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Analysis of the possibilities of using sewage sludge for agricultural use

Analiza możliwości wykorzystania osadów ściekowych do celów rolniczych

Dominika Łomińska-Płatek, Łucja Figura*)

Keywords: *osady ściekowe, zastosowanie rolnicze, metale ciężkie, rekultywacja*

Abstract
The primary purpose of wastewater treatment plants (WWTPs) is to treat wastewater and prevent water pollution, and consequently to protect the health of their users. These facilities have been viewed in this way for decades. Currently, this approach is being transformed and WWTPs are beginning to be seen as bioenergy plants for water reclamation and resource recovery. The change in the classical wastewater treatment paradigm is the result of the transformation of a linear economic system into a circular one. Therefore, the goal is not only highly efficient wastewater treatment, but also resource production.
The aim of this paper was to analyse the possibility of using sewage sludge for agricultural purposes. Samples were taken from two different WWTPs in Poland. As part of the research, basic physical and chemical parameters were examined. Then, the content of biogenic elements such as nitrogen (N) and phosphorus (P) was tested. Fourier transform infrared spectroscopy (FTIR) was used to identify and analyse the chemical structure of organic and inorganic compounds. An important part of the research was the analysis of the content of heavy metals and the analysis of the microbiological tests.
The research showed that the sludge analysed has potential for agricultural use due to its nutrient and organic matter content and low levels of heavy metals, although further stabilisation may be required to ensure safe levels of pathogens. However, it should be remembered that before sewage sludge is used for agricultural purposes, regular laboratory testing of its composition should be carried out.

Słowa kluczowe: *inner coating, pipeline, isolation, pipeline diameter*

Streszczenie
Podstawowym celem oczyszczalni ścieków (OŚ) jest oczyszczanie ścieków i zapobieganie zanieczyszczeniu wody, a w konsekwencji ochrona zdrowia ich użytkowników. Obiekty te są postrzegane w ten sposób od dziesięcioleci. Obecnie, to podejście się zmienia, a oczyszczalnie ścieków zaczynają być postrzegane jako zakłady produkcji surowców. Zmiana klasycznego paradygmatu oczyszczania ścieków jest wynikiem transformacji w gospodarkę o obiegu zamkniętym, gdzie głównym zadaniem OŚ jest nie tylko oczyszczanie ścieków, ale także produkcja cennych zasobów. Celem niniejszego artykułu była analiza możliwości wykorzystania osadów ściekowych do celów rolniczych. Próbki pobrano z dwóch różnych oczyszczalni ścieków zlokalizowanych w południowej Polsce. W ramach badań przeprowadzono podstawowe analizy parametrów fizyczno-chemicznych. Następnie zbadano zawartość pierwiastków biogennych, takich jak azot (N) i fosfor (P). W celu identyfikacji i analizy struktury chemicznej związków organicznych i nieorganicznych.zastosowano spektroskopię w podczerwieni z transformacją Fouriera (FTIR). Istotną częścią badań była analiza zawartości metali ciężkich oraz testów mikrobiologicznych.
Badania wykazały, że analizowane osady ściekowe mają potencjał do wykorzystania w rolnictwie ze względu na zawartość składników odżywczych i materii organicznej oraz niski poziom metali ciężkich, chociaż może być wymagana dalsza stabilizacja, aby zapewnić bezpieczny poziom patogenów. Należy jednak pamiętać, że przed wykorzystaniem osadów ściekowych do celów rolniczych należy przeprowadzać regularne badania laboratoryjne ich składu.

Introduction

Over the past few years, global warming has increasingly set the tone for the world economy. Combined with global population growth and increasing urbanisation in more and more regions of the world, demand for agricultural and food production is rising. There is a growing need to increase agricultural productivity while reducing its environmental impact. At the same time, the issue of water management is of particular importance in an era of global climate change. Over-exploitation of natural sources of drinking water and intensive agricultural practices that contaminate already scarce groundwater resources create an unfavourable balance, exacerbated by low rainfall. Recognising this problem, much emphasis has been placed in recent years on the effective purification and return of water to its natural cycle in the environment. However, this process is associated with the generation of a huge amount of sewage sludge (SS), the disposal of which is not a simple process and represents a significant challenge to society. The sharp increase in the mass of sludge produced in recent years has made the management of municipal sludge a very important environmental, technical and economic problem. A desirable solution that not only meets the need to dispose of sewage sludge, but at the same time uses it in an environmentally friendly way, is the use of sewage sludge in agriculture, which makes it possible to close the chain in line with the idea of a closed-loop economy. By using sewage sludge, it is possible to avoid the contamination of ground and surface water by the leaching of pollutants that would result from sludge storage [11]. There is also a risk of inadequately treated

*) **Dominika Łomińska-Płatek**, dominika.lominska@pk.edu.pl https://orcid.org/0000-0001-9377-5590; **Łucja Figura,** Cracow University of Technology, Faculty of Environmental Engineering and Energy, Department of Environmental Technologies

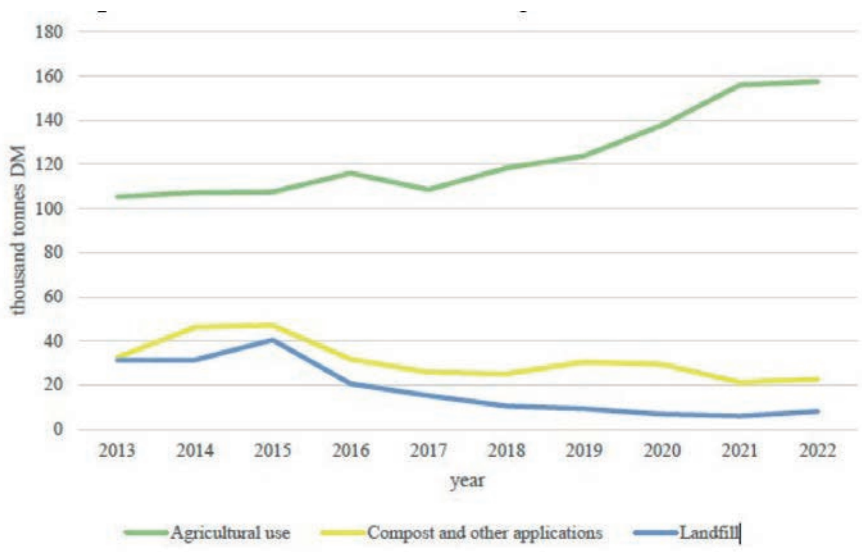


Fig. 1 Management of sludge from municipal WWTPs over the period 2013-2022 in Poland (own study based on [2])

Rys. 1. Gospodarka osadami z oczyszczalni komunalnych w latach 2013-2022 w Polsce (opracowanie własne na podstawie [2])

sewage sludge being re-circulated, which is toxic to the environment due to its high levels of pathogens and heavy metals. It follows that inadequately treated sludge can have negative effects on plants, soil and even human health and life. Numerous regulations on the reuse of sewage sludge, especially for natural purposes, aim to eliminate these risks through regular testing and monitoring of sludge composition and its impact on crop yields. Raising public awareness of both the dangers of improper sludge management and the benefits of sludge reuse will make it possible to introduce several technological solutions aimed at treating sludge for reuse as early as the design stage of a newly built wastewater treatment plant (WWTP).

Agriculture as a sludge use direction has an increasing share in the sludge management structure. The growing need to reduce dependence on industrial synthetic fertilisers, driven by their environmental impact and rising market costs, combined with the decreasing availability of farmyard manure, significantly increases the importance of alternative organic fertiliser resources. It's important to recognise that agriculture depletes soil nutrients faster than they are naturally replenished, necessitating the use of external inputs to maintain soil fertility. In this context, sewage sludge offers a valuable opportunity to play a more prominent role in crop fertilisation [1]. The use of SS in agriculture not only provides an opportunity to reuse a by-product of wastewater treatment, which is part of a closed-loop economy, but also fits in with the 12th Sustainable Development Goal: Responsible Consumption and Production. In 2022, up to 157.4 thousand tonnes of dry solid SS will be used for agricultural purposes in Poland [2], an increase of 50% compared to 2013, as shown in Figure 1.

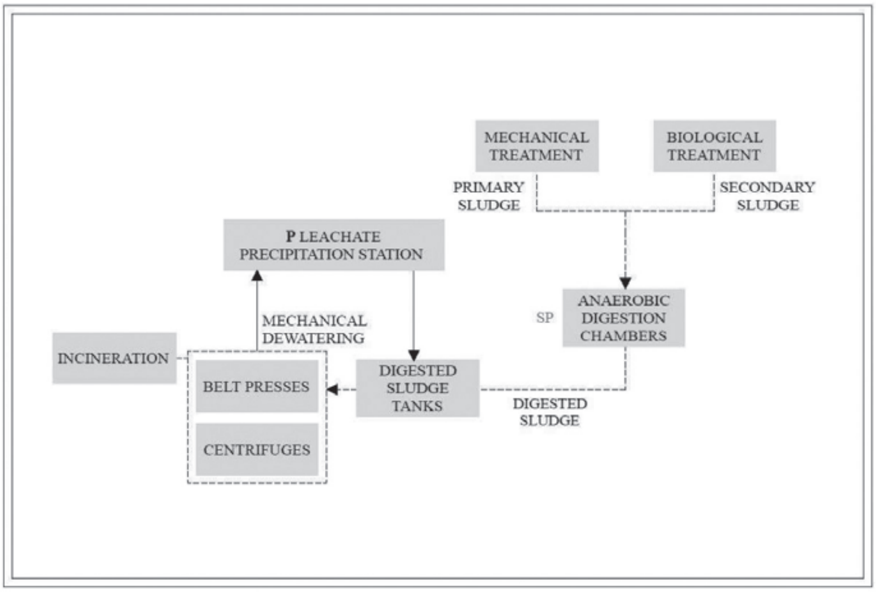
Agricultural intensification has led to significant soil degradation, contributing to problems such as erosion, acidification and salinisation that undermine the sustainability of agricultural systems. Fertilisers, while necessary for crop production, can exacerbate soil acidification and salinisation and pose serious risks to water quality through nitrate leaching and other nutrient run-off. There is also growing concern about the release of nitrous oxide and other greenhouse gases into the atmosphere. The decline in soil organic matter, a key indicator of soil health and a critical component of sustainable agriculture, further threatens soil resilience. Maintaining adequate levels of organic matter is essential to improve soil water retention, aeration, buffering capacity and to support microbial activity, which is essential for nutrient cycling and overall soil fertility [1], [4], [3]. Sewage sludge is a rich source of organic matter and biogenic elements, including N, P, K, macronutrients such as Ca, Mg and S, and micronutrients such as B, Cu, Fe and many others. Its use in agriculture has the potential to improve soil properties and increase crop growth and yield. Sludge characteristics play an important role when considering the final disposal of treated sludge, particularly when used for natural applications. The effects of sludge properties on soil and plants can be divided into three categories: physical, chemical and biological [5]. The primary, but difficult to measure, benefit of sludge reuse is the environmental aspect. The reuse of raw materials produced during wastewater treatment, which is an integral part of ever-increasing technological advances, offers an opportunity for sustainable development. Not only does it make it possible to use sludge with its nutritional potential, which could otherwise cause significant environmental damage during storage, but it also eliminates the need for highly energy-intensive fertiliser production. It has been observed that certain crops achieve higher yields when fertilised with sewage sludge instead of artificial fertiliser, providing a cost-effective option for farmers [7]. Another important issue is the high phosphorus content of organic sediments. This is an element that is essential for the development of all living organisms and cannot be replaced. Moreover, in 2017 it was included by the European Commission in the EU's Critical Raw Materials (CRM) list, which is a list of raw materials, mostly minerals, that are considered strategic for the EU's economy and have a high supply risk [21]. This means that the availability of phosphorus in the countries of the European Union is in deficit, while at the same time its global production is limited, with 70% of the reserves located in Morocco. "The production of phosphate fertilisers is based on the extraction of phosphate rock, the resources of which are unevenly distributed around the world and are rapidly diminishing. Therefore, the use of alternative sources of phosphorus, such as sewage sludge, is essential to avoid environmental pollution and to counteract negative scenarios related to the depletion of its resources" [8].

The use of sewage sludge in agriculture also carries risks related to potential contamination, which can cause damage to both the environment and human health. The main risks are contamination of crops with pathogens and bioaccumulation of toxic chemicals such as heavy metals. Irrigation of crops where sludge is present can release harmful bacteria and viruses into groundwater. This is a particular threat "as groundwater is a major source of drinking water for many people in developed countries". In addition, "long-term use of sewage sludge can have adverse effects on soil resources – increases in salinity, heavy metals in soils that can reduce the capacity of the soil to produce in the long term" [7]. The use of sewage sludge in agriculture thus offers many opportunities, but remains an innovative method that requires constant monitoring, ongoing research and development. Despite the challenges posed by this method of sludge management, it offers many advantages that fit in with sustainable development and the circular economy that is now the mainstream of civilisation.

Materials and methods

The purpose of the research was to analyse the possibilities of using sewage sludge for agricultural purposes. Samples were taken from 2 selected mechanical-biological WWTPs in southern Poland. The technological process in WWTP1 includes several stages that ensure effective removal of organic, chemical and biological contaminants from wastewater. Pre-sludge is formed in the mechanical part of the plant – the wastewater first passes through the coarse screens, then it is pumped to the fine screens, which enable the removal of larger solids. The effluent then goes to grit tanks where sand and other heavier particles are separated. The final stage of mechanical treatment is the primary clarifier, where organic and mineral suspended solids are removed by sedimentation. The next stage of treatment is biological, which takes place in 5 biological reactors where nitrification and denitrification take place to reduce nitrogen levels. The effluent is then sent to 10 secondary clarifiers for sedimentation of biological sludge. This is where the biological treatment processes take place, resulting in the formation of activated sludge, which is part of the excess sludge. It is then sent to separate digesters for further treatment. "These sludges are mechanically thickened by centrifuges to an average dry matter content of 5.9%. They are then subjected to common anaerobic stabilisation together with pre-sludge with a dry matter content of about 7.4%. The average amount of sludge fed to the SFC is 8700 m3/d" [18]. Methane digestion takes place at a temperature of 38°C. Mixing takes place in the chambers using slow-speed vertical mixers, while heat exchangers are used to heat the sludge. "The resulting digested sludge is dewatered on decanter centrifuges and belt presses, where it reaches a dry matter content of 23%" [18]. The dewatered sludge is incinerated in the fluidised bed incinerator at the thermal sludge disposal station to complete the mass balance. Almost 85% of the stabilised municipal sewage sludge is thermally transformed at the thermal sludge disposal station, which is the main direction of its management. The remaining 15% is transported and disposed of off-site by external companies. It is not possible to incinerate all the sludge because of the periodic maintenance of the Thermal Sludge Disposal Station. This is due to the fact that the station is shut down for about one month per year. At the selected WWTP, most of the energy is produced by CHP units, which produce both electricity and heat thanks to a significant amount of biogas from the methane fermentation of the sludge. The use of renewable energy sources makes it possible to meet 100% of the heat demand and 40% of the electricity demand. Using the energy potential of biogas has many positive effects. One is the use of sewage sludge with reduced emissions of gases with greenhouse potential, such as methane, which brings significant environmental benefits. At the same time, the use of the biogas produced significantly reduces the cost of running the plant [18].

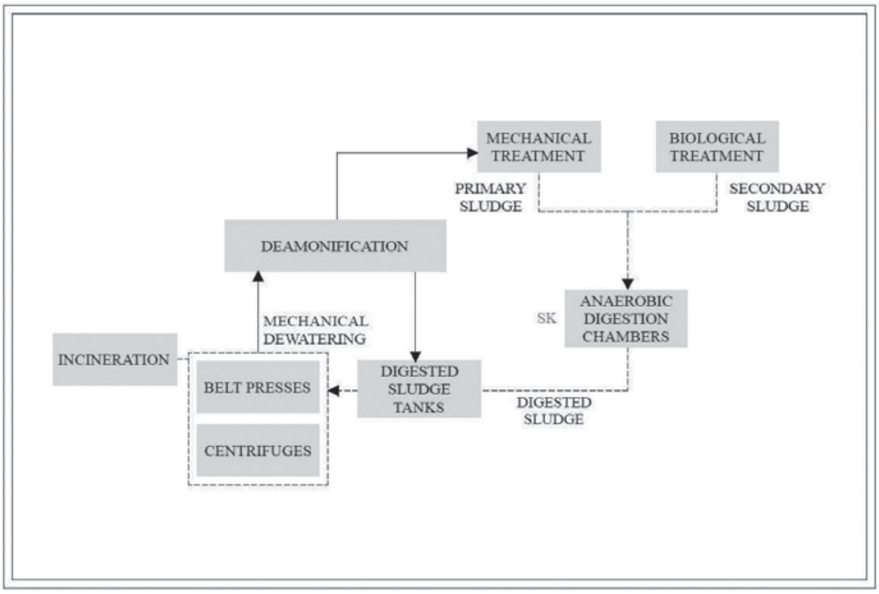
The technological scheme of WWTP2 includes a series of mechanical, biological and chemical processes that together ensure effective wastewater treatment. The wastewater first passes through the gravel, where pre-filtration takes place. The next stage is the coarse screens, where large solids are removed. The pre-treated wastewater then goes to the grit tanks, where heavy solids and sand are separated. Fine screens, the next stage of treatment, prevent larger contaminants from entering the pumping station. From there, the wastewater is pumped to the primary clarifier, the final stage of mechanical treatment. The biological processes, which are the next stage of treatment, take place in three-phase reactors with "separate sections: anaerobic, hypoxic and aerobic, with internal recirculation". There are currently four bioreactor process lines in operation, each terminated by two secondary clarifiers" [10]. Preliminary sludge is thickened by gravity, while excess sludge is thickened mechanically. Methane fermentation allows sludge stabilisation and results in biogas production. Centrifuges and filter presses are used to dewater the sludge, further reduce its volu-



*SP – Sampling point WWTP1

Fig. 2. Process scheme of selected WWTPs with marked sampling points

Rys. 2. Schemat procesowy wybranej OŚ1 z zaznaczonymi punktami poboru próbek



*SK – Sampling point WWTP2

Fig. 3. Process scheme of selected WWTPs with marked sampling points

Rys. 3. Schemat procesowy wybranej OŚ2 z zaznaczonymi punktami poboru próbek.

me and prepare it for disposal, which takes place after the sludge is transported to the Thermal Sludge Utilisation Station. In the selected WWTP2, self-generation of energy takes place in cogeneration units, which produce heat and electricity thanks to biogas from the methane digestion of sludge. The production of biogas for electricity and heat reduces operating costs and also reduces methane emissions during sludge disposal. Dewatered sludge is utilised in the Sludge Thermal Utilisation Station.

The following shows the sampling location plotted on the process scheme of selected WWTPs (Fig. 2) and (Fig. 3)

The study determined and compared the basic parameters determining the quality of the sludge and analysed the possibility of using it for agricultural purposes. The physico-chemical properties of the sludge were investigated (pH, temperature, dry matter, organic matter, chemical oxygen demand (COD) and alkalinity). The content of biogenic elements such as nitrogen (N) and phosphorus (P) was then tested. Fourier transform infrared spectroscopy (FTIR) was used to identify and analyse the chemical structure of organic and inorganic compounds. An important part of the research was the analysis of the content of heavy metals and the analysis of microbiological tests (data received from the waterworks).

Results

The analysis of the physico-chemical properties and chemical composition of sewage sludge is a key element in managing its use, especially in the context of agriculture. It allows the assessment of its fertiliser value and the identification of potential risks to human, animal and environmental health. The main aspects of the physico-chemical analysis of sewage sludge are outlined below. The tests were performed in 3 replicates and the results were averaged.

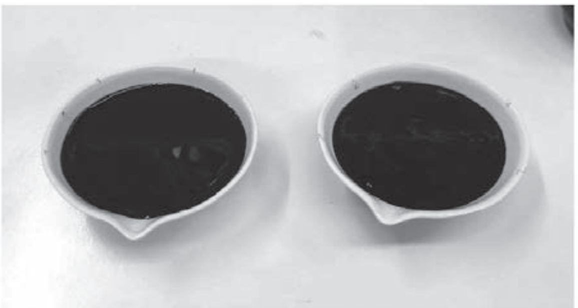


Fig. 4. Sample WWTP1 (left one) and sample WWTP2 (right one)
Rys. 4. Próbka OŚ 1 (po lewej) i próbka OŚ 2 (po prawej)

Analaysed sewage sludge was digested and taken from the Anaerobic Digestion Chamber. The results for the physico-chemical properties of tested sewage sludge are presented below.

Table 1 Physico-chemical properties of sewage sludge from selected WWTPs

Samples	WWTP1	WWTP2
pH [-]	7.3	7.34
Temperature [°C]	16.43	17.5
Dry matter [%]	4.47	2.66
Organic matter [%]	61.47	58.93
COD [mgO_2/dm^3]	23416.67	23013.33
Alkalinity [mg $CaCO_3/dm^3$]	3913	3457

*Averaged results

The pH in solution is a physico-chemical characteristic that describes the quality of the sludge produced. The pH of the SS from both treatment plants averaged 7.3, which is not close to the <5.6 value implied by national standards [14]. This is a safe level for SS used in nature as they are not acidic. The temperature is 16.43°C (WWTP1) and 17.5°C (WWTP2). The dry matter content, at an average level of 4.47% of DM (WWTP1) and 2.66% of DM (WWTP2), indicates a high hydration of the sludge. This is not an obstacle to the use of the sludge tested in agriculture, but treatments that reduce the moisture content of the sludge, and thus its volume and mass, should be considered. The choice of treatment depends on the intended use of the sludge (use as fertiliser, composting, etc.). The organic content of sewage sludge has a significant effect on, among other things, the binding of heavy metals. The sludge produced by the analysed WWTPs was characterised by a similar concentration of organic matter in DM, with an average of 61.47% of DM (WWTP1) and 58.93% of DM (WWTP2). According to the literature, sludge is stabilised when the organic matter content has been reduced by at least 38% after processes to reduce its susceptibility to mineralisation (decomposition of organic matter) [13]. For this condition to be met and for the sludge to be accepted as stabilised, the initial organic matter content of the raw sludge should be around 75%. The average organic matter content is 61.47% (WWTP1) and 58.93% (WWTP2). The average COD of the analysed sludge is 23 416.67 mgO_2/dm^3 (WWTP1) and 23013.33 mgO_2/dm^3 (WWTP2), while the alkalinity is 3913 $mgCaCO_3/dm^3$ and 3457 $mgCaCO_3/dm^3$ (WWTP2). The sludge analysed was characterised by a typical composition and structure compared to literature data. The biogenic elements (N and P) were determined in order to investigate the possibility of using the analysed sewage sludge in agriculture. The results for the N and P contents of the sludges analysed are presented below.

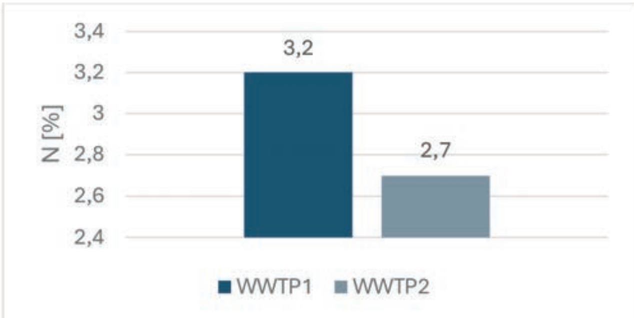


Fig. 5. Nitrogen content of digested sewage sludge from WWTP1 and WWTP2
Rys. 5. Zawartość azotu w przefermentowanych osadach ściekowych z oczyszczalni ścieków OŚ1 i OŚ2.

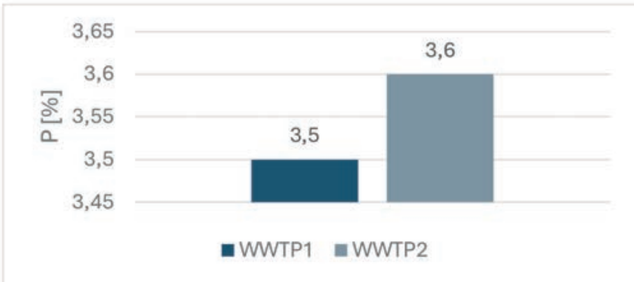


Fig. 6 .Phosphorus content of digested sewage sludge from WWTP1 and WWTP2
Rys. 6. Zawartość fosforu w przefermentowanych osadach ściekowych z oczyszczalni ścieków OŚ1 i OŚ2

The N content (Figure 5), which is the average of the three measurements, is 3.2% (WWTP1) and 2.7% (WWTP2), while the P content (Figure 6) is equal to 3.5% (WWTP1) and 3.6% (WWTP2). To compare the results of the study, the authors of [14] obtained values for N equal to 3.89% DM and P equal to 0.46% DM. Similar results were obtained in [19] where the N concentration was equal to 2.99% DM and P 0.2275% DM. In studies [9], the values presented

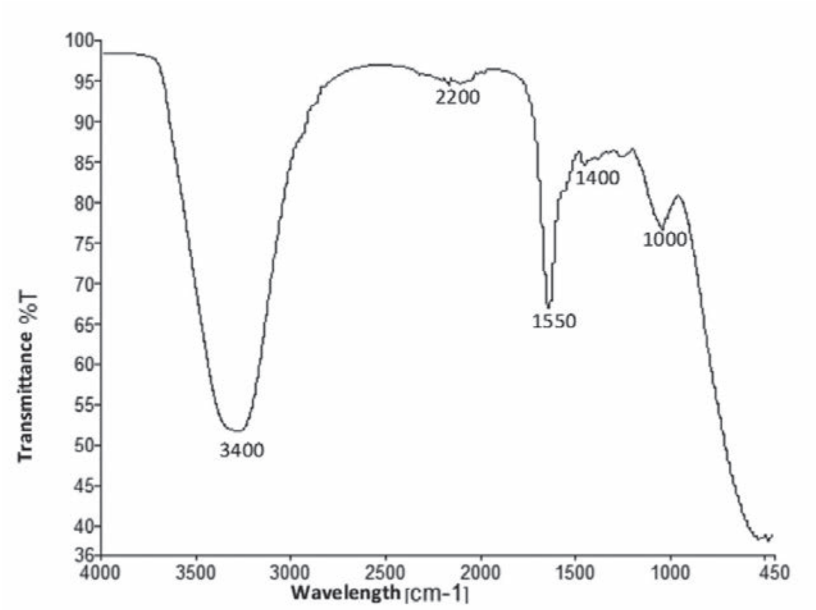


Fig. 7. FTIR of digested sewage sludge from WWTP1

Rys. 7. Widmo FTIR przefermentowanych osadów ściekowych z oczyszczalni ścieków OŚ1

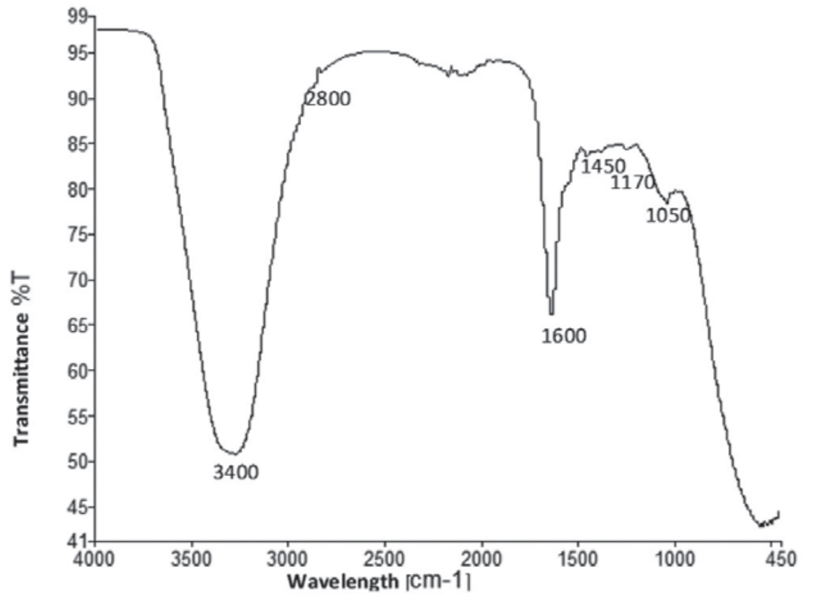


Fig. 8. FTIR of digested sewage sludge from WWTP2

Rys. 8 . Widmo FTIR przefermentowanych osadów ściekowych z oczyszczalni ścieków OŚ2

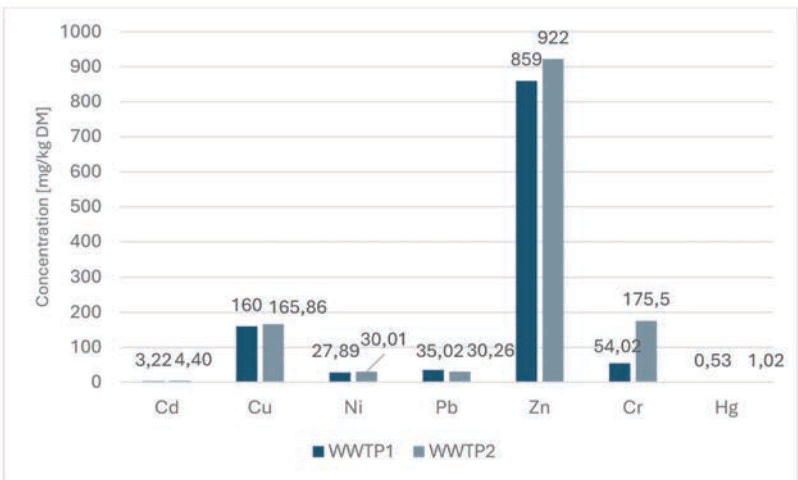


Fig. 9. Averaged heavy metal content in digested SS (own study based on data obtained from the Wastewater Treatment Plants)

Rys. 9. Średnia zawartość metali ciężkich w przefermentowanych osadach ściekowych (opracowanie własne na podstawie danych uzyskanych z Oczyszczalni Ścieków)

are in the range: for N 4.01-6.08% DM while for P 3.51-8.96% DM. Based on the literature review, it can be observed that the results obtained are close to the average nitrogen and phosphorus content of stabilised sewage sludge.

Fourier transform infrared spectroscopy indicates a similar chemical structure of both samples and suggests the presence of hydroxyl groups, alkyl chains, possibly some aromatic rings and C-O containing functional groups in the samples. As shown in Figures 7 and 8, the occurrence of absorption bands at wave numbers was typical of the literature data provided for sewage sludge.

The broad absorption around 3400 cm^{-1} was observed in both samples and is typically associated with O-H stretching vibrations, indicative of hydroxyl groups (e.g. alcohols, phenols) or N-H stretching (amines, amides). The broad nature of the peak suggests hydrogen bonding, which is common in water. The region with a peak around 2800 cm^{-1} was observed in WWTP2 and corresponds to C-H stretching vibrations. These peaks are characteristic of alkyl groups (C-H bonds). The peaks at 1600 (WWTP2) and 1550 cm^{-1} (WWTP1) are typically attributed to C=C stretching vibrations in aromatic rings, which are often present in organic compounds with aromatic structures. It could also be indicative of N-H bending (for amines). The peak at 1170 cm^{-1} (WWTP2) is associated with C-O stretching vibrations which are common in alcohols, esters and ethers. The region of the peak at 1050 cm^{-1} (WWTP2) and 1000 cm^{-1} (WWTP1) is characteristic of C-O stretching vibrations or C-H bending in alkanes [22].

The heavy metal content was checked for dewatered sludge taken from the sludge dewatering station.

Analysis of elemental composition showed that SS from WWTP1 contained an average of 0.53 mg/kg DM Hg, 3.22 mg/kg DM Cd, 27.89 mg/kg DM Ni, 35.02 mg/kg DM Pb, 54.02 mg/kg DM Cr, 160 mg/kg DM Cu and 859 mg/kg DM Zn. SS from WWTP2 contained on average 1.02 mg/kg DM Hg, 4.40 mg/kg DM Cd, 30.01 mg/kg DM Ni, 30.26 mg/kg DM Pb, 175.50 mg/kg DM Cr, 165.86 mg/kg DM Cu and 922 mg/kg DM Zn. The content of the listed trace elements in stabilised sewage sludge presented in [19], [20], [6] was 84.4-176.5 mg/kg dry matter for copper, 324.7-1376.5 mg/kg dry matter for zinc, 6.44-69.73 mg/kg dry matter for nickel, 4.49-17.44 mg/kg dry matter for lead, 9.67-112.53 mg/kg dry matter for chromium, 0.3-2.83 mg/kg dry matter for cadmium and 0.11 mg/kg dry matter for mercury. The results obtained are close to the heavy metal contents reported in the literature. The limits of quantification (LOQ) for Cd, Ni, Pb using FAAS (flame atomic absorption spectrometry) according to [20] typically depend on the sensitivity of the equipment used and the specific sample preparation methods. However, in general, typical LOQ values for FAAS are : ~0.001 – 0.01 mg/L for Cd and ~0.01 – 0.05 mg/L for Ni and Pb [15]. The standard [17] specifies methods for determining the concentration of Cr in water using atomic absorption spectrometry (AAS). For this method, the LOQ is in the range of approximately 0.005 to 0.01 mg/L [17]. The Hg concentration range for atomic absorption spectrometry with amalgamation technique is 0.0004 to 0.005 mg/L according to [16]. The permissible levels of the metals Cd, Cu, Ni, Pb, Zn, Cr and Hg were not exceeded in any of the samples tested. This indicates that these sediments are of low concern in terms of heavy metal content and are therefore suitable for agricultural use. However, due to the accumulation properties of plants and soil, it is necessary to monitor this parameter continuously, especially if SS is reused in the area.

The last parameter to be tested before using sludge in agriculture is the presence of Salmonella bacteria and live eggs of parasites (Ascaris sp., Trichuris sp. and Toxocara sp.). In the studies analysed, the presence of bacteria was detected to determine the suitability of SS samples for agriculture. However, studies from WWTP1 and WWTP2 showed the absence of Salmonella. All samples tested showed the presence of viable parasitic eggs Ascaris sp., Trichuris sp. and Toxocara sp. at a level of 141 – 282 eggs per kg dry matter, while national standards do not allow them in SS for agricultural use (own study based on data obtained from the Wastewater Treatment Plants).

Based on the results of the study, it can be concluded that the analysed digested sludge can be a valuable source of organic matter and nutrients. The dewatered sludge from the above treatment plants does not exceed the permissible concentrations of heavy metals. However, they do not meet the requirements for the presence of Salmonella bacteria and live parasite eggs: Ascaris sp., Trichuris sp. and Toxocara sp. for sludge used in agriculture according to [14]. Further stabilisation to eliminate pathogens could enable SS to be reused for natural purposes.

Conclusions

Sewage sludge produced during wastewater treatment is a reservoir of many valuable substrates, resources and non-renewable raw materials. It can be used directly in wastewater treatment plants to produce electricity and heat, or it can be returned to the natural cycle indirectly through agricultural use. However, this management route carries a high level of responsibility as it has a direct impact on the environment and on human and animal health. The requirements for sewage sludge for natural purposes are strict, but this ensures the safety of its use and greater public acceptance. The sludge analysed in this study came from two wastewater treatment plants in Poland. The average pH of the samples from both WWTPs was close to neutral (7.3 and 7.34), which is a great advantage as an acidic sludge pH would favour increased heavy metal mobility. The moisture content of the averaged sludge was more than 95% of the sample weight (95.53% and 97.34%), which could be changed by dewatering or drying, depending on the intended application technique. The organic matter content after averaging was 64% and 60%, which together with the nitrogen content of 3.2% and 2.7% and the phosphorus content of 3.5% and 3.6% represent a good source of nutrients for plants. Fourier Transform Infrared Spectroscopy (FTIR) analysis indicates similar chemical structure of both samples and suggests the presence of hydroxyl groups, alkyl chains, possibly some aromatic rings and C-O containing functional groups in the samples. The heavy metal content did not exceed the levels permitted by Polish and European legislation. One parameter that required further stabilisation (for the possibility of using the tested sludge in agriculture) was the content of pathogens. Thermal hygienisation (thermal drying or high temperature composting) or chemical stabilisation would inactivate bacteria and parasite eggs present in SS. It is possible that no further stabilisation would be required, in which case the sludge analysed could be used for land reclamation, adaptation of land to specific needs resulting from waste management plans, zoning plans or land use decisions, cultivation of plants for compost production, cultivation of non-food and fodder crops [14].

The use of sewage sludge in agriculture is undoubtedly a disposal method that fits into a circular economy and sustainable development. However, due to the lack of uniform and reproducible chemical composition, regular testing and monitoring of the composition of the SS used is required. The research results highlight the important role of sludge monitoring, treatment and management, which are key to safe sludge disposal, minimising environmental risks and preventing potential health hazards.

The research was carried out as part of master's thesis in the laboratory of the Department of Environmental Technologies at the Faculty of Environmental Engineering and Energy at the Kraków University of Technology.

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