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Analysis of heavy metal content in sewage sludge as an instrument of selecting new method of sustainable sewage sludge management

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ABSTRACT

The paper presents the monitoring of qualitative and quantitative changes of raw wastewater entering Rybnik–Orzepowice wastewater treatment facility, Poland as well as the changes in the composition of sewage sludge in the period of 2005–2018. The analyses conducted in the study proved that despite the increasing amount of raw wastewater entering the treatment plant, the introduction of a constant monitoring system of the raw wastewater and sewage sludge along with an innovative bioconversion technology will enable to significantly improve the treatment processes and to produce biomass fuel for professional heat and energy generation. The monitoring of the composition of the produced sewage sludge showed that with the development of wastewater treatment technology, the average concentration of zinc and lead systematically decreased in the analyzed period of 2005–2018. The only exception was the average annual concentration of copper which increased in the course of the conducted monitoring.

Keywords: Wastewater, Monitoring; Heavy metals; Sewage sludge; Biodiversity; Wastewater management legislation; Bioconversion

1. Introduction

The improper management of domestic wastewater and sewage resulting from industrial activities as well as inadequate treatment processes may lead to the deterioration of water quality in rivers into which the effluents from wastewater treatment plants are discharged. The discharges from treatment plants may also adversely affect the quality of both drinking water and tap water resources, and, in consequence, cause the decline of biodiversity [1,2]. According to Polish Legislation, sewerage services and the disposal and treatment of municipal wastewater belong to the tasks of local municipalities [3]. These are public services that aim at satisfying the collective needs of the local community. The Act on Maintaining Cleanliness and Order in Municipalities [4] defines wastewater as liquid waste temporarily collected in septic tanks. The definitions of wastewater were also included in the Act on Environmental Protection Law [5] and Water Law Act [6] in which the legislator specifies wastewater as:

- water which was used for economic or domestic purposes;
- liquid animal waste excluding livestock manure and urine intended for agricultural use;
- leachates from waste landfills and extractive waste dumping facilities where hazardous, non-hazardous and inert extractive waste is disposed, storage sites and recycling sites; used brines, curative and thermal waters;
- waters from cooling systems in electricity and heat generation plants;
- water from the drainage of mining plants excluding waters injected into the rock-mass under the condition that the types and amounts of substances contained in

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the injected water are the same as those in the abstracted water with the exception of non-contaminated waters from the drainage of mining plants (saline waters). Mine waters usually contain an excessively high content of chloride and sulfate ions, and their sum is commonly called salinity.

- used waters discharged from fish culture sites or flow-through fish farming systems characterized by reverse uptake if the types and amounts of substances contained in the waters exceed the values determined in the conditions of wastewater discharge into waters stipulated by the Water Law Act;
- used waters discharged from fish culture sites or fish and other aquatic organisms farming systems in still water ponds if the feed conversion ratio in consecutive production cycles exceeds 1,500 kg per 1 ha surface in 1 y of a given cycle.

Moreover, these two legal acts include three additional definitions, namely the definition of domestic wastewater, industrial wastewater and municipal wastewater.

Domestic wastewater means wastewater from residential buildings, residential settlements or public services which originate from the human metabolism or household activities as well as wastewater of similar content coming from such places. Industrial wastewater means wastewater that does not fall into the category of domestic wastewater, run-off rainwater or meltwater and which originates from commercial or industrial activities, storage, transportation and service sector or their mixture with wastewater generated by another entity and discharged by means of a sewerage system belonging to this entity. Municipal wastewater means domestic wastewater or the mixture of domestic wastewater and industrial wastewater, run-off rainwater and/or meltwater discharged by means of sewerage infrastructure and wastewater treatment systems belonging to the municipality.

The issue of wastewater discharge and treatment has been regulated by the Act on Collective Water Supply and Collective Sewage Disposal [7]. The treatment of wastewater is inherently connected with the necessity of sewage sludge management. The legal definition and the permitted methods of sewage sludge management to be used by the entity generating the sludge are included in the Act on Waste [8] and in its executive act – The Regulation of the Minister of Environment on the Municipal Sewage Sludge [9].

Under the provisions of the Act on Waste, municipal sewage sludge should be understood as sewage sludge that comes from wastewater treatment plants, fermentation chambers or other installations processing both municipal wastewater and wastewater of other origins which is characterized by a similar composition.

The above-mentioned acts implement the EU directives concerning wastewater treatment and water protection, in particular, Council Directive 91/271/EEC of 21 May 1991 on urban wastewater treatment [10], Directive 2000/60/EC of 23 October 2000 establishing a framework for Community action in the field of water policy [11] and Council Directive 86/278/EEC of 12 June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture [12].

The accession of Poland to the European Union brought about a dynamic development of sewerage networks and wastewater treatment plants in the country. At the same time, rapid economic development resulted in the generation of large volumes of municipal sewage sludge. In practice, almost the whole volume of the wastewater flow entering the plant is transformed into biomass, and, thus wastewater treatment means producing sewage sludge [13]. Since 2005, a regular increase in the volume of waste generated in Poland has been observed [14]. In 2005, 486.1 thousand Mg of dry mass sewage sludge was created in municipal wastewater treatment plants; in 2012 the amount of dry sewage sludge reached the level of 533.3 thousand Mg, while in 2018 as much as 583.1 thousand Mg [15].

Despite the necessity to design an integrated system for the adequate processing and management of the produced sewage sludge, the situation is not getting better. However, some activities intended to minimize the volume of the generated sewage sludge have been undertaken. In 2015, over 7% of municipal sewage sludge was deposited, approx. 14% thermally conversed, 19% was used in agriculture, 4% was used for land reclamation (including agricultural applications), and finally, over 8% was used in the cultivation of plants for compost production [15]. For the purpose of comparison, data concerning the year 2018 show that 1.8% of municipal sewage sludge was deposited, 19.1% underwent thermal conversion, 20.3% was used in agriculture, 3% was used for land reclamation (including arable lands), while 4.3% was used in the cultivation of plants for compost production [16]. Almost 43% of sewage sludge is intended for other purposes, which justifies the need to search for and to intensify sludge treatment processes in order to achieve new products. The selection of sewage sludge treatment processes, and in particular the method of its final management (utilization) constitutes a common challenge for the majority of wastewater treatment plants in Poland [17,18].

The operators of wastewater treatment plants are compelled to select the most relevant option of sewage sludge stabilization and management (i.e., gasification [19,20], co-gasification [21–23], combustion [24,25]). The method should be the most efficient one under given conditions in addition to being environmentally friendly, cost-effective and most of all providing a secure long-term solution to the problem. The proper selection of an individual solution depends on a combination of factors such as the quality of the sewage sludge, the recent development of technologies aimed at dehydrating, drying, the bioconversion or incineration of the sludge as well as LCA [26]. Municipal sewage sludge comes from wastewater treatment plants, fermentation chambers or other installations processing both municipal wastewater and wastewater of other origins which is characterized by a similar composition. In the past, the only available method of sewage sludge management was its disposal to landfill facilities, or alternatively, a treatment that allowed utilizing it for purposes connected with the natural environment. Technologies that enable the recovery of biogas in the processes of stabilizing sewage sludge and its subsequent use in electricity and/or heat generation for the operator's own needs constitute some of the preferable solutions to sewage sludge management [27]. Legal standards permit the use of sewage sludge in agriculture, for the cultivation of plants for compost production, for the cultivation of plants that are not intended for human consumption and feed, for land reclamation (including arable lands), for compost production or forestry, etc. The use of sewage sludge is permissible after some very restrictive requirements have been met. Sewage sludge has an increasing potential to be used as a source of biomass energy [28]. When sewage sludge is co-incinerated in the amount of up to 1% by fuel weight, fuel emission standards do not change. When the sludge is co-incinerated in an amount of more than 1%, continuous measurements of pollutant emissions, including HCl and HF, should be carried out, as well as continuous measurements of the exhaust gas flow velocity, exhaust gas temperature, exhaust gas static pressure and humidity coefficient. According to the law in force, sewage sludge is considered to be pure CO_2-neutral biomass with a zero CO_2 emission factor. The stabilization of the sewage sludge, that is, eliminating its putrescibility as well as environmental threats and hazards for human health and life, constitutes the fundamental issue to address. Sewage sludge which leaves the wastewater treatment facility must be safe for both the environment and human health [15].

Municipal incineration plants constitute an option that facilitates sewage sludge management despite the fact that this is one of the last methods in the hierarchy of its disposal [27]. In such a case, the incineration installation limits to the minimum the necessity of transferring the sludge to other facilities which are onerous to the local residents. For small wastewater treatment plants, the construction of an incineration facility is not cost-effective; therefore, the sewage sludge has to be removed from the plant and disposed of or recycled. Incineration is the best option in the case of sewage sludge whose heavy metal content exceeds the permissible levels. Hence, this method is most suitable for wastewater treatment plants located in large cities on account of a considerable share of industrial wastewater with a high concentration of heavy metals. Due to the relatively high content of nitrogen and sulfur in addition to heavy metals, the incineration facilities have to meet several technical requirements intended to limit the emission of harmful gases so that they comply with the Integrated Pollution Prevention Control (IPPC) standards [29].

Professional incineration plants and energy generation plants that thermally utilize sewage sludge face the challenge of handling the ash produced in the process because it is often characterized by a high content of heavy metals. In order to be adequately disposed of or commercially utilized, for example in road construction, the ash requires additional high-temperature transformation – the process of vitrification. The total output of incineration plants operating in Poland amounts to 176,000 Mg/y. An alternative solution consists of utilizing the treated sewage sludge in the process of co-combustion with coal dust in rotary cement kilns. Sewage sludge co-combustion is a common procedure in the EU, especially in cement plants in Germany, Switzerland, Belgium and Holland [30,31]. The mass fraction of fuel coming from sewage sludge usually does not exceed 10% in the process of co-combustion. The clear advantage of this method lies in the low investment cost, as well as the technological and environmental safety.

The aim of this study is to validate the thesis that a system analysis of heavy metal content in wastewater entering a wastewater treatment plant may contribute to the selection of an effective future method of sustainable sewage sludge management. The research was conducted using 2005–2018 data obtained from the Rybnik–Orzepowice treatment facility, Poland and can serve as an example of an innovative solution to the challenges connected with sewage sludge management. Additionally, it demonstrates that sewage sludge may be considered as a base for new products to be successfully introduced into the market. The applied technology of sewage sludge bioconversion is designed for the production of biomass fuel for professional heat and energy generation. The produced energy biomass has the adequate form and calorific value in order to be combusted in the process of heat or electrical energy generation. The fuel is composed of sewage sludge and the admixture of other components of average calorific value; as a result, the calorific value of this bioconversion product is about 9.5 MJ/kg, which is comparable with coal mixtures of low calorific value.

2. Materials and methods

The following two methods were used to analyze the content of heavy metals: inductively coupled plasma mass spectrometry (ICP-MS) and atomic absorption spectroscopy (AAS) for determining the content of mercury. The ICP-MS method is applied according to Polish standard PN-EN ISO 17294-2:2016-11 and constitutes one of the most innovative techniques of elemental analysis used in determining the content of heavy metals in wastewater and sewage sludge. The ICP-MS method is characterized by a high level of sensitivity and precision in addition to the ability to simultaneously detecting numerous chemical elements because each chemical element emits its characteristic electromagnetic radiation. Inductively coupled plasma is generated during the flow of gas (argon) through a tube (torch) wrapped with an induction coil, whereas a radiofrequency generator (27 or 40 MHz) produces an oscillating current in the induction coil.

The AAS method according to Polish standard PN-EN 1483:2007 is applied in the quantitative determination of chosen chemical elements (predominantly metals) in liquid and gaseous samples. The measuring principle is based on the phenomenon of the absorption of specific wavelength radiation by free atoms of a given chemical element. Quantitative and qualitative analyses are carried out in a continuous mode on the premises of the Rybnik–Orzepowice wastewater treatment facility. The analyzed data covers the period of 2005–2018. The analyses are conducted by a designated laboratory and involve such parameters as the contents of zinc, chromium, copper, lead and mercury in mg/L of the wastewater entering the plant as well as the content of heavy metals per 1 kg of the dry mass of sewage sludge. Furthermore, there is standard monitoring of the volume of wastewater entering the plant as well as the volume of the discharged sewage sludge. Five pressure pipelines that supply the wastewater to the treatment plant are equipped with electromagnetic flowmeters. The analysis of wastewater parameters is performed in a continuous mode; the chemical oxygen demand is determined using the spectrophotometric method according to Polish standard PN-ISO 15705:2005, while the biological oxygen demand within a

5 d period is determined by means of the optical method in accordance with Polish standard PN-EN 1899-1:2002.

The dry mass of sewage sludge is determined by means of weight method according to Polish standard PN-EN 15934:2013-02. The leachates produced in the dewatering chamber during the processes of excess sludge dewatering and the compaction of fermented sludge are returned to the system at the inlet of the wastewater treatment plant. Leachate analyses are made randomly by the onsite laboratory if the need arises. The samples are examined mainly in terms of total suspended solids in wastewater, total phosphorus, total nitrogen and ammonia. The sewage sludge parameters are recorded for statistical purposes in a register of municipal sewage sludge which provides information concerning sludge composition, properties and the way of its management. Heavy metal tests are continuously carried out by an external research laboratory with principal component analysis (PCA) accreditation, which means the tests are performed according to the CRM standard.

3. Results and discussion

The initial stage of the research involved analyzing the changes of the volume and the content of heavy metals in the wastewater entering the plant and the generated sewage sludge over the 14-year period of 2005–2018. The analyzed parameters included the average annual flow of raw wastewater, the annual volume of generated sewage sludge (Mg/y), the average annual chemical oxygen demand (m^3/y) and the average annual content of zinc, chromium, copper and lead (mg/L). The analysis of the amount and content of heavy metals in raw wastewater provides information concerning the currently generated pollutants, while the analysis of sewage sludge understood as a certain kind of "pollution memory" provides data concerning the accumulation of pollutants over a longer period of time. Other parameters, such as Cd, Ni and Hg, did not exceed the values delineated by the ordinance of the Minister of the Environment; therefore they were not considered in the comparative analyses. The results of the study on the changes in the content of heavy metals in the sewage sludge will facilitate the selection of an effective future method of sewage sludge management.

Data concerning the raw wastewater entering the treatment facility were arranged into matrix X (14 × 6), where the rows determine the averaged sample of wastewater entering the plant in the period of 2005–2018, whereas the columns represent the following parameters: the flow of raw wastewater in a given year (m^3/y), the chemical oxygen demand as well as the averaged concentrations of heavy metals – zinc, chromium, copper and lead (parameters 1–6, mg/L). Data concerning the content of heavy metals in the sewage sludge were arranged in matrix Y (14 × 5), where the rows reflect the sample of sewage sludge taken in the period of 2005–2018, while the columns represent the averaged volumes of the sewage sludge generated in a given year (Mg/y, parameter 1) and the averaged concentrations of the heavy metals – zinc, chromium, copper and lead (mg/L of dry mass, parameters 2–5). The simplest method of tracing the differences and similarities among the averaged samples of wastewater or the averaged samples of sewage sludge is their visualization in the space of measured parameters. Due to the fact that it would require a 6-dimensional space, the PCA was applied [32–35], which effectively enables dimensionality reduction and simultaneously allows preserving the information on the analyzed phenomena. The PCA constitutes one of the most fundamental classic chemometric methods of dimensionality reduction, and, in consequence the partial elimination of measurement error, with subsequent visualization if data compression is effective.

From the mathematical point of view, it can be presented as follows:

$$X(m,n) = S(m,\mathrm{fn}) \times D'(n,\mathrm{fn}) \quad (1)$$

where matrix S is the score matrix and matrix D is the loading matrix. Matrix S contains all information regarding the analyzed samples (in the case of the analyzed data, these are the average annual samples of raw wastewater entering the plant); whereas matrix D contains all information on the analyzed parameters. The columns in matrix S and the rows in matrix D are called the principal components (PCs), while fn signifies the number of significant Principal Components which is determined based on % of the described data variance. If the data compression using the PCA is effective, the analyzed data may be visualized by means of the projection of objects and parameters on the planes defined by particular principal components (e.g., PC1 vs. PC2, PC1 vs. PC3, etc.). The PCA model constructed for matrix X (14 × 6) with three significant principal components described 86.03% of the data variance. The score plots and loading plots obtained as a result of the analysis are presented in Fig. 1.

The PC1, which described 51.34% of the total data variance, allowed dividing the studied objects into two main groups. The first group collects the averaged samples of wastewater entering the treatment plant in the period of 2005–2009 (objects nos. 1–5) and the other group is composed of the averaged samples of wastewater entering the treatment plant in 2010 and in 2012–2018 (objects nos. 6 and 8–14). The uniqueness of the averaged sample of wastewater entering the treatment plant in 2011 (object no. 7) can be also observed. Based on the loading plot, it is possible to conclude that the averaged samples of wastewater entering the treatment plant in the period of 2005–2009 (objects nos. 1–5) are unique due to relatively high annual average chemical oxygen demand, and the annual average concentration of chrome and lead (parameters nos. 2, 4 and 6, respectively), as well as the low annual concentration of the remaining parameters. A contrary tendency could be observed for the averaged samples of wastewater entering the treatment plant in 2010 and in 2012–2018 (objects nos. 6 and 8–14). Namely, the objects collected in the second group are characterized by a relatively higher average annual raw wastewater flow as well as the average annual concentration of zinc and copper (parameters nos. 1, 3 and 5) than the remaining objects. The greatest difference along PC1 is observed between the averaged samples of wastewater entering the treatment plant in 2010 and in 2012–2018 (objects nos. 6 and 8–14) and the averaged samples of wastewater entering the treatment plant in 2006 and in 2009 (objects nos. 2 and 13, respectively). Namely, object no. 2 is characterized by the highest annual concentration of chrome and lead (parameters nos. 4 and 6) and the lowest annual concentration of copper (parameter no. 5), whereas the averaged sample of wastewater entering the treatment plant in 2017 (object no. 13) is unique due to the highest average annual raw wastewater flow (parameter no. 1), the highest annual average concentration of copper (parameter no. 5) and the lowest annual average concentrations of chrome and lead (parameters nos. 4 and 6).

The PC2, describing 19.97% of the total data variance, reflects the difference between the averaged sample of wastewater entering the treatment plant in 2011 (objects no. 7) and the averaged samples of wastewater entering the treatment plant in 2005, 2006 and 2010 (objects nos. 1, 2 and 6) due to the highest average annual chemical oxygen demand (parameter no. 2) observed for object no. 7 and the highest annual average concentration of zinc (parameter no. 3) observed for objects nos. 1, 2 and 6. The PC3, which described 14.72% of the total variance, is constructed mainly due to the difference between the averaged sample of wastewater entering the treatment plant in 2016 (object no. 12) and the averaged sample of wastewater entering the treatment plant in 2011 (object no. 7). Object no. 12 is characterized by the highest average annual chemical oxygen demand (parameter no. 2), whereas object no. 7 is unique due to the highest annual average concentration of chrome (parameter no. 4). Moreover, the loading plots revealed a negative correlation between the annual average chemical oxygen demand and the annual average concentration of zinc (parameters nos. 2 and 3), between the average annual raw wastewater flow and the average annual concentration of chrome (parameters nos. 1 and 4) as well as between the average annual raw wastewater flow and the annual mean concentration of copper (parameters nos. 1 and 5).

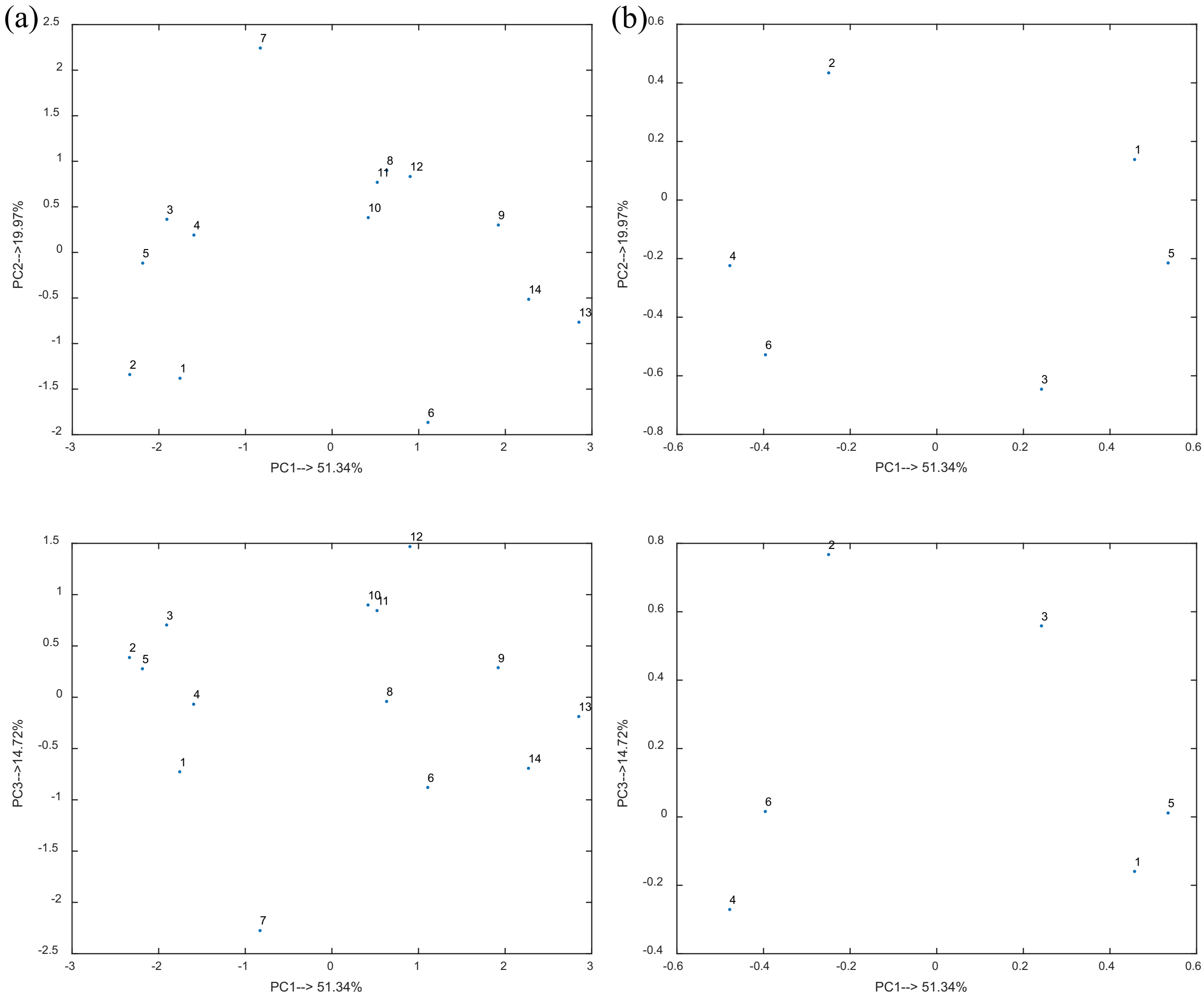

Fig. 1. (a) Score plots and (b) loading plots as a result of PCA for the centered and standardized data *X* (14 × 6).

Different observations can be made based on the analysis of the PCA model constructed for the heavy metal content in the sewage sludge collected between 2005 and 2018. The PCA model constructed for matrix Y (14 × 5), with three significant Principal Components, described 87.60% of the total data variance. The score plots and loading plots obtained as a result of the analysis are presented in Fig. 2.

The PC1 describes 46.00% of the total data variance. It is constructed mainly due to the difference between the samples of sewage sludge collected in 2005, 2006, 2009 and 2010 (objects 1, 3, 5 and 6, respectively) and all the remaining objects. Based on the loading plots, it is possible to conclude that the samples of sewage sludge collected in 2005, 2006, 2009 and 2010 (objects 1, 3, 5 and 6) differ from the remaining objects due to the relatively higher annual average concentration of zinc and lead (parameters nos. 2 and 5, respectively). The samples of sewage sludge collected in 2006, 2008 and in 2011–2018 (objects nos. 2, 4 and 7–14) are characterized by the relatively higher annual concentration of copper (parameter no. 4) and a low annual average concentration of zinc and lead (parameters nos. 2 and 5, respectively). Moreover, the sample of sewage sludge collected in 2007 (object no. 3) is unique due to the highest annual average concentration of lead (parameter no. 5), whereas the sample of sewage sludge collected in 2018 (object no. 14) is characterized by the lowest value of the annual average concentration of chromium (parameter no. 3) among all the studied samples. The PC2 which describes 23.13% of total data variance is constructed mainly due to the greatest difference between the sample of sewage sludge collected in 2015 (object no. 11) and in 2010 (object no. 6). Object no. 11 is characterized by the highest annual average concentration of copper (parameter no. 4) and a relatively low annual amount of produced sewage sludge (parameter no. 1), whereas object no. 6 is unique due to the lowest annual average concentration of copper (parameter no. 4). The PC3 which describes the 18.44% of the total data variance is constructed due to the significant difference between the sample of sewage sludge collected in 2008 (object no. 4) and the samples of sewage sludge collected in 2012 and 2013 (objects nos. 8 and 9, respectively). The sample of sewage sludge collected in 2008 (object no. 4) is unique due to the lowest annual average concentration of copper (parameter no. 4), whereas the samples of sewage sludge collected in 2012 and 2013 (objects nos. 8 and 9) are characterized by a relatively higher

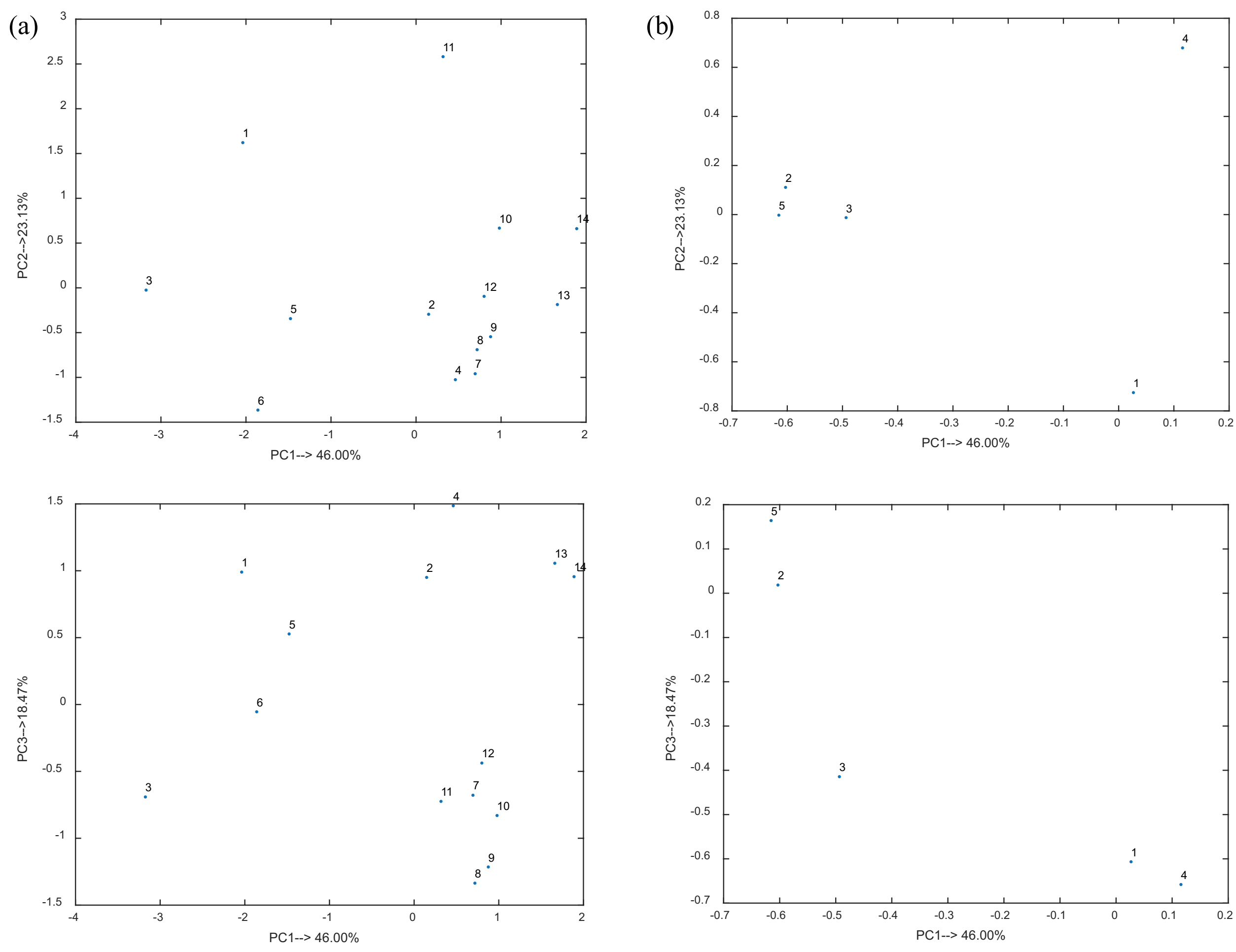

Fig. 2. (a) Score plots and (b) loading plots as a result of PCA for the centered and standardized data Y (14 × 5).

Table 1
The contents of heavy metals in raw wastewater entering the facility Rybnik–Orzepowice, Poland in 2018

Heavy metal	Unit	Values for Q_1, Q_2, Q_3 and Q_4				Average	Minimum	Maximum
Zinc	mg/L	0.1200	0.1400	0.1300	0.1500	0.1350	0.1200	0.1500
Chromium[a]	mg/L	0.0000[c]	0.0000[c]	0.0023	0.0036	0.0015	0.0000	0.0036
Copper	mg/L	0.0320	0.0400	0.0500	0.0600	0.0455	0.0320	0.0600
Lead[b]	mg/L	0.0000[c]	0.0000[c]	0.0059	0.0000[c]	0.0015	0.0000	0.0059

[a]Lower limit of quantification – 0.002 mg/L;
[b]Lower limit of quantification – 0.005 mg/L;
[c]The determined value was below the lower limit of quantification.

Table 2
The contents of heavy metals (mg/kg) in stabilized sewage sludge from the facility Rybnik–Orzepowice, Poland in 2018

Heavy metal	Average	Minimum	Maximum
Zinc	504.83	322.00	829.00
Chromium	25.70	14.80	45.30
Copper	179.17	127.00	293.00
Lead	18.83	11.00	30.00

annual amount of produced sewage sludge (parameter no. 1) in comparison to the remaining studied objects. Moreover, the sample of sewage sludge collected in 2012 (object no. 8) is characterized by the highest annual amount of produced sewage sludge (parameter no. 1).

In 2018, 6.4 million m^3 of raw wastewater entered the treatment plant Rybnik–Orzepowice, Poland. The largest volume was recorded in May – 596 thousand m^3 and the smallest one in November – 460 thousand m^3. The inflow characterizes of a high degree of regularity. In terms of the consecutive quarters of the year, the inflow of wastewater to the treatment plant can be broken down as follows: Quarter 1 – 25%, Quarter 2 – 27%, Quarter 3 – 24% and Quarter 4 – 24%. The content of heavy metals in the wastewater which enters the plant constitutes an important factor determining the future method of sewage sludge management. The averaged contents of zinc, chromium, copper and lead in the raw wastewater for particular quarters of the year 2018 are shown in Table 1.

In 2018, the treatment facility generated 5,869 Mg of sewage sludge, which converted to dry mass totals 1,356 Mg. The sewage sludge was subject to the processes of fermentation, hygienization and dewatering. The test results for stabilized sewage sludge (sewage sludge after liming) with reference to year 2018 are presented in Table 2. The sewage sludge was characterized by stable parameters. The only significant changes occurred in the pH values which ranged from 7.90 (September, 2018) to 12.00 (January and May, 2018), with the average of 10.85.

The content of heavy metals in the analyzed sewage sludge occurs in the following sequence: Zn > Cu > Cr > Pb, which confirms the observations concerning municipal wastewater treatment plants [15,36]. The average content of heavy metals in the studied sewage sludge was within the limits prescribed in the Regulation of the Minister for the Environment on Municipal Sewage Sludge and in Directive 86/278/EEC [37]. Similarly, the parameter values for Cd, Ni, and Hg which obviously constitute an important criterion for assessing the possibility of using the sludge for reclamation or agricultural purposes did not exceed the limited values in the monitored period. Moreover, the maximum values did not exceed the permissible levels. In light of the above, it may be stated that the sewage sludge from the Rybnik–Orzepowice facility is suitable to be used for agricultural purposes as well as for land reclamation.

4. Conclusions

The EU Water Framework Directive stipulated the ecological and chemical status of rivers, lakes as well as ground and coastal waters. Like in the whole EU, the dynamic industrial development in Poland generates an ever increasing amount of wastewater containing substances which adversely impact water ecosystems. The aim of this study was to qualitatively and quantitatively analyze the sewage entering the wastewater treatment plant as well as to assess the content of heavy metals in the sewage sludge based on the example of 2005–2018 data from the Rybnik–Orzepowice facility, Poland. It was found that the qualitative and quantitative parameters of raw wastewater entering the treatment facility over a period of several years have changed significantly. In the initial period of the monitoring (years 2005–2009), within a year the wastewater characterized of a relatively higher chemical oxygen demand as well as higher concentrations of lead and chromium. With the introduction of restrictive regulations concerning water protection and sewage management along with the implementation of a systematic monitoring of pollutants and more effective water treatment processes, it was observed that despite an increased amount of raw wastewater entering the facility the concentrations of heavy metals considerably decreased. Data analysis of the amount of the monitored sewage sludge and the content of heavy metals over the period of 14 y confirmed that the average annual concentrations of lead and zinc in sewage sludge samples in 2005–2010 were higher than those in 2011–2018. The tendency was not confirmed in the case of the average annual concentration of copper in the sewage sludge. In addition, it was found that in 2018, the average annual concentration of chromium was the lowest in the whole monitored period.

References

[1] M. Garrido-Baserba, M. Molinos-Senante, J.M. Abelleira-Pereira, L.A. Fdez-Güelfo, M. Poch, F. Hernandez-Sancho, Selecting sewage sludge treatment alternatives in modern wastewater treatment plants using environmental decision support systems, J. Cleaner Prod., 107 (2015) 410–419.
[2] F.P. Camargo, P.S. Tonello, A.C.A. dos Santos, I.C. Silveira Duarte, Removal of toxic metals from sewage sludge through chemical, physical, and biological treatments—a review, Water Air Soil Pollut., 227 (2016) 433–437.
[3] Act of 8 March 1990 on Commune Self-Government (Dz.U. z 2020 r. poz. 713).
[4] Act of 13 September 1996 on Maintaining Cleanliness and Order in Municipalities (Dz.U. z 2020 r. poz. 1439).
[5] Act of 27 April 2001, Environmental Protection Law (Dz.U. z 2020 r. poz. 1219).
[6] Act of 20 July 2017 Water Law (Dz.U. z 2020 r. poz. 310).
[7] Act of June 7, 2001 on Collective Water Supply and Collective Sewage Disposal (Dz.U. z 2019 r. poz. 1437).
[8] Act of 14 December 2012 on Waste (Dz. U. z 2020 r., poz. 797).
[9] Regulation of the Minister of Environment of 6 February 2015 on Municipal Sewage Sludge (Dz. U. z 2015 r., poz. 257).
[10] Directive 91/271/EEC of 21 May 1991 Concerning Urban Waste Water Treatment (Dz. Urz. WE L 135 z 30.05.1991).
[11] Directive 2000/60/EC of 23 October 2000 Establishing a Framework for Community Action in the Field of Water Policy (Dz. Urz. WE L 327 z 22.12.2000).
[12] Directive 86/278/EEC of 12 June 1986 on the Protection of the Environment, in Particular the Soil, When Sewage Sludge is Used in Agriculture (Dz. Urz. WE L 181 z 04.07.1986).
[13] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the Use of Energy from Renewable Sources, Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC.
[14] Central Statistical Office, Environment Protection, 2019. Available at: http://stat.gov.pl
[15] M. Tytła, Assessment of heavy metal pollution and potential ecological risk in sewage sludge from municipal wastewater treatment plant located in the most industrialized region in Poland – Case Study, Int. J. Environ. Res. Public Health, 16 (2019) 2430–2433.
[16] H. Bauman-Kaszubska, M. Sikorski, Methodological basis for environmental impact assessments of sewage sludge used for agricultural or natural purposes, Inżynieria i Ochrona Środowiska, 17 (2014) 199–210.
[17] Strategy for Dealing with Municipal Sewage Sludge for Years 2019–2022, Ministry of Environment, 18 November 2018.
[18] Council Directive of 12th June 1986 on the Protection of the Environment, and in Particular of the Soil, When Sewage Sludge is Used in Agriculture (86/278/EEC).
[19] M. Speidel, G. Kraaij, A. Wörner, A new process concept for highly efficient conversion of sewage sludge by combined fermentation and gasification and power generation in a hybrid system consisting of a SOFC and a gas turbine, Energy Convers. Manage., 98 (2015) 259–267.
[20] B. Urych, A. Smolinski, Kinetics of sewage sludge pyrolysis and air gasification of its chars, Energy Fuels, 30 (2016) 4869–4878.
[21] A. Smolinski, N. Howaniec, A. Bąk, Utilization of energy crops and sewage sludge in the process of co-gasification for sustainable hydrogen production, Energies, 11 (2018) 809, doi: 10.3390/en11040809.
[22] A. Ramos, E. Monteiro, V. Silva, A. Rouboa, Co-gasification and recent developments on waste-to-energy conversion: a review, Renewable Sustainable Energy Rev., 81 (2018) 380–398.
[23] A. Smoliński, N. Howaniec, Co-gasification of coal/sewage sludge blends to hydrogen-rich gas with the application of simulated high temperature reactor excess heat, Int. J. Hydrogen Energy, 41 (2016) 8154–8158.
[24] Y. Lin, Y. Liao, Z. Yu, S. Fang, X. Ma, The investigation of co-combustion of sewage sludge and oil shale using thermogravimetric analysis, Thermochim. Acta, 653 (2017) 71–78.
[25] S. Niu, M. Chen, Y. Li, J. Song, Co-combustion characteristics of municipal sewage sludge and bituminous coal, J. Therm. Anal. Calorim., 131 (2018) 1821–1834.
[26] Y.J. Suh, P. Rousseaux, An LCA of alternative wastewater sludge treatment scenarios, Resour. Conserv. Recycl., 35 (2002) 191–200.
[27] The Act of 20 February 2015 on Renewable Energy Sources [Dz.U. 2020. poz. 261].
[28] B. Kołodziej, J. Antonkiewicz, Assessment of different doses of sewage sludge application on Virginia fanpetals biomass feedstock production, Annu. Set Environ. Prot., 22 (2020) 488–513.
[29] Summary of Directive 2008/1/EC Concerning Integrated Pollution Prevention and Control (The IPPC Directive), European Commission, 2008.
[30] N. Skoglund, L. Bäfver, J. Fahlströmd, E. Holmén, C. Renström, Fuel design in co-combustion of demolition wood chips and municipal sewage sludge, Fuel Process. Technol., 141 (2016) 196–201.
[31] Z. Xiao, X. Yuan, L. Jiang, X. Chen, H. Li, G. Zeng, L. Leng, H. Wang, H. Huang, Energy recovery and secondary pollutant emission from the combustion of co-pelletized fuel from municipal sewage sludge and wood sawdust, Energy, 91 (2015) 441–450.
[32] T. Joliffe, Principal Components Analysis, 1st ed., Springer, New York, 1986.
[33] N. Howaniec, A. Smoliński, Influence of fuel blend ash components on steam co-gasification of coal and biomass – chemometric study, Energy, 78 (2014) 814–825.
[34] A. Smoliński, N. Howaniec, K. Stańczyk, A comparative experimental study of biomass, lignite and hard coal steam gasification, Renewable Energy, 36 (2011) 1836–1842.
[35] S. Wold, Principal components analysis, Chemom. Intell. Lab. Syst., 2 (1987) 37–52.
[36] J. Gawdzik, B. Gawdzik, Mobility of heavy metals in municipal sewage sludge from different throughput sewage treatment plant, Pol. J. Environ. Stud., 21 (2012) 1603–1611.
[37] Directive 86/278/EEC of 12 June 1986 on the Protection of the Environment, and in Particular the Soil, When Sewage Sludge is Used in Agriculture (Dz. Urz. WE L 181).