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Analysis of the possibility of using sewage sludge from wastewater treatment plants operating with membrane technology (MBR) as fertilizers

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Abstract
Membrane technology in wastewater treatment is considered the best method available. However, the high efficiency of wastewater treatment results in increased contaminants in sewage sludge, a byproduct of wastewater treatment processes. Sewage sludge has soil-forming and fertilizing properties. The best method of managing sludge is to use it as fertilizer. However, the main criterion for possibly using them as fertilizers is determined by the content of heavy metals and parasite eggs. This study compared the heavy metal content of sludge from three different wastewater treatment plants before and after upgrading to MBR technology. Speciation analysis of the metals was performed, and risk indicators were calculated to estimate the actual risk of contamination from the use of sewage sludge as fertilizers. The main research problem of the paper is to answer the question of whether the elevated heavy metal content of sludge from MBR treatment plants can indeed cause a risk of environmental contamination.

Keywords
membrane, sewage sludge, MBR, membrane technology, wastewater treatment, fertilizers

Introduction

The introduction of increasingly stringent requirements for the quality of treated wastewater discharged into waterways is forcing the use of new technological solutions to achieve better wastewater treatment efficiency than in conventional systems. In recent years, there has been a decline in the capital cost of membranes, which has resulted in an increase in the number of units sold (Judd et al., 2011). Nowadays, modern wastewater and water treatment systems have to meet increasingly high ecological and technological requirements. In particular, recovery and reuse of valuable components and raw materials are sought. One of the components of industrial wastewater treatment plants is membrane systems (Judd et al., 2011; Bodzek et al., 1997). Membrane technology in wastewater treatment is now BAT (Best Available Technology) technology. Membrane technology for wastewater treatment is an improvement on the popular activated sludge method. In MBR technology, the secondary settling tank is replaced by a system of micro or ultrafiltration membranes immersed in a special aerated chamber. After membrane processes, treated wastewater is characterized by extremely high quality so that it can be discharged to water recipients without major obstacles. However, the high quality of wastewater is associated with increased pollutants in sludge, which are the byproducts of treatment processes. In order for a wastewater treatment plant to fully fit into the idea of a closed cycle, the problem of sludge management must also be solved. From an ecological perspective, the best form of sludge management is its natural or agricultural use. Unfortunately, it is strongly dependent on the total heavy metal content of the sludge (Mucha et al., 2010; Mucha, 2014). The maximum values of metals that, according to the law, sludge can contain for natural use in Poland and around the world are presented in (Minister of the Environment,2015; Minister of Agriculture and Rural Development, 2008; European Commission,1986; Ministry of Environmental Protection of the People's Republic of China, 2002; Code of Federal Regulations, 2010). Due to the high efficiency of membranes, the content of heavy metals in sludge from MBR-type treatment plants can be increased compared to classical technologies, thus disqualifying further use of sludge. Nevertheless, not always the total high content of metals in the sludge disqualifies such sludge as a potential fertilizer. In this case, the form of mobility in which metals occur is important. This paper analyzes sewage sludge from wastewater treatment plants upgraded to MBR technology before and after the upgrade, performs a speciation analysis of heavy metals, and finally determines the real risk of using this sludge for agro-natural purposes, using risk indicators (Gao et al., 2010; Struckey, 2012; Metcalf and Eddy, 1991).

Membrane bioreactors in wastewater treatment

MBR technology is a combination of various biochemical and membrane processes. A membrane bioreactor combines the processes of microfiltration and ultrafiltration, as well as the process of aerobic biological wastewater treatment. Membranes (tubular, semi-fibrous and flat-film elements) serve in MBR as a barrier that allows water to be treated from the contaminants it contains with high selectivity (high-molecular-weight compounds, suspended substances, active silt microorganisms, etc.) (Hermanowicz, 2011; Konieczny et al., 2014). Depending on the technological tasks, the membrane bioreactor can be used both at the final purification stage (before the disinfection stage) and for pretreatment before nanofiltration and reverse osmosis if it is necessary to desalinate the treated water. Activated sludge microorganisms are not removed from the MBR system, so the bioreactor operates at high biomass concentrations of considerable age (Grzegorzek et al., 2024). In addition, constant circulation leads to mechanical effects on the membranes of bacteria (Kimura et al., 2007; Woźniak, 2010; Ana Flávia Bilmayer et al., 2025). The effect of this is that the main energy consumed by bacteria is used to sustain life activity rather than for reproduction, as in the case of classical biotechnologies, with the result that excess biomass growth is limited. (Guo et al., 2008). A diagram of how membrane reactors work in wastewater treatment is shown in Figure 1.

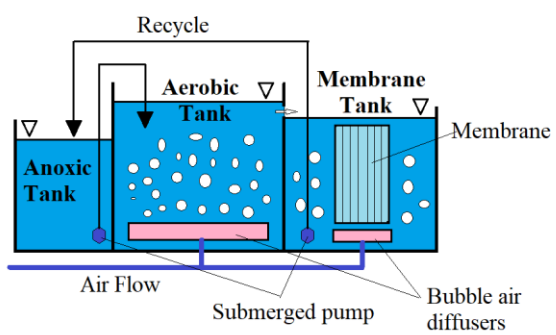

Fig. 1. Wastewater treatment in Membrane Biological Reactor technology (Kowalik et al., 2021a)

Thus, the MBR system produces a smaller amount (by 20-50%) of excess activated sludge compared to the classical aerobic treatment method. This, in turn, significantly reduces the total operating costs since the cost of excess sludge disposal accounts for 30-40% of the total operating costs of the treatment plant (Shin et al., 2018; Yoon et al., 2013; Aleksić et al., 2023).

Membranes require cleaning after a certain period of use in order to remove accumulated deposits on their coatings and restore their initial filtration properties. The membrane block in MBR systems is easily removed from the reactor and then cleaned in a separate room using a circulation pump. Cleaning of the membranes takes about a few hours and takes place several times a year; the process is fully automated (Robles et al., 2013).

Advantages of MBR wastewater treatment plants include:

- absence of odours
- 2-4 times reduction in the area occupied by the treatment plant compared to traditional technologies
- reduced consumption of electricity and chemicals
- operation in automatic mode, with remote supervision mode
- excellent quality of treated wastewater compared to the first class of purity of flowing water,
- possibility of reuse of treated wastewater
- the highest degree of elimination of microplastics, pharmaceuticals, pathogenic bacteria and viruses among all available wastewater treatment technologies
- harmonious integration of the facility into the surrounding landscape
- environmental protection, MBR technology can be used in protected areas
- MBR technology is recommended by the European Union as the best wastewater treatment method available on the market (Di Bella et al., 2019; Bodzek et al., 2004; Drews et al., 2010).

The MBR wastewater treatment plant is committed to a closed-loop economy, an economic concept in which products, materials and raw materials should remain in the economy as long as possible, and waste generation should be minimized as much as possible (Radek et al., 2020).

A wastewater treatment plant based on MBR (membrane bioreactor) fits perfectly into the idea of a closed-loop economy by:

- reuse of treated wastewater as process water for the operation of the treatment plant equipment (rinsing of the screen in the screen-sand unit, rinsing of the centrifuge, polymer dissolution, rinsing of the membrane modules, rinsing of the feed wastewater catchment station, cleaning of the yard, vehicles), thus saving usable water,
- thanks to the excellent quality of the treated wastewater, after additional UV disinfection, it is possible to use the water recovered from wastewater in complete safety for maintenance of cleanliness, irrigation of green areas, artificial snow-making, powering car washes, etc., which helps save precious drinking water resources,
- in the future, it is planned to recover raw materials and energy through the process of hydrothermal carbonization
- enabling the disposal of screenings and sludge generated in the treatment process and after additional gasification
- production of fuel of the future hydrogen, as well as recovery of leachate rich in nitrogen and phosphorus compounds for fertilizer production
- it is also planned to subject the filtrate to a plasmalization process that enables the production of green hydrogen from treated wastewater. This innovative technology will not only allow the production of the most desirable form of hydrogen from treated wastewater but will also make the treated wastewater meet even more stringent quality standards (Bodzek et al., 2004; Deng et al., 2014; Mutamim et al., 2012).

Materials and Methods

Sludge samples were taken on a cyclic basis from a wastewater treatment plant operating using membrane bioreactor (MBR) technology. The wastewater treatment plant is located in Swietokrzyskie province, central Poland. The wastewater treatment plant was modernized and converted to MBR technology for better wastewater treatment results. The membrane technology used is also expected to achieve compliant results in terms of phosphorus and nitrogen treatment. This is very important due to the location of the wastewater treatment plant, which is located in the Swietokrzyskie Protected Landscape Area, in close proximity to the Swietokrzyskie National Park. The receiver of treated wastewater is a drainage ditch flowing into the Grabowa River, which then feeds into a water reservoir used as a bathing area. MBR (membrane) technology will ensure proper water quality, which is not insignificant for those using the bathing area.

Heavy metal speciation

Sludge analysis was performed for four different independent samples for each treatment plant. The tests were performed in accordance with PN-EN 12880:2004 and PN-EN 12879:2004. Heavy metal speciation was performed using a Perkin Elmer Optima 8000 emission spectrophotometer.

Heavy metals mobility

The chemical forms of metals present in sewage sludge can be identified by sequential extraction or speciation based on the fractionation of compounds. The use of this analytical procedure ensures the separation of the test material into fractions characterized by different degrees of mobility (Kowalik et al., 2024; Mizerna et al., 2018). Various variations of sequential extraction are currently in use, but they are all based on a repetitive process of leaching metal forms using chemical reagents to increase aggressiveness. Once dissolved in the eluent used, the test sludge is centrifuged to separate the solid phase of the sample from the solution with the adsorbed heavy metals, then eluted by another extractor until all the mobility fractions tested have been determined. The liquid phase with individual forms of trace elements is subjected to subsequent quantitative analysis. Sequential analysis methods generally differ in the number of metal fractions extracted and the reagents used. The ability of individual eluents to leach metals depends on their form and the reactivity of a given extraction solution (Nartowska et al., 2024; Karwowska et al., 2017).

Results

Table 1 shows the wastewater treatment plants from which sludge samples were taken before modernization when they operated with activated sludge technology and after they were upgraded to membrane technology. Masłów, located in close proximity to all the wastewater treatment plants, was taken as the measurement point for heavy metal content in soils. The heavy metal contents of the measuring points soils were studied and reported by the Monitoring of Soil Chemistry in Poland.(http://www.gios.gov.pl/pl/stan-srodowiska/monitoring-jakosci-gleby-i-ziemi, 2022). (Figure 2).

Tab. 1. Characteristics of wastewater treatment plants (before and after modernization)

WWTP1	Wastewater Treatment Plant A		Wastewater Treatment Plant B		Wastewater Treatment Plant C	
Location	Święta Katarzyna		Pawłów		Kunów	
Equivalent Number of Residents	before modernization	after upgrade to MBR	before modernization	after upgrade to MBR	before modernization	after upgrade to MBR
	1256	2605	2235	3 863	5120	6687

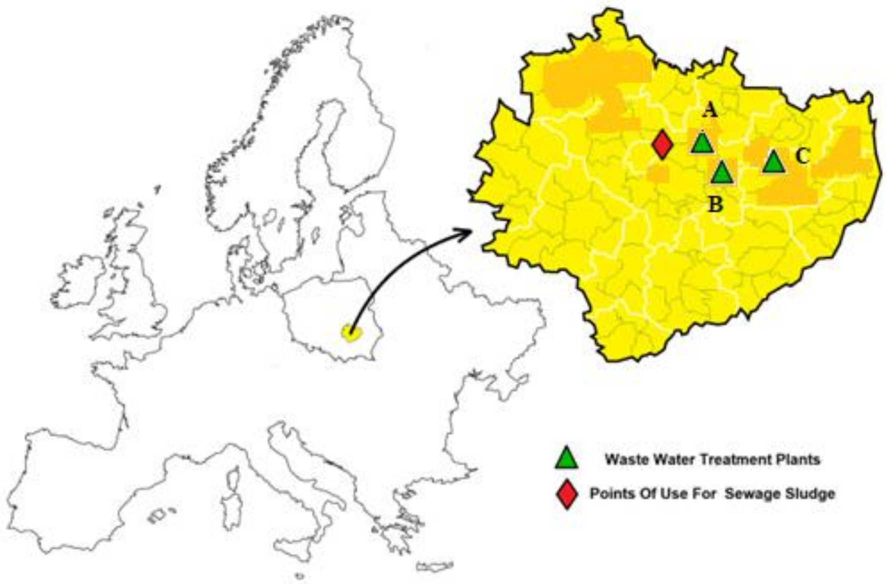

Fig. 2. Location of wastewater treatment plants (own research)

In tests conducted on sewage sludge, the BCR method was used. In the BCR method, four fractions of heavy metals can be distinguished during analysis: ion-exchangeable (carbonate), bound to iron and manganese oxides with iron oxides (reducible), bound to organic matter (oxidizable), and residual matter (Janaszek et al., 2024; Kowalik et al., 2021a; Latosińska et al., 2021).

A scheme of the BCR procedure is shown in Figure 3:

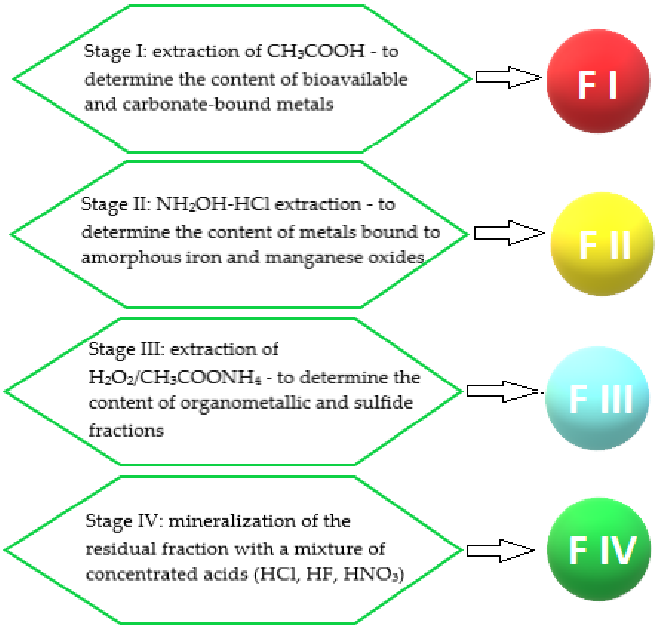

Fig. 3. A scheme of the BCR procedure (own research)

Table 2 shows the results of the speciation analysis of heavy metals in sewage sludge. As can be seen, except for Cadmium for WWTP B (before upgrading to MBR), they met all the criteria for maximum heavy metal contents in sludge intended for nature, agriculture or reclamation purposes. Significantly, the highest HMs content was observed for the residual fraction, especially for sludge from MBR technology. The exchangeable fraction was at a low level and showed very similar concentration values for sludge collected from treatment plants before and after the upgrade.

Tab. 2. Chemical speciation of heavy metal in sewage sludge, mg/kg d.m. (heavy metal content with standard deviation calculated for 4 samples using Grubbs' statistical tests).

	Heavy Metal [mg/kg d.m.]					
Fraction	Cu	Cr	Cd	Ni	Pb	Zn
WWTP Sewage sludge						
Sewage sludge Święta Katarzyna—A1 (before modernization)						
Fraction I	5.21±0.1	0.9±0.1	0.1±0.1	4.5±0.2	5.2±0.2	62.2±1.0
Fraction II	2.45±0.1	1.0±0.1	0.1±0.1	0.2±0.1	0.4±0.1	123.5±0.6
Fraction III	82.7±0.9	10.8±0.9	1.1±0.1	3.2±0.1	3.2±0.1	432.1±5.8
Fraction IV	14.1±0.1	16.4±2.8	0.7±0.1	18.3±0.3	7.1±0.2	111.4±1.5
ΣFI…IV	104.46±0.9	29.1±2.9	2±0.2	26.2±0.6	15.90±0.05	729.2±10.1
Sewage sludge Święta Katarzyna—A2 (after upgrade to MBR)						
Fraction I	7.53±0.1	0.37±0.1	1.19±0.1	4.59±0.2	7.97±0.2	26.2±1.2
Fraction II	0.44±0.1	0.21±0.1	0.24±0.1	0.31±0.5	0.83±0.1	8.45±0.8
Fraction III	101.92±0.9	17.8±0.9	3.48±0.1	10.35±0.1	17.05±0.3	795.87±9.8
Fraction IV	15.14±0.1	82.18±2.8	33.55±0.2	25.03±0.3	62.15±0.3	176.14±2.0
ΣFI…IV	125.03±0.9	100.56±2.9	38.46±0.2	40.28±0.6	88.00±0.05	1006.66±10.1
Sewage sludge Pawłów—B1 (before modernization)						
Fraction I	3.3±0.1	3.1±0.1	3.7±0.1	1.1±0.1	1.0±0.2	11.5±9.3
Fraction II	6.8±0.1	3.2±0.2	0.9±0.1	0.3±0.2	0.1±0.2	19.7±9.1
Fraction III	67.4±0.6	1.5±0.1	1.5±0.1	1.4±0.2	2.3±0.2	143.4±9.8
Fraction IV	2.3±0.1	3.7±0.4	0.3±0.1	2.9±0.2	55.2 ±4.5	131.5±7.1
ΣFI…IV	79.8±0.6	11.5±1.0	6.4±0.5	5.7±0.6	58.6±5.5	306.1±13.8

Sewage sludge Pawłów —B2 (after upgrade to MBR)						
Fraction I	5.49±0.1	0.44±0.1	2.19±0.1	1.91±0.2	1.2±0.1	8.04±3.3
Fraction II	14.38±0.1	0.13±0.1	0.28±0.1	1.15±0.1	0.01±0.2	10.38±9.1
Fraction III	125.79±0.3	7.88±0.3	1.8±0.1	5.04±0.2	7.1±0.1	96.01±7.1
Fraction IV	109.45±0.1	11.85±0.4	5.26±0.1	16.22±0.3	153.52±3.3	108.55±9.1
ΣFI…IV	255.11±0.6	20.30±2.6	9.53±0.4	24.32±0.6	161.83±9.3	222.98±15.1
Sewage sludge Kunów—C1 (before modernization)						
Fraction I	0.0±0.1	1.34± 0.2	0.2 ± 0.1	0.3 ± 0.2	1.5 ± 0.2	59.9 ± 9.0
Fraction II	1.3±0.1	1.2 ± 0.2	0.5 ± 0.1	0.9 ± 0.1	0.0 ± 0.1	47.3 ± 9.5
Fraction III	156.6 ± 0.9	19.4 ± 1.6	3.7 ± 0.1	6.1 ± 0.5	16.2 ± 0.3	1219 ± 15
Fraction IV	66.5 ± 0.4	59.1 ± 2.3	3.0 ± 0.1	9.7 ± 0.6	48.4 ± 9.1	593.2 ± 8.4
ΣFI…IV	224.4±0.9	81.04±2.9	7.4±0.2	17±0.8	66.1±3.8	1919.4±21,6
Sewage sludge Kunów—C2 (after upgrade to MBR)						
Fraction I	2.72±0.1	0.16±0.1	0.07±0.1	0.76±0.5	0.4±0.1	53.93±1.1
Fraction II	7.39±0.6	0.09±0.1	0.00±0.1	0.54±0.5	0.00±0.2	29.13±1.2
Fraction III	298.64±0.9	18.89±0.9	2.04±0.2	30.64±0.1	12.57±0.2	1544.97±15
Fraction IV	255.62±0.2	79.71±2.7	9.88±0.1	75.60±0.1	91.60±1.3	835.44±4.2
ΣFI…IV	564.36±0.4	98.84±2.8	11.99±0.2	107.53±0.7	104.57±0.3	2463.46±15.6

Risk indicators for accumulation of heavy metals

The Risk Assessment Code (RAC) is a method that uses the heavy metal content of the most mobile fraction I and the total metal content to determine the risk of environmental contamination (Perin et al., 1985; Zhang et al., 2017). Since exchangeable fraction I is considered the most mobile, it is considered the only source of metals entering the soil in the RAC indicator. RAC was introduced by Perin and co-authors in 1985 (Perin et al., 1985) as a percentage ratio of the first fraction to the total metal content. Five risk categories were established for values ranging from 1 to 50%, which are shown in Table 2.

Tab. 2. The Risk Assessment Code classification

RAC Value	Level of pollution	δ
<1	No pollution	1.0
1÷10	Low pollution	1.0
11÷30	moderate pollution	1.2
31÷50	High pollution	1.4
>50	Very high pollution	1.6

The first indicator analyzed was the RAC risk assessment code. It took into account the ratio of the metal content in the first fraction to the total metal content. In most cases, the RAC indicator does not show high risk. As can be seen in Figure 4, in each case, the values of the RAC indicator for a given treatment plant were higher before the upgrade to MBR technology, despite the fact that the total heavy metal content increased, a fact explained by the fact that the increased metal content was mainly in the stable fractions.

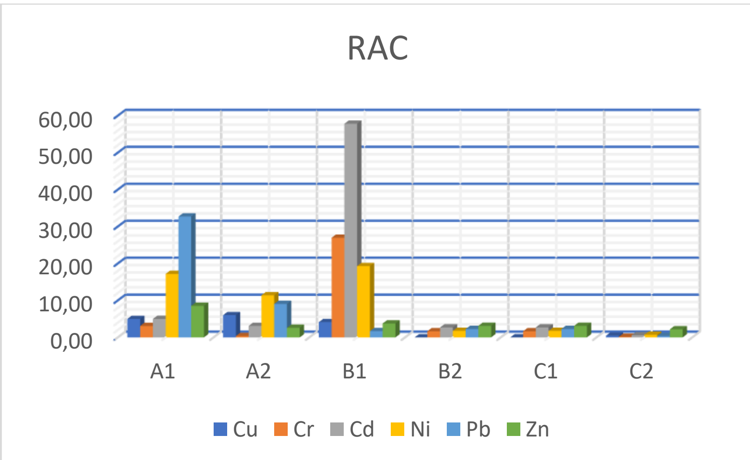

Fig. 4. Value of RAC Indicator of heavy metals in sewage sludge.

Potential environmental risk indicator (PERI)

The PERI index was formulated in 1980 by Hakanson (Hakanson, 1980). It is used to assess the risk of heavy metal contamination of soils. It is one of the most widely used indicators by scientists and researchers to analyze the risk of contamination of the soil-water environment. Its main advantage is the use of a listed degree of toxicity for individual metals. However, it does not take into account their mobility. The indicator is described by the following formulas (Muller, 1969; Hakanson, 1980):

$$C_f^i = \frac{C_D^i}{C_R^i} \quad (1)$$

where:

C_f^i - contamination coefficient,
C_D^i - is the present concentration of heavy metals in sewage sludge, mg/kg d.m.,
C_R^i - is the pre-industrial record of heavy metal concentration in soil, mg/kg d.m.

$$E_r^i = T_r^i \cdot C_f^i \quad (2)$$

where:

E_r^i– indicator of the potential ecological risk of the *i*-th element of heavy metals,
T_r^i – toxicity factor of the *i*-th element of heavy metals.

Based on the Hakanson (Kowalik et al., 2021b) approach, the toxic-response factors for Pb, Cu, Cd, and Zn are 5, 5, 30 and 1, respectively.

The classification of risk has been categorized in terms of ER and is tabulated in Table 3.

Tab. 3. ER indicator classification (Perin et al, 1985; Muller G., 1969; Hakanson, 1980).

E_r^i Value	Level of risk
<40	Low
40—80	Medium
80—320	High
>320	Very high

The PERI index proved critical for the analyzed sludge, especially cadmium. It proved to be highly toxic in all analyzed samples, regardless of technology. This may explain the fact that it is assigned a high toxicity index (Figure 5). This is because the Er indicator only analyzes the total metal content of the sludge and compares it to the content in the geological substrate. This is a rather crude indicator, mainly because some of these metals will not tend to migrate.

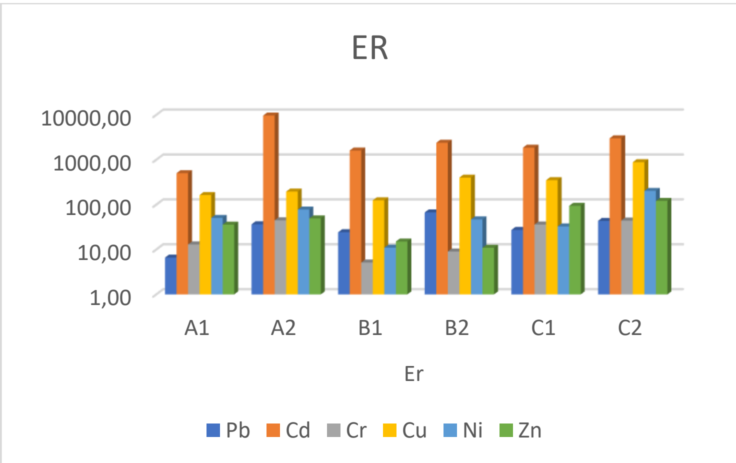

Fig. 5. Value of Er Indicator of heavy metals in sewage sludge.

Modified index of potential ecological risk (MRI)

Although the RAC index, which considered the mobile fraction, was not perfect and was improved by Zhu and co-authors (Zhu et al., 2012) in 2012. A modified potential index was presented, dependent on RAC and δ values. The formula for calculating the MRI is shown below (Zhu et al., 2012) :

$$\boldsymbol{\Omega} = \boldsymbol{RAC} \cdot \boldsymbol{\delta} + \boldsymbol{B} \qquad (3)$$

Where:
$\boldsymbol{\Omega}$ – modified index of heavy metal concentration
$\boldsymbol{\delta}$ – toxic index corresponding to different ratios of exchangeable and carbonate fraction
$\boldsymbol{B}$ – value of RAC -1

The classification of risk has been categorized in terms of MRI and is tabulated in Table 3.

Tab. 4. MRI indicator classification (Zhu et al., 2012).

MRI Value	Level of pollution
<1	No pollution
1÷20	Low pollution
21÷60	moderate pollution
61÷100	High pollution
>100	Very high pollution

Analyzing the MRI index is a modification of the RAC index. It can be seen that the results were very similar to those of the RAC index. This is due to the fact that only cadmium for the sludge from treatment plant B1 and lead for treatment plant A1 showed elevated values (Figure 6).

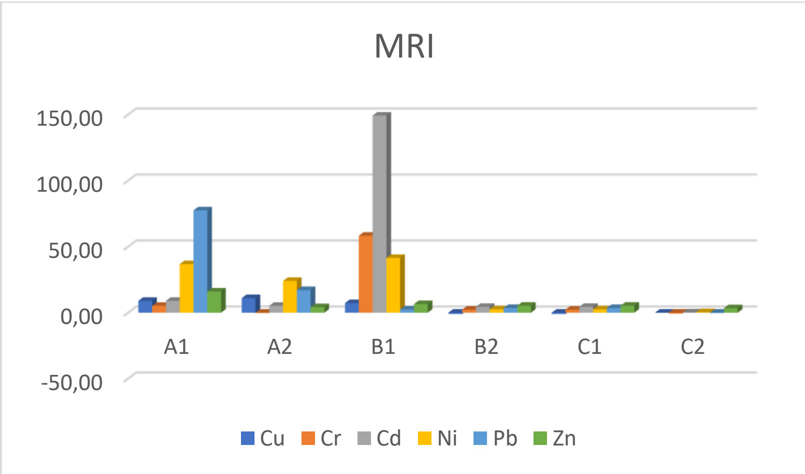

Fig. 6. Value of MRI Indicator of heavy metals in sewage sludge.

Metal mobility risk factor (MRF)

Considering the mobility of heavy metals, it can be seen that only fraction IV is completely stable and does not migrate into the soil and water environment. The reducible and oxidizable fraction can, to some extent and under the right environmental conditions, become mobile and migrate into the soil, posing an ecological hazard. Given the above information, it makes sense to introduce an index that considers the first three fractions of mobility, however, on appropriate weight scales. The authors proposed using the following formula:

$$\boldsymbol{MRF} = \boldsymbol{1} \cdot \%\boldsymbol{F1} + \boldsymbol{0,7} \cdot \%\boldsymbol{F2} + \boldsymbol{0.2} \cdot \%\boldsymbol{F3} \qquad (4)$$

where:

%F(X) - Percentage content of a given fraction in relation to the total sum content.

The classification of the *MRF* results is: $0 < MRF \leq 0.35$—low risk; $0.35 < MRF \leq 0.6$—medium risk; $0.6 < MRF \leq 0.8$—high risk; $0.8 < MRF$—very high risk.

The *MRF* index does not refer to the value of the total content of a given heavy metal but only to the percentage content in the mobile fractions. The index transparently illustrates the tendency of metals to be mobile in the soil and the risk of their migration. As can be seen in Figure 7, sludge taken from sewage treatment plants before their upgrade to membrane technology had a higher risk despite the increase in total metal content. Therefore, it can be concluded that the amount of heavy metals is increased in membrane technologies. However, they tend to be in stable fractions that cannot migrate into the soil water environment.

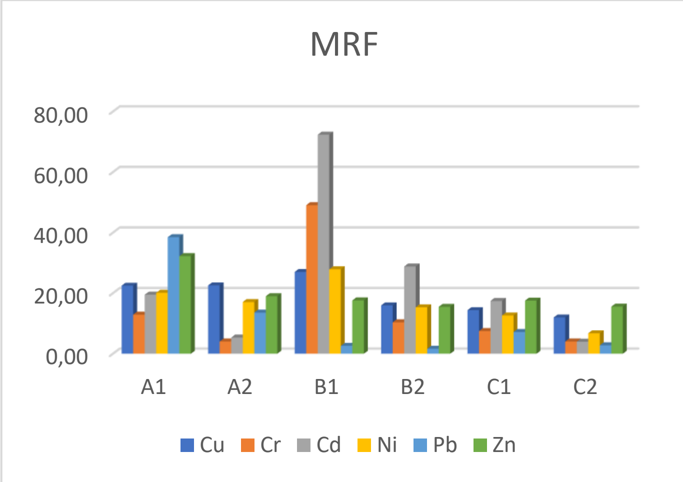

Fig. 7. Value of MRF Indicator of heavy metals in sewage sludge.

Discussion

The conducted analysis of sewage sludge from three wastewater treatment plants upgraded to membrane bioreactor (MBR) technology revealed that, although the total concentrations of heavy metals (Cu, Cr, Cd, Ni, Pb, Zn) increased significantly after modernization, their environmental mobility and related risk were notably reduced. The increased concentrations are a result of the high separation efficiency of MBR membranes, which effectively retain heavy metals within the sludge matrix rather than allowing them to pass into the treated effluent.

However, what is crucial from an environmental safety perspective is not only the total content of metals but their chemical form and availability. The speciation analysis indicated that metals were predominantly associated with stable residual fractions (fraction IV), which are not readily bioavailable or mobile, in the case of sludge from MBR-based plants. This was further confirmed by the Risk Assessment Code (RAC) values, which were consistently lower in sludge collected after modernization. Despite the higher overall concentrations, the proportion of metals in mobile fractions was lower, confirming that MBR technology effectively immobilizes potentially hazardous elements.

The PERI (Potential Ecological Risk Index), which is based on total concentrations and metal-specific toxicity, highlighted cadmium (Cd) as the primary ecological concern due to its high toxicity coefficient. Nevertheless, because this index does not account for metal mobility, it may overestimate the actual risk posed by elements present mainly in stable forms.

Additional indicators such as MRI (Modified Risk Index) and MRF (Metal Mobility Risk Factor) were applied to address this limitation. These indices combined toxicity with mobility data and revealed that only isolated cases—such as cadmium in one sludge sample and lead in another—presented a moderate ecological risk. In most cases, values fell within low-risk categories. The MRF index, in particular, confirmed that sludge generated from MBR facilities contains metals in forms that are significantly less prone to migration in the soil-water environment.

In conclusion, while the use of membrane technology results in the accumulation of heavy metals in sewage sludge, it simultaneously alters their chemical form in a way that limits environmental availability. Therefore, sludge from MBR systems can be considered environmentally safe for recovery or agricultural use, provided that regular monitoring is conducted and usage complies with relevant regulatory standards.

Conclusions

This study examined sewage sludge collected from three wastewater treatment plants located in the Świętokrzyskie region of Poland, all of which had been upgraded to membrane bioreactor (MBR) technology. MBR is currently considered one of the Best Available Techniques (BAT) for wastewater treatment.

In all analyzed samples, the concentration of heavy metals (e.g., Cu, Cr, Cd, Ni, Pb, Zn) was significantly higher compared to levels measured before the technological upgrade. This indicates that the newly installed membranes are highly effective at retaining heavy metals, which are prevented from passing into the treated effluent and are instead accumulated in the sludge. While this enhances effluent quality, it simultaneously increases the contaminant load in the sewage sludge.

However, a key focus of the study was not only the total content of metals but also their environmental availability and mobility, particularly with respect to the potential use of sewage sludge in natural applications such as agriculture or land reclamation. Fractionation analysis revealed that, despite the elevated total concentrations, the metals in all cases are predominantly bound in stable fractions—associated with mineral or organo-mineral components. Such forms are characterized by low bioavailability and reduced mobility, which greatly limits the risk of migration through soil and entry into the food chain.

Therefore, it can be concluded that sewage sludge from wastewater treatment plants upgraded with MBR technology, despite its higher content of heavy metals, does not pose an immediate environmental risk, provided it is managed and applied in accordance with regulatory standards. Nevertheless, it is important to note that environmental changes (e.g., a drop in pH or oxidative conditions) could potentially trigger the remobilization of metals from their stable forms. For this reason, continuous monitoring of sludge composition and long-term environmental risk assessment are recommended.

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