zhao J., Tang J., Xu J., Lin X., Xu X. (2011b) The phosphorus fractions and alkaline phosphatase activities in sludge. Bioresource Technol. 102: 2455 - 2461.
22. Ye Z., Shen Y., Ye X., Zhang Z., Chen S., Shi J. (2014) Phosphorus recovery from wastewater by struvite crystallization: Property of aggregates. Journal of Environmental Sciences 26: 991 - 1000.