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EVALUATION OF THE EFFECT OF USING SEWAGE SLUDGE AS A FERTILIZER ON THE CONCENTRATION OF HEAVY METALS IN SOIL AND THE ECONOMIC IMPLICATIONS OF ITS APPLICATION

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ABSTRACT: The costs of fertilising the soil with sewage sludge were reduced to the operating time of the equipment and the working time of the labourers operating the equipment in the two main operations (manure spreading and ploughing), for three sewage sludge application doses, namely 50, 100 and 200 Mg • ha-1. The costs were calculated using the Katalog Nakładów Rzeczowych nr 2-21: Tereny zielone/Ministerstwo Gospodarki Przestrzennej i Budownictwa (2009) and the current prices from Sekocendbud (2023). The effectiveness of fertilisation was assessed by studying the level and change in heavy metal content after the soil was fertilised with sewage sludge at three proportional doses, namely 50, 100 and 200 Mg•kg-1. The sewage sludge used for fertilisation complied with the sanitary requirements for sludge to be utilised for natural purposes (Regulation, 2015). The estimated total cost of sludge application ranged from PLN 12646.19 to PLN 20456.73 per 1 ha for doses from 50 to 200 Mg per 1 ha. The results of the estimation confirmed the hypothesis that the unit cost of fertilisation with stabilised sewage sludge increases with the dose of sludge in relation to the area of fertilised soil and decreases with the increase of the mass of sludge deposited in the soil. Optimising fertiliser costs, therefore, requires selection – increasing the sludge dose per unit area. No contamination of the soil with copper, cadmium, lead and zinc was found despite an obvious increase in the content of these metals when mixed into the soil. The application of sewage sludge, even in multiple doses, did not result in exceeding the permissible limit for the content of these elements in the soil, as defined in the Minister of the Environment Regulation of 2015 (Regulation, 2015).

KEYWORDS: heavy metals, soil, sewage sludge, sewage sludge fertilisation, costs, agriculture

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Introduction

The Polish legislator defined municipal sewage sludge in the Waste Act of 14 December 2012 (Act, 2012) as "sludge from sewage treatment plants from digestion towers and other installations for the treatment of municipal sewage and other wastewater with a composition similar to that of municipal sewage". The increasing amount of sewage sludge produced in municipal sewage treatment plants resulting from improvements in the infrastructure of the sewage system and its expansion, as well as improvements in the efficiency of technological processes of sewage treatment, is a serious problem for society (Bień et al., 2011). An additional impediment to the effective management of sewage sludge is the lack of its consistent, typical composition and uniform characteristics, both in terms of quantity and quality. Sewage sludge is the end product of a complex sewage treatment process, and its composition and quantity are determined by the degree and method of treatment. Sewage sludge represents only 1-3% of the volume of municipal wastewater (Jakubus, 2012; GUS, 2020); however, due to the need for its further management, it is a major problem for the municipal economy of local governments. In addition to the aforementioned Act, the management of sewage sludge is also regulated by other national normative acts, such as the Act of 27 April 2001 – Environmental Protection Act (Act, 2001) and the Act of 10 July 2007 on fertilisers and fertilisation (Act, 2007), as well as secondary legislation on these acts in the form of regulations and notices issued by the Minister of the Environment or the Minister of Agriculture and Rural Development. Similarly, the National Waste Management Plan (Resolution, 2016) set out a range of objectives for the management of municipal sewage sludge, which were supposed to be achieved by 2022. In Poland, a significant increase in the production of municipal sludge has been observed since 2010. The question is what to do with it and how to manage it without increasing the pressure on the environment. This article attempts to identify the possibility of using municipal sewage sludge as a source and method of soil fertilisation (Niemiec & Zdeb, 2014), without the risk of increasing heavy metal contamination in the soil, despite the fact that the sewage sludge contains such elements.

Properties and potential influence of sewage sludge on soil and subsoil for reclamation and fertilisation

Municipal sewage sludge is characterised by a high content of organic and nitrogen compounds, a low content of organic toxic substances, a high degree of hydration, varying concentrations of trace elements and a certain degree of sanitary risk. Therefore, it exhibits a spectrum of chemical, physical, fertilising, sanitary and technological properties (Pietraszek & Podedworna, 1992; Podedworna & Umiejewska, 2008). These properties are related to the quality and quantity of the sewage entering the WWTP, especially industrial sewage, the type of sewage network in a given area, the technology used for sewage treatment and sludge processing, and the presence of a primary settling tank in the process line (Czekała, 2002; Fukas-Płonka & Zielewicz, 2010). Recognition of the properties and fertilising purpose of municipal sludge is well established in the literature and agricultural practice (Krasowksa et al., 2022; Stabnikova et al., 2005; Silva et al., 2010; Bień et al., 2015). Sewage sludge fertilisation involves the reuse of the biological and chemical components present in the sewage sludge, in particular macro- and micronutrients, in order to reclaim a degraded soil environment or to increase the fertility of cultivated soils (Baran et al., 2008; Kacprzak et al., 2014). Researchers evaluate the effect of sewage sludge fertilisation on crop yields in different ways (Czekała, 2011; Dobrowolska et al., 2007; Singh & Agrawal, 2008; Li et al., 2009). Validation of the increase in soil fertility requires long-term monitoring. This is because the release of nutrients from sludge is gradual (Iżewska, 2007; Stańczyk-Mazanek, 2012). The total concentration of trace elements in sludge is not a reliable parameter for predicting the degree of heavy metal migration to soil and bioaccumulation, i.e. actual toxicity. The content of heavy metals in municipal sewage sludge mostly does not exceed the legal limits (Table 1).

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Table 1. Ranges of heavy metal content in municipal sewage sludge

Element	Unit	Poland
Cd	mg·kg⁻¹	0.005-14.40
Cr		6.90-2 405.0
Ni		8.9-911.0
Pb		2.91-246.0
Hg		0.09-2.70

Source: authors' work based on Jakubus (2012).

Above-normal levels may result from illegal discharges of industrial effluent or surface runoff and may enter domestic wastewater via indirect pathways (Urbaniak, 1997; Jakubus, 2012).

Possible options for sludge management

Sewage sludge is not only used in agriculture and in nature but also it is deposited in municipal landfills and WWTPs (Janosz-Rajczyk, 2008; Bień et al., 2011). Only sludge that is free of pathogenic organisms does not contain excessive concentrations of heavy metals and is in a dehydrated or liquid state can be utilised in agriculture (Dymaczewski et al., 1997; Siebielec et al., 2015). Sewage sludge is not an agricultural fertiliser in the strict sense, like manure, so it should be used in a stabilised form, provided that it has high organic matter content and acceptable concentrations of heavy metals (Bień et al., 2020). For natural purposes, sewage sludge is used for compost production, soil fertilisation and land reclamation (Czekała, 1999; Siebielec & Stuczyński, 2008). The Regulation of the Minister of the Environment of 6 February 2015 on municipal sewage sludge (Regulation, 2015) defined the permissible levels of quality indicators for the use of stabilised sewage sludge in agriculture. The set standards referred to the content of selected heavy metals, intestinal parasite eggs and pathogenic bacteria (Table 2).

Table 2. Permissible heavy metal content in mg kg-1 DM in municipal sewage sludge for agricultural and non-agricultural use

Element	Use of municipal sewage sludge		
	Agricultural use and reclamation	Non-agricultural land reclamation	Compost production, vegetated land consolidation
Cadmium	20	25	50
Chromium	500	1000	2500
Nickel	300	400	500
Copper	1000	1200	2000
Lead	750	1000	1500
Zinc	2500	3500	5000
Mercury	16	20	25

Source: authors' work based on Regulation (2015).

A relatively small percentage of sewage sludge is managed agriculturally. Composting is considered to be one of the most environmentally friendly methods of disposal while managing municipal sludge and is preferred in non-urbanised areas (Konieczny & Kopiec, 2011; Bień et al., 2020).

Compost is a safe organic fertiliser, and its production costs are relatively low (Białobrzewski et al., 2015; Czekała et al., 2017). The dewatered and stabilised sludge is stored (Dymaczewski et al., 1997), and economic considerations can provide the main justification for such a solution (Butarewicz, 2013). Sludge dried in thermal dryers becomes a potential source of alternative fuel for CHPs and cement plants (Suszyński, 2010). In industry, sludge can also be utilised as an ingredient in glazes, cement or building products.

Research methodology – plot preparation, heavy metal content and the course of the research of the municipal sludge fertilisation process

Field tests on the content of heavy metals in soils before and after sewage sludge application were carried out on a private plot in the village of Klecza Dolna in the municipality of Wadowice in the Lesser Poland Voivodship. The native soil of the established plots belonged to the wheat-agricultural complex, good middle mountainous and foothill soil, and silty clay loam soil.

The tested soil material is clay dust (granulometric composition – clay 17%, dust 65%, sand 18%), classified as cISi (PTG, 2019), the average organic matter content was 1.77%, the dry soil density was 1.46 $Mg \cdot m^{-3}$, and the density of the solid phase was 2.58 $Mg \cdot m^{-3}$.

The area of the agricultural plot on which the experimental plots were set had been fallow for twenty years, which made it possible to eliminate the influence of external fertilisation and other factors that could affect the soil composition and the interpretation of the results. The field tests were carried out by mixing the fallow native soil with sewage sludge at doses of 50, 100 and 200 $Mg \cdot ha^{-1}$ in the arable layer from the ground level to a depth of 40 cm. As the study was empirical, the doses of sewage sludge used exceeded the limit doses specified in the Sewage Sludge Regulation (Regulation, 2015). The field study utilised sewage sludge from the Trepcza WWTP (the Podkarpackie Voivodship), which was suitable for natural purposes, including agricultural use (Table 3).

Table 3. Physical and chemical properties of sewage sludge used in a field study in Klecza Dolna (Wadowice Municipality)

Parameter	Unit	Sewage sludge in Trepcza
pH	–	8,1
Ammonium Nitrogen	% DM	0,58
Kjeldahl Nitrogen	% DM	5,40
Chromium	mg/kg	38,0
Zinc	mg/kg	1350
Total Phosphorus	% DM	4,72
Cadmium	mg/kg	1,50
Magnesium	% DM	0,54
Copper	mg/kg	163
Nickel	mg/kg	35,4
Lead	mg/kg	24,1
Mercury	mg/kg	0,67
Calcium	%	4,37
Presence of specific DNA (Salmonella) Sp.	in the investigated mass or volume	not found
Number of Ascaris sp., Trichuris sp., Toxocara sp.	number / kg	0

Source: Sludge analyses carried out by the Pszczyna Environment, Health & Safety Certified Laboratory on behalf of the Trepcza Wastewater Treatment Plant (test report no. SB/15543/03/2017).

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The laboratory analyses did not reveal any excessive heavy metal content in the sludge. It also met the sanitary requirements for sludge to be used for natural purposes (Regulation, 2015). Microbiologically, it did not show the presence of pathogenic bacteria of the Salmonella type or Ascaris, Trichuris, or Toxocara parasite eggs, the presence of which limits the possibility of using the sludge for the above-mentioned purposes. The area covered by the experiment was divided into 6 plots. Each plot had the shape of a 2×2m square. In total, the study area of all the experimental plots covered 24m^2 (Figure 1).

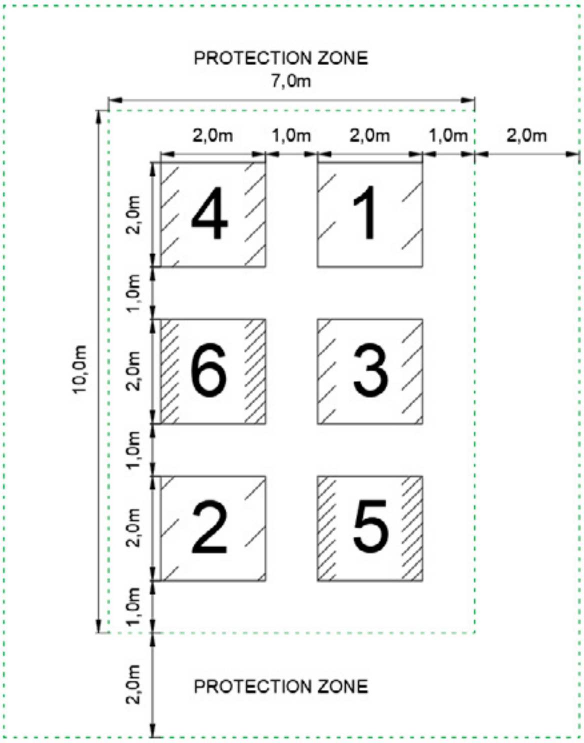

Figure 1. Scheme of the experimental plots in Klecza Dolna (Wadowice municipality)

Plot no 1,2 – dose of 50 [Mg·ha^{-1}], 3,4 – dose of 100 [Mg·ha^{-1}], 5,6 – dose of 200 [Mg·ha^{-1}]. Prior to sludge application, the top layer of humus (0 to 20 cm) was entirely removed from each plot, and agricultural practices were performed to fertilise (loosen) the soil. The plots were then numbered from 1 to 6. One type of native soil, that is silty clay loam soil, was fertilised. In the so-called arable layer of the experimental plots (40 cm thick), sewage sludge was applied once in doses appropriate for experimental purposes (Table 4).

Table 4. Fertiliser doses were applied in a field experiment in Klecza Dolna (Wadowice municipality)

No of plot	Single plot area [m^2]	Sludge fertilisation dose [Mg·ha^{-1}]	Native soil type
1-2	4	50	Silty clay loam
3-4	4	100	
5-6	4	200	

An agrotechnical tool was employed to loosen and evenly mix the soil and sludge through the cultivator. The research was undertaken between June and August 2017. In September 2017, soil material was collected twice from each of the six study plots and subjected to laboratory analyses. The determination of total cadmium, lead, copper and zinc in soil (Jasiewicz et al., 2010) was performed at the Agricultural University of Krakow, applying the FAAS method directly in the filtrate, using the instrument parameters of the spectrometer in accordance with the manufacturer's guidelines.

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Research results on the content of heavy metals in the soil after fertilisation with municipal sewage sludge

The soils with experimental plots were first subjected to laboratory analysis (Table 5) to determine the content of heavy metals. The results obtained were below the permissible content of these elements in soils according to the Regulation of the Minister of the Environment of 2015. This allowed the area to be classified as uncontaminated.

Table 5. Content of heavy metals in the soil material collected from the experimental plots located in the Klecza Dolna area prior to the application of sewage sludge

Heavy metal analysed	Results [$mg \cdot kg^{-1}$]
Cd	0.1
Pb	13
Zn	45
Cu	10.5

The cadmium content for soil without sludge application ranged from 0.1 to 0.4 $g \cdot 10^{-3} \cdot kg^{-1}$. The average cadmium content in the sample (Table 6) for the sludge application dose of 50 $Mg \cdot ha^{-1}$ was 0.488 $g \cdot 10^{-3} \cdot kg^{-1}$.

Table 6. Determination of cadmium content in soil after sewage sludge application

Granuleometric fraction	Sludge dose [$Mg \cdot ha^{-1}$]	Repetition	Content of Cadmium [$g \cdot 10^{-3} \cdot kg^{-1}$]	Average content of Cadmium [$g \cdot 10^{-3} \cdot kg^{-1}$]
Silt dust	0	1	0.400	0.250
		2	0.100	
	50	1	0.556	0.488
		2	0.419	
	100	1	0.394	0.462
		2	0.531	
	200	1	0.436	0.445
		2	0.454	
sludge	–	1	1,450	1,500

The average cadmium content for the application dose of 100 $Mg \cdot ha^{-1}$ was 0.462 $g \cdot 10^{-3} \cdot kg^{-1}$. The average cadmium content for the soil sample with the sludge application dose of 200 $Mg \cdot ha^{-1}$ was 0.445 $g \cdot 10^{-3} \cdot kg^{-1}$ (Table 6). The cadmium content for the sewage sludge sample ranged from 1.45 to 1.55 $g \cdot 10^{-3} \cdot kg^{-1}$. The lead content (Table 7) for the soil without sludge addition ranged from 13.0 to 20.0 $g \cdot 10^{-3} \cdot kg^{-1}$. The average lead content in the sample for the sewage sludge application dose of 50 $Mg \cdot ha^{-1}$ reached 25.79 $g \cdot 10^{-3} \cdot kg^{-1}$.

The lead content of the soil without sludge application ranged from 13.0 to 20.0 $g \cdot 10^{-3} \cdot kg^{-1}$. The average lead content in the sample for the sludge application dose of 50 $Mg \cdot ha^{-1}$ was 25.79 $g \cdot 10^{-3} \cdot kg^{-1}$. The average lead content in the sample for sludge applied at 100 $Mg \cdot ha^{-1}$ amounted to 25.17 $g \cdot 10^{-3} \cdot kg^{-1}$. The average lead content in the sample for the sludge application dose of 200 $Mg \cdot ha^{-1}$ amounted to 25.96 $g \cdot 10^{-3} \cdot kg^{-1}$. For the sewage sludge sample, the lead content ranged from 24.0 to 24.2 $g \cdot 10^{-3} \cdot kg^{-1}$. The zinc content for the soil without sludge addition ranged from 45.0 to 60.0 $g \cdot 10^{-3} \cdot kg^{-1}$, with an average of 52.5 $g \cdot 10^{-3} \cdot kg^{-1}$. The zinc content for the sludge application dose of 50 $Mg \cdot ha^{-1}$ ranged from 87.16 to 89.74 $g \cdot 10^{-3} \cdot kg^{-1}$. The zinc content for the sludge application dose of 100 $Mg \cdot ha^{-1}$ ranged from 94.99 to 97.54 $g \cdot 10^{-3} \cdot kg^{-1}$. The zinc content for the sludge application dose of 200 $Mg \cdot ha^{-1}$ ranged from 83.75 to 98.50 $g \cdot 10^{-3} \cdot kg^{-1}$ (Table 8).

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Table 7. Determination of lead content in soil after sewage sludge application

Granuleometric fraction	Sludge dose [Mg·ha^{-1}]	Repetition	Content of Lead [g·10^{-3}·kg^{-1}]	Average content of Lead [g·10^{-3}·kg^{-1}]
Silt dust	0	1	20.00	16.50
		2	13.00	
	50	1	28.36	25.79
		2	23.18	
	100	1	23.16	25.17
		2	27.19	
	200	1	23.72	25.96
		2	28.20	
sludge	–	1	24.00	24.10

Table 8. Determination of zinc content in soil after sewage sludge application

Granuleometric fraction	Sludge dose [Mg·ha^{-1}]	Repetition	Content of Zinc [g·10^{-3}·kg^{-1}]	Average content of Zinc [g·10^{-3}·kg^{-1}]
Silt dust	0	1	60.00	52.5
		2	45.00	
	50	1	87.16	88.45
		2	89.74	
	100	1	97.54	96.26
		2	94.99	
	200	1	83.75	91.12
		2	98.50	
sludge	–	1	1349	1350
		2	1351	

The zinc content for the sewage sludge sample ranged from 1349 to 1351 g·10-3·kg^{-1}. The copper content for the soil without sludge addition ranged from 8.30 to 10.50 g·10-3·kg^{-1} with an average of 9.40 g·10-3·kg^{-1} (Table 9).

Table 9. Determination of copper content in soil after sewage sludge application

Soil type	Sludge dose [Mg·ha^{-1}]	Repetition	Content of Copper [g·10^{-3}·kg^{-1}]	Average content of Copper [g·10^{-3}·kg^{-1}]
Silt dust	0	1	8.30	9.40
		2	10.50	
	50	1	16.68	18.01
		2	19.34	
	100	1	21.01	19.64
		2	18.36	
	200	1	18.31	18.84
		2	19.38	
sludge	–	1	162.50	163.00
		2	163.50	

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The copper content for the soil without sludge addition ranged from 8.30 to 10.50 $g \cdot 10^{-3} \cdot kg^{-1}$, with an average of 9.40 $g \cdot 10^{-3} \cdot kg^{-1}$. The copper content for the sludge application dose of 50 $Mg \cdot ha^{-1}$ ranged from 16.68 to 19.34 $g \cdot 10^{-3} \cdot kg^{-1}$. The copper content for the sludge application dose of 100 $Mg \cdot ha^{-1}$ ranged from 18.36 to 21.01 $g \cdot 10^{-3} \cdot kg^{-1}$. The copper content for the sludge application dose of 200 $Mg \cdot ha^{-1}$ ranged from 18.31 to 19.38 $g \cdot 10^{-3} \cdot kg^{-1}$ (Table 9). For the sludge sample collected, the copper content ranged from 162.5 to 163.5 $g \cdot 10^{-3} \cdot kg^{-1}$.

Results of the author's own research on heavy metal content after application of municipal sludge in relation to literature references – discussion of results

As noted by (Kabata-Pendias, 2004), the accumulation of cadmium in the upper soil layers depends on the history of the area in question, as well as the current pattern and intensity of soil use. In the field study, the cadmium content for silt clay increased by up to 78% after application of the highest dose of 200 $Mg \cdot ha^{-1}$, and by up to 95.2% at the dose of 50 $Mg \cdot ha^{-1}$. The source of trace amounts of lead in topsoils is considered (Kowicka, 1997) to be the application of metallurgical waste as fertiliser. In the field studies, the application of sewage sludge resulted in an increase in lead concentration of 56.3% for the 50 $Mg \cdot ha^{-1}$ dose, 52.3% for the 100 $Mg \cdot ha^{-1}$ dose and 57.3% for the 200 $Mg \cdot ha^{-1}$ dose. Lead in soil can also be considered in the context of traffic pollution. As noted by (Jankowski et al., 2014), there is a decrease in average soil lead content with increasing distance between the sampling site and motorways. As reported by the authors, at a distance of 1 m from the edge of the roadway, the lead concentration reached 2.52 $mg \cdot kg^{-1}$, while at 15 m it decreased to the level of 1.64 $mg \cdot kg^{-1}$. The higher accumulation of this metal in the soil results in the inhibition of organic matter decomposition. This applies to both acid and alkaline soil compounds. According to (Węglarzy, 2007; Gondek & Filipek-Mazur, 2006), zinc accumulated in organic compounds is relatively easily absorbed by plants. In field studies, the application of sewage sludge led to an increase in soil zinc concentration by 68% at the dose of 50 $Mg \cdot ha^{-1}$, by 83.4% at the dose of 100 $Mg \cdot ha^{-1}$, and by 73.6% at the dose of 200 $Mg \cdot ha^{-1}$. In the studies of agricultural soils in Poland, the average concentration of copper is 10.3 [$g \cdot 10\text{-}3 \cdot kg^{-1}$] and, as monitoring in recent years has shown, it remains at a constant level (IUNG-PIB, 2017). As reported by (Rogóż, 2003), the average copper content in the Lesser Poland Voivodship ranged from 0.7 to 14.3 [$g \cdot 10\text{-}3 \cdot kg^{-1}$]. This is in line with the results of the control sampling. In field studies, sewage sludge application resulted in an increase in copper concentrations of 92% for the 50 $Mg \cdot ha^{-1}$ dose, 108% for the 100 $Mg \cdot ha^{-1}$ dose and 100.5% for the 200 $Mg \cdot ha^{-1}$ dose. Sludge application, even at multiple doses, did not exceed the permissible limit for this metal (Regulation, 2015).

Estimation of direct costs of the investigated process of soil fertilisation with municipal sewage sludge

The cost of agricultural application of sewage sludge is an aspect often overlooked in sludge management. In this study, the necessary expenses related to sewage sludge fertilisation were calculated on the basis of a cost estimate of the necessary work for the applied doses (Tables 10-13). The estimated costs ranged from PLN 12,646.2 to PLN 20,456.7 per ha for doses from 50 to 200 Mg per ha. Direct costs were defined as the sum of labour, materials and equipment necessary to achieve the objective of fertilising the agricultural land. The labour costs of field workers and agricultural machine operators directly involved in preparing the soil for sewage sludge application, i.e. transporting the material, spreading the sewage sludge on a unit area of soil and mixing it by subsoiling ploughing followed by harrowing and surface tillage, were classified as labour costs. The research assumed that the material itself was obtained free of charge. The use of sewage sludge was considered a direct material cost. At the same time, it was assumed that the sludge would be treated as waste and that its producer (the WWTP) would provide it free of charge. The direct labour costs of the equipment included the cost of transport (hire, fuel, depreciation) of the sludge in self-unloading trucks with a maximum permissible payload of 20Mg, as well as the hire and working time of the equipment, including fuel costs for wheeled tractors and combined spreaders, tillers, harrows and cultivators. The cost of the operation was the mass of sludge required for management. The cost calculation was

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based on the Katalog Nakładów Rzeczowych nr 2-21: Tereny zielone / Ministerstwo Gospodarki Przestrzennej i Budownictwa (2009) for soil category III and current prices from Sekocendbud (2023).

Table 10. Calculation of direct costs of fertilising native soil (category III soil) with stabilised sewage sludge at the dose of 50 Mg·ha^{-1}

Light soil – category III soil – sewage sludge50 Mg·ha^{-1}								
No.	Specification of labour, materials and machinery	Unit	Quantity	Price PLN	Direct cost PLN			Total cost PLN
					L (labour)	M (material)	E (Equipment)	
1	KNR 2-21 – Table 0208 – Manure spreading (sewage sludge analogy)							
2	Gardeners – Group I (analogy)	r-g	49.67	27	1341.1			3314.5
3	Stabilised sewage sludge – dose of 50 Mg·ha^{-1} – transport within 50 km (analogy) KNR 201 0207-B	kg	50000	22.9		0 (free of charge)	1147.2	
4	Manure spreader 10.5 m^3 (without tractor)	m-g	4.16	85.5			355.7	
5	Wheeled tract (1)	m-g	4.92	83			408.4	
6	Harrow (without tractor)	m-g	1.13	55			62.2	
7	KNR 2-21 – Table 0207 – Ploughing with a trailed cultivator and mechanical harrowing and cultivating before ploughing							
8	Gardeners – Group I	r-g	276.95	27	7477.65			9331.7
9	Wheeled tractor 25-30 KM (1)	m-g	4.54	83			376.8	
10	Rototiller (without tractor)	m-g	4.54	85.5			388.2	
11	Harrow (without tractor)	m-g	6.96	55			382.8	
12	Cultivator (without tractor)	m-g	8.26	85.5			706.2	
Total								12646.2

The individual doses were related to an area of 1 ha and a ploughing depth of up to 40 cm, resulting in unit costs of approximately 126.5 PLN/are for the 50 Mg·ha^{-1} (0.0125 Mg·m^{-3}) dose, 153.6 PLN/are for the 100 Mg·ha^{-1} (0.025 Mg·m^{-3}) dose and 204.6 PLN/are for the 200 Mg·ha^{-1} (0.050 Mg·m^{-3}) dose.

Direct costs of fertilisation with stabilised sewage sludge, in relation to the area, increased with the dose of sludge applied. The cost difference between the lowest sludge application dose of 50 Mg·ha^{-1} and the highest application rate of 200 Mg·ha^{-1} reached 162% (Table 12).

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Table 11. Calculation of direct costs of fertilisation of native soil (category III soil) with stabilised sewage sludge at the dose of 100 $Mg \cdot ha^{-1}$

Light soil – category III soil – sewage sludge100 $Mg \cdot ha^{-1}$								
No.	**Specification of labour, materials and machinery**	**Unit**	**Quantity**	**Price PLN**	**Direct cost PLN**			**Total cost PLN**
					L (labour)	**M (material)**	**E (Equipment)**	
1	KNR 2-21 – Table 0208 – Manure spreading (sewage sludge analogy)							
2	Gardeners – Group I (analogy)	r-g	113.7	27	3069,1			6030,0
3	Stabilised sewage sludge – dose of 50 Mg*ha-1 – transport within 50km (analogy) KNR 201 0207-B	kg	100000	21.34		0 (free of charge)	2134.74	
4	Manure spreader 10.5 m^3 (without tractor)	m-g	4.2	85.5			355.7	
5	Wheeled tract (1)	m-g	4.9	83			408.4	
6	Harrow (without tractor)	m-g	1.1	55			62.2	
7	KNR 2-21 – Table 0207 – Ploughing with a trailed cultivator and mechanical harrowing and cultivating before ploughing							
8	Gardeners – Group I	r-g	276.95	27	5079.8			9331.7
9	Wheeled tractor 25-30 KM (1)	m-g	4.54	83			376.8	
10	Rototiller (without tractor)	m-g	4.54	85.5			388.2	
11	Harrow (without tractor)	m-g	6.96	55			382.8	
12	Cultivator (without tractor)	m-g	8.26	85.5			706.2	
Total								15361.7

Table 12. Calculation of direct costs of fertilisation of native soil (category III soil) with stabilised sewage sludge at the dose of 200 $Mg \cdot ha^{-1}$

Light soil – category III soil – sewage sludge200 $Mg \cdot ha^{-1}$								
No.	**Specification of labour, materials and machinery**	**Unit**	**Quantity**	**Price PLN**	**Direct cost PLN**			**Total cost PLN**
					L (labour)	**M (material)**	**E (Equipment)**	
1	KNR 2-21 – Table 0208 – Manure spreading (sewage sludge analogy)							
2	Gardeners – Group I (analogy)	r-g	241.67	27	6525.1			11,461.0
3	Stabilised sewage sludge – dose of 50 Mg*ha-1 – transport within 50km (analogy) KNR 201 0207-B	kg	200000	20.6		0 (free of charge)	4109.7	
4	Manure spreader 10.5 m^3 (without tractor)	m-g	4.16	85.5			355.7	
5	Wheeled tract (1)	m-g	4.92	83			408.4	
6	Harrow (without tractor)	m-g	1.13	55			62.2	
7	KNR 2-21 – Table 0207 – Ploughing with a trailed cultivator and mechanical harrowing and cultivating before ploughing							

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8	Gardeners – Group I	r-g	276.9	27	7477.7			8,995.7
9	Wheeled tractor 25-30 KM (1)	m-g	4.5	9			40.9	
10	Rototiller (without tractor)	m-g	4.5	85.5			388.2	
11	Harrow (without tractor)	m-g	6.9	55			382.8	
12	Cultivator (without tractor)	m-g	8.3	85.5			706.2	
Total								20,456.7

Relating the total costs obtained, however, to the mass of sludge managed (density ρ=1.46Mg·m^{-3}) and the volume of the arable layer (0 to 40 cm), the unit price was 252.9 PLN/Mg for the dose of 50 Mg·ha^{-1}, 153 PLN/Mg for the dose of 100 Mg·ha^{-1}, 102.3 PLN/Mg for the dose of 200 Mg·ha^{-1}, respectively. The reduction in unit cost between the lowest sludge dose of 50 Mg·ha^{-1} and the highest dose of 200 Mg·ha^{-1} was as much as 59.6%. In terms of cost, it is, therefore, optimal to use the highest possible sludge dose per unit area (Table 13).

Table 13. Cost calculation summary

No.	Sludge dose [Mg·ha^{-1}]	Direct costs [PLN] per 1 ha	Costs related to the soil surface [PLN/are]	Cost increase in relation to investigated soil area Δk_A[%]	Cost per deposited sludge mass [PLN/Mg]	Cost increase related to the mass of sludge deposited Δk_V[%]
1.	50	12,646.2	126.5	100%	252.9	100%
2.	100	15,361.7	153.6	121%	153.6	39.3%
3.	200	20,456.7	204.6	162%	102.3	59.6%

Due to its manure-like properties, in particular its high content of nitrogen, phosphorus and organic matter, sewage sludge is a valuable fertiliser for agriculture. The use of sewage sludge in agriculture is also very often associated with the heavy metal content. If it meets the ministerial criteria for sewage sludge, the legislation allows it to be effectively disposed of and managed in agriculture. A balanced approach to optimising costs and calculating proper management costs should be the starting point for further action.

Summary and conclusions

The aim of this article was to determine the heavy metal content of soils following the application of sewage sludge as a source and method of fertilisation and to attempt to estimate the costs of this process.

The thesis assumed that the selected unit cost of fertilisation with stabilised sewage sludge would increase with the amount of sludge applied in relation to the area of fertilised soil and would decrease with the increase in the mass of sludge deposited in the soil.

The results obtained allow the following conclusions to be drawn:

1. The sludge under investigation can be used as an agricultural fertiliser. No contamination of the soil with copper, cadmium, lead and zinc was found, despite an obvious increase in the content of these metals after sludge application. The application of sludge, even in multiple doses, did not cause the permissible limit for the content of these elements in the soil to be exceeded in accordance with the Regulation of the Minister of the Environment of 2015 (Regulation, 2015).
2. The cost of fertilisation with stabilised sewage sludge, related to the area of soil, increased with the amount of sludge applied. The cost difference between the lowest sludge application dose of 50 Mg·ha^{-1} and the highest application dose of 200 Mg·ha^{-1} reached 162%. However, when the value of total cost was related to the mass of sludge applied, a reduction in unit cost of about 60% was observed between the lowest sludge dose of 50 Mg·ha^{-1} and the highest dose of 200 Mg·ha^{-1}.

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In terms of cost (reduction), it is, therefore, optimal to use the highest possible sludge dose per unit area.

3. Municipal sewage sludge fertilisation costs ranged from PLN 12,646.19 to PLN 2,456.73 per hectare for doses between 50 and 200 Mg per hectare.
4. The analysis of sludge transport costs for individual sludge doses shows that these costs increase with the weight of the sludge.
5. The additional cost of sewage sludge distribution in agriculture due to its volume should be considered one of the essential aspects of sludge management.

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The contribution of the authors

Conceptualization, A.P., M.R. and S.G.; literature review, A.P., M.R.; methodology, A.P.; formal analysis, A.P., M.R. and S.G.; writing, A.P., S.G.; conclusions and discussion, A.P., M.R. and S.G.

The authors have read and agreed to the published version of the manuscript.

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OZNACZANIE ZAWARTOŚCI METALI CIĘŻKICH W GLEBACH ZMIESZANYCH Z OSADAMI ŚCIEKOWYMI I SZACOWANIE KOSZTÓW ICH NAWOŻENIA NA PRZYKŁADZIE PRYWATNEJ DZIAŁKI ROLNEJ W GMINIE WADOWICE

STRESZCZENIE: Celem artykułu było określenie zawartości metali ciężkich w glebach po aplikacji do nich osadu ściekowego jako źródła i sposobu nawożenia oraz próba oszacowania kosztów tego procesu. Koszty związane z nawożeniem gleby osadami ściekowymi, sprowadzono do czasu pracy sprzętu oraz robotników obsługujących sprzęt w dwóch podstawowych etapach prac (rozrzucanie obornika i orka), dla trzech wysokości dawek osadów ściekowych: 50, 100 oraz 200 $Mg{\cdot}ha^{-1}$. Kalkulacja kosztów została wykonana na podstawie Katalogu Nakładów Rzeczowych nr 2-21: Tereny zielone / Ministerstwo Gospodarki Przestrzennej i Budownictwa (2009) oraz aktualnych cen z bazy danych Sekocendbud (2023). Skuteczność nawożenia została oceniona przez zbadanie poziomu i zmiany zawartości metali ciężkich po zasileniu gleby osadami ściekowymi w proporcjonalnych, trzech dawkach: 50, 100, 200 $Mg{\cdot}ha^{-1}$. Zastosowane do nawożenia osady spełniały wymagania sanitarne stawiane osadom, które mają być wykorzystane w celach przyrodniczych (Regulation, 2015). Oszacowane koszty całkowite aplikacji osadu, wyniosły od 12646,19zł do 20456,73zł na 1 ha, odpowiednio dla dawek od 50 do 200 Mg na 1 ha. Wyniki szacunku potwierdziły założoną tezę, a mianowicie: koszty jednostkowe nawożenia ustabilizowanymi osadami ściekowymi rosną wraz z dawką osadu w odniesieniu do powierzchni nawożonej gleby a maleją wraz ze wzrostem masy zdeponowanych w glebie osadów. Optymalizacja kosztów nawożenia wymaga zatem doboru – zwiększania dawki osadu na jednostkę powierzchni. Nie stwierdzono skażenia gleby miedzią, kadmem, ołowiem i cynkiem pomimo oczywistego zwiększenia zawartości tych metali po ich zmieszaniu z glebą. Stosowanie osadu, nawet dawki wielokrotnej, nie wpłynęło na przekroczenie dopuszczalnego progu zawartości tych pierwiastków w glebie, określonej w Rozporządzeniu Ministra Środowiska z 2015 r. (Regulation, 2015).

SŁOWA KLUCZOWE: metale ciężkie, gleba, osady ściekowe, nawożenie osadami ściekowymi, koszty, rolnictwo