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Case Study on the Use of Sewage Sludge for the Reclamation of Mining Sites Contaminated with Heavy Metals

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ABSTRACT

The aim of the study was to determine the heavy metal content of soils after sewage sludge application and to calculate the costs associated with fertilising the soil with sewage sludge, which have not been analysed in the available literature so far. The soil for the pot experiments came from villages where the soil was contaminated with heavy metals. Sewage sludge was proposed as a material for the reclamation of land degraded by the mining industry in the aforementioned settlements, and its effect on improving the physical and chemical properties of the soil after application was demonstrated. The cost of applying three doses of municipal sludge to restore areas damaged (degraded) by human activity was estimated. The calculation was carried out on the basis of KNR (National Contractors Estimator) No. 2–21 Tereny Zieleni (Green Areas) and the current prices from Sekocendbud Bulletin 5/2023 (2145), 1st quarter 2023. The cost of fertilising with stabilised sewage sludge for category II land is relatively low. The cost difference between the lowest sludge application of 50 $Mg \cdot ha^{-1}$ and the highest of 200 $Mg \cdot ha^{-1}$ is 85%. Therefore, it is cost-effective to apply the highest possible sludge dose per unit area. The study used sewage sludge that was suitable for natural purposes, including agricultural use, and that met the requirements [Journal of Laws 2015, item 257]. In Karniowice, no contamination of the soil with copper, cadmium, zinc and lead was found, although the content of these metals clearly increased after sludge application at the aforementioned sludge doses. The application of sludge, even in multiple doses, had no influence on exceeding the permissible concentration for these metals according to the Regulation of the Minister of the Environment of 2015, which allowed the area to be classified as uncontaminated after sludge application. In Lgota, soil contamination standards were exceeded for cadmium, lead and zinc after sludge application. In the case of copper after sludge application, the results were in line with the regulation.

Keywords: heavy metals, soil, sewage sludge, fertilisation, cost estimation.

INTRODUCTION

Municipal sewage sludge, a product of human life and economic activities, is a special type of waste. A significant reduction in the possibility of landfilling sewage sludge as of 1 January 2016 has forced municipal companies to seek other ways of managing it. In turn, soil degradation is a consequence of progressive urbanisation, intensification of industrialisation and irrational agricultural activities. This leads to a reduction in the retention, production and sanitary-ecological functions of the soil structure. Degradation processes take the form of changes in the geotechnical, hydrological, physical, chemical and biological properties of the soil [Jasiewicz et al. 2010]. Beneficial chemical and biological changes in degraded soil substrate may result from fertilising soils with sewage sludge or composts produced from it. For many years, both in the literature and in agricultural practice, the problem of identifying the properties and the use of municipal sewage sludge for fertilising agricultural land has been addressed [Stabnikova et al. 2005; Silva et al. 2010; Bień et al. 2015].

SEWAGE SLUDGE MANAGEMENT

The Polish legislator defined municipal sewage sludge in the Waste Act of 14 December 2012

(Journal of Laws 2019, item 701, as amended) as "sludge from sewage treatment plants from digestion towers and other installations for the treatment of municipal sewage and other waste water with a composition similar to that of municipal sewage". The use of sewage sludge referred to in the Act is defined as "distribution on the surface of the ground or its introduction into the soil". The handling of sewage sludge is also regulated, in addition to the aforementioned Act, by other national normative acts, such as the Act of 27 April 2001 - Environmental Protection Act (Journal of Laws of 2001, No. 62, item. 627, as amended) and the Act of 10 July 2007 on fertilisers and fertilisation (Journal of Laws of 2007, No. 147, item. 1033, as amended), 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. In Poland, a clear increase in municipal sludge production has been observed since 2010. This is mainly due to the modernisation of existing WWTPs and the construction of new ones, as well as the progressive extension of the sewage network in urban and rural areas [Bień et al. 2011]. According to CSO data, the use of sewage sludge in agriculture in Poland has increased since 2010 (Table 1). An increase in the amount of sludge thermally transformed is also observed.

The Regulation of the Minister of the Environment of 6 February 2015 on municipal sewage sludge (Journal of Laws of 2015, item 257) established the permissible values of quality indicators for the use of stabilised sewage sludge in agriculture. The set standards related to the content of selected heavy metals, intestinal parasite eggs and pathogenic bacteria (Table 2).

THE IMPACT OF SEWAGE SLUDGE ON THE SOIL AND ON THE SUBSTRATES FOR LAND RECLAMATION

Soil degradation is a consequence of progressive urbanisation, intensification of industrialisation and irrational agricultural activity. It leads to a reduction in the retention, production and sanitary-ecological functions of the soil structure. The degradation processes take the form of changes in the geotechnical, physical, chemical and biological properties of the soil [Jasiewicz et al. 2010]. The beneficial chemical and biological changes that occur in a degraded soil substrate may be associated with the fertilisation of the soil with sewage sludge or compost which is produced from it. Recognition of the properties and fertilising purpose of municipal sludge is well established in the literature and agricultural practice [Stabnikova et al. 2005; Silva et al. 2010; Bień et al. 2015].

Natural management of sewage sludge can take the form of fertilisation that completely replaces or complements the effect of natural fertilisers from livestock farms [Środa et al. 2013]. Inappropriate fertilisation with sewage sludge is

Table 1. Sewage sludge from industrial and municipal wastewater treatment plants

Specification	2000	2005	2010	2015	2018	2019
	In thousands of tonnes of dry matter					
Total sludge production per year	1063.1	1124.4	895.1	951.5	1046.5	1048.7
Agricultural use	212.2	98.2	136.9	126.6	134.2	141.9
Use for land reclamation incl. land for agricultural purposes	154.9	324.9	150.4	31.3	27.8	24.5

Table 2. Permissible contents of heavy metals in $mg \cdot kg^{-1}$ DM in municipal sewage sludge intended for agricultural and non-agricultural use

Element	Method for the use of municipal sewage sludge		
	Agricultural use and reclamation	Non-agricultural land reclamation	Compost production, consolidation of vegetated areas
Cadmium	20	25	50
Copper	1000	1200	2000
Lead	750	1000	1500
Zinc	2500	3500	5000

Note: source – drawn up pursuant to The Regulation of the Minister for the Environment [2015].

recognised as a risk factor leading to deterioration of soil substrate quality and even contamination. This risk increases with high concentrations of toxic components and heavy metals in the sludge doses applied to the soil [Iżewska 2007; Nafez et al. 2015]. The content of heavy metals in municipal sewage sludge does not exceed the permissible ministerial standards in most cases (Table 3). Exceedances may result from illegal discharges of industrial wastewater or surface runoff, as well as from indirect entry into domestic wastewater [Urbaniak 1997; Jakubus 2012].

The improvement in soil microbial development resulting from the systemic application of sewage sludge also correlates with an increase in soil biochemical activity [Pascual et al. 2007]. Stabilised sewage sludge contains similar content of nitrogen and phosphorus as natural fertilisers. At the same time, it contains less potassium than conventional fertilisers [Stańczyk-Mazanek 2012]. Due to their nitrogen and phosphorus content, they can stimulate nitrogen transformation (ammonification) and ammonium ion oxidation (nitrification) processes in the soil. The uptake of phosphorus by plants is reported to be lower than that of nitrogen, which may be explained by the presence in sediments of poorly soluble forms of this element, characterised by low plant uptake due to their slow decomposition [Krzywy et al. 2002; Joniec et al. 2012]. Given the low potassium content in municipal sewage sludge due to the high solubility of its mineral compounds, it is recommended that sewage sludge fertilisation be supplemented with mineral fertilisers [Czekała 2000; Skobiłowicz 2002; Bień 2007].

Table 3. Ranges of heavy metal contents 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

Note: source – table compiled by Jakubus [2012].

METHODOLOGY AND CHARACTERISTICS OF THE AREA UNDER STUDY

The areas from which soil material was collected for the pot experiments represent the area of historic coal, iron, zinc and lead mines and smelters, as well as current mineral deposits and pollution emitters. Historically, the area has been mined since ancient times. Its origins date back to the late 14th century. The villages of Karniowice and Lgota are located in the western part of the Lesser Poland Voivodship in the municipality of Trzebinia. Karniowice is home to the "Karniowicka Martwica" travertine quarries and the eastern shaft of the "Siersza" coal mine, while Lgota is a historic mining site of zinc deposits and the "Katarzyna" mine shaft. The degradation of the soil structure in the investigated areas is connected with the intensive mining, metallurgical, refining and energy activities [Pietraszek 1961; Szuwarzyński and Kryza 1995]; Pęckowski 2013]. Soil for the study was collected from the depth of 40 cm. Sewage sludge from the Trepcza Sewage Treatment Plant (the Podkarpackie Voivodship) was utilised in the pot experiments, which was suitable for natural purposes, including agricultural use (Table 4). Laboratory analyses showed that the heavy metal content of the sludge was not above normal. The sludge also met the sanitary requirements for sludge to be used for natural purposes [Journal of Laws 2015, item 257]. Microbiologically, it did not contain

Table 4. Physical and chemical properties of the sewage sludge used in the pot experiment

Parameter	Unit	Sewage sludge in Trepcza
Zinc	mg·kg^{-1}	1350
Cadmium	mg·kg^{-1}	1.50
Copper	mg·kg^{-1}	163
Lead	mg·kg^{-1}	24.1
Presence of specific DNA Salmonella Sp.	in the investigated mass or volume	not found
Number of Ascaris sp., Trichuris sp., Toxocara sp.	number·kg^{-1}	0

Note: source – sludge analyses commissioned by the Trepcza Wastewater Treatment Plant and performed by the Pszczyna Environment, Health & Safety Certified Laboratory.

pathogenic bacteria of the Salmonella type or Ascaris, Trichuris, Toxocara parasite eggs, the content of which limits the possibility of using the sludge for the above-mentioned purposes. 12 identical polypropylene pots with ∅30 cm and a capacity of 8 dm^3 were employed for the pot experiments. The pots were filled with a mixture of soil and sewage sludge. Three sewage sludge fertilisation doses were applied in the pot experiment, on two separate occasions for each soil type, at doses corresponding to 50, 100 and 200 $Mg·ha^{-1}$. Due to the empirical nature of the study, the applied sewage sludge doses exceeded the limit doses specified in the Sewage Sludge Regulation [Journal of Laws 2015, item 257].

RESEARCH FINDINGS

The electrolytic conductivity of the soil was determined using the conductometric method. The pH of the soil in 1M KCl, H_2O and water was determined by means of the potentiometric method. The granulometric composition of the soil was calculated using the Casagrande method modified by Prószyński [according to Industry Standard BN-78/9180-11]. The determination of the total content of cadmium, lead, copper and zinc in the soil [Jasiewicz et al. 2010] was performed at the Agricultural University of Krakow employing the FAAS method directly in the filtrate, using the apparatus parameters of the spectrometer in accordance with the manufacturer's guidelines. The average cadmium content in the soil in Karniowice (Table 5) at the depth of 0-40 cm reached 1.06 $mg·kg^{-1}$. The average cadmium content in the soil after sludge application at the dose of 50 $Mg·ha^{-1}$ amounted to 1.10 $mg·kg^{-1}$, at the dose of 200 $Mg·ha^{-1}$ to 1.22 $mg·kg^{-1}$. The average lead content in the soil at the depth of 0–40 cm amounted to 38.55 $mg·kg^{-1}$. The average lead content in soil after sludge application at the dose of 50 $Mg·ha^{-1}$ was 40.09 $mg·kg^{-1}$, for the dose of 200 $Mg·ha^{-1}$ it reached 44.33 $mg·kg^{-1}$. The average zinc content in soil at the depth of 0–40 cm was equal to 126.44 $mg·kg^{-1}$. The average zinc content in the soil after sludge application at the dose of 50 $Mg·ha^{-1}$ was 131.50 $mg·kg^{-1}$, at the dose of 200 $Mg·ha^{-1}$ it reached 145.41 $mg·kg^{-1}$. The average copper content in the soil at the depth of 0–40 cm was equal to 13.2 $mg·kg^{-1}$. The average copper content in the soil after sludge application at the dose of 50 $Mg·ha^{-1}$ amounted to 13.73 $mg·kg^{-1}$, for the dose of 200 $Mg·ha^{-1}$, it was 15.18 $mg·kg^{-1}$. The average percentage of soil organic matter for the 0–40 cm depth reached 3.46%. The average soil pH value determined in water for the 0–40 cm layer was 5.93 assuming an acid reaction. The average electrolytic conductivity of the soil for the 0–40 cm depth was equal to 149.85µS. The average percentage of the silt fraction reached 55.33%, the sand fraction 34% and for the clay fraction 10.67%.

The average cadmium content in the soil in Lgota (Table 6) at the depth of 0–40 cm was 3.77 $mg·kg^{-1}$. The average cadmium content in soil after sludge application at 50 $Mg·ha^{-1}$ reached 3.92 $mg·kg^{-1}$and at 200 $Mg·ha^{-1}$, it equalled 4.34 mg/

Table 5. Basic statistics of the heavy metal content in soil before and after sludge application in soil samples from the village of Karniowice

Parameter		Average (loam without added sludge)	Average (mixed loam – dose of 50 $Mg·ha^{-1}$)	Average (mixed loam – dose of 100 $Mg·ha^{-1}$)	Average (mixed loam – dose of 200 $Mg·ha^{-1}$)
Organic matter [%]	0–40 cm	3.46	7.27	7.47	7.92
Heavy metals in soil 0–40 cm [mg/kg]	Cd	1.06	1.10	1.23	1.22
	Pb	38.55	40.09	44.72	44.33
	Zn	126.44	131.50	146.67	145.41
	Cu	13.20	13.73	15.31	15.18
pH	in water	5.93	6.61	6.75	6.87
	in KCl	5.48	5.64	5.81	6.03
Electrolytic conductivity [µS/cm]		149.85	153.45	156.59	170.33
Share of fraction [%]	Sand	34.00			
	Silt	55.33			
	Clay	10.67			

Table 6. Basic statistics of heavy metal content in soil before and after sludge application in soil samples from the village of Lgota

Parametre		Average (clay without added sludge)	Average (mixed loam – dose of 50 Mg·ha^{-1})	Average (mixed loam – dose of 100 Mg·ha^{-1})	Average (mixed loam – dose of 200 Mg·ha^{-1})
Organic matter [%]	0–40 cm	3.15	6.62	6.80	7.21
Heavy metals in soil 0-40 cm [mg·kg^{-1}]	Cd	3.77	3.92	4.37	4.34
	Pb	266.66	277.33	309.33	306.66
	Zn	578.37	601.50	670.91	665.13
	Cu	6.94	7.22	8.05	7.98
pH	in water	6.39	6.61	6.75	6.87
	in KCl	5.97	6.15	6.33	6.57
Electrolytic conductivity [µS·cm^{-1}]		157.51	161.29	164.60	179.03
Share of fraction [%]	Sand	71.00			
	Silt	19.43			
	Clay	9.57			

kg. The average lead content in soil at 0–40 cm depth was 266.66 mg·kg^{-1}. The average lead content in soil after sludge application at the dose of 50 Mg·ha^{-1} amounted to 277.33 mg/kg, at the dose of 200 Mg·ha^{-1} it was 306.66 mg·kg^{-1}. The average zinc content in the soil at 0–40 cm depth reached 578.37 mg·kg^{-1}. The average soil zinc content after sludge application at 50 Mg·ha^{-1} was 601.50 mg·kg^{-1}, for the dose of 200 Mg·ha^{-1}, it was 665.13 mg·kg^{-1}. The average copper content in the soil at the depth of 0–40 cm was equal to 6.94 mg·kg^{-1}. The average copper content in soil after sludge application at 50 Mg·ha^{-1}was 7.22 mg·kg^{-1}, for the 200 Mg·ha^{-1} dose, it was 7.98 mg·kg^{-1}.

The average percentage of organic matter in the soil for the depth of 0–40 cm was 3.15%. The average electrolytic conductivity of the soil at 0–40 cm depth equalled 157.51 µS. The average pH value of the soil determined in water for the layer was 6.39 assuming an acid reaction. The average percentage of sand fraction was 71%, silt fraction – 19.43% and clay fraction – 9.57%.

DISCUSSION

In the village of Karniowice, the average cadmium content in the soil of the sample collected from the site did not exceed the permissible concentrations of the element according to the national regulations [Journal of Laws 2016] for arable land (land group II-2) (<3 g·10^{-3}·kg^{-1} DM). The average cadmium content of the sewage sludge sample amounted to 1.50 [g·10^{-3}·kg^{-1}]. This value was in line with the ministerial requirements [Journal of Laws 2015] for agriculture and land reclamation for agricultural purposes (<20 [g·10^{-3}·kg^{-1}]), for land reclamation for non-agricultural purposes (<25 [g·10^{-3}·kg^{-1}]) and for land adaptation for land development plans (LDPs), compost crops and crops not intended for food and fodder production (<50 [g·10^{-3}·kg^{-1}]). From the analysis of the above data, it can be concluded that fertilisation at doses of 50, 100 and 200 [Mg·ha^{-1}] did not change the cadmium content in the soil solution for sandy loam soils after sludge application. In the village of Lgota, the average cadmium content in the soil of the sample collected from the site exceeded the values of permissible concentrations of the element according to the national regulations [Journal of Laws 2016] for arable land (land group II-2) (<3 g·10^{-3}·kg^{-1} DM). The analysis of the above data shows that fertilisation at doses of 50, 100 and 200 [Mg·ha^{-1}] increased the cadmium content in the sandy loam soil solution. In Lgota, the values of permissible concentrations of the element according to national regulations [Journal of Laws 2016] for arable land (land group II-2) were exceeded (<3 g·10^{-3}·kg^{-1} DM) after sewage sludge application. Fernandez et al. [2000] linked the deposition of heavy metals in soils to the impact of point sources of pollution, especially local industrial plants or CHP plants. The average cadmium content of agricultural soils in the Lesser Poland Voivodship was 0.57 mg/kg DM, while for Poland the value amounted to 0.21 mg/kg DM [Terelak et al. 2000; Terelak et al. 1998]. Kabata-Pendias and Pendias

[1999] noted that the highest concentrations of cadmium in soils were found predominantly in the areas of lead, zinc and copper ore smelters and mines. Therefore, the content of cadmium seems to be related to the production of non-ferrous metals and to the combustion of coal. Kabata-Pendiasi Pendias [1999] reported that the natural cadmium content in plants could range from <0.1 to 1 $mg \cdot kg^{-1}$ DM, while the critical one in the range of 5–10 $mg \cdot kg^{-1}$ DM.

In the village of Karniowice, the average content of lead in soil in the sample taken from the site exceeded the values of permissible concentrations of this element according to the national regulations [Journal of Laws 2016] for arable land (land group II-2) (<250 $mg \cdot 10^{-3} \cdot kg^{-1}$ DM) for sandy loam soils. The average lead content of the collected sewage sludge sample was 24.1 $g \cdot 10^{-3} \cdot kg^{-1}$. This value complied with the ministerial requirements [Journal of Laws 2015] for agriculture and land reclamation for agricultural purposes (<750 $g \cdot 10^{-3} \cdot kg^{-1}$), for land reclamation for non-agricultural purposes (<1000 $g \cdot 10^{-3} \cdot kg^{-1}$) and for land adaptation for land development plans (LDPs), compost crops and crops not intended for food and fodder production (<1500 $g \cdot 10^{-3} \cdot kg^{-1}$). The analysis of the aforementioned data shows that fertilisation with doses of 50, 100 and 200 $Mg \cdot ha^{-1}$ did not change the lead content in the sand loam soil solution, the soil after sludge application did not exceed the national standards. In the village of Lgota, the average content of lead in the soil of the sample taken from the site exceeded the values of permissible concentrations of the element according to the national regulations [Journal of Laws 2016] for arable land (land group II-2) (<250 $g \cdot 10^{-3} \cdot kg^{-1}$ DM). The analysis of the above data shows that fertilisation with doses of 50, 100 and 200 $Mg \cdot ha^{-1}$ influenced the increase of lead content in the sand loam soil solution. In Lgota, the values of permissible concentrations of the element according to the national regulations [Journal of Laws of 2016] for arable land (land group II-2) were exceeded (<250 $g \cdot 10^{-3} \cdot kg^{-1}$ DM) after sewage sludge application. According to the research conducted by Gambus [1993], the average lead concentration in the soils of the former Cracow Voivodship did not exceed 28.4 $mg \cdot kg^{-1}$ DM. In Karniowice and Lgota, lead content in soil decreases with depth. The occurrence of the highest lead concentrations in the 7–14 cm soil layer, according to Weber [1995], may be due to disturbance of the natural structure of the soil profiles as a result of construction and reclamation activities. According to [Petkowski 1995], heavy mining, chemical and manufacturing industries are the main sources of lead emissions. Wierzbicka [1991] also identified steel, iron and copper smelting, cement production and zinc ore mining as potential sources of industrial lead contamination.

In the village of Karniowice, the average content of zinc in the soil of the sample taken in the area did not exceed the values of permissible concentrations of the element according to the national regulations [Journal of Laws 2016] for arable land (land group II-2) (<500 $mg \cdot 10^{-3} \cdot kg^{-1}$ DM). In pot experiments for the sample taken from sewage sludge, the average content of zinc was 1350 $g \cdot 10^{-3} \cdot kg^{-1}$. It was in line with the ministerial requirements [Journal of Laws 2015] for agriculture and land reclamation for agricultural purposes (<2500 $g \cdot 10^{-3} \cdot kg^{-1}$), for land reclamation for non-agricultural purposes (<3500 $g \cdot 10^{-3} \cdot kg^{-1}$) and for land adaptation for land development plans (LDPs), compost crops and crops not intended for food and fodder production (<5000 $g \cdot 10^{-3} \cdot kg^{-1}$). The analysis of the above data shows that fertilisation with doses of 50, 100 and 200 $Mg \cdot ha^{-1}$ did not change the zinc content in the sandy loam soil solution, the soil after sludge application did not exceed the national standards. In the village of Lgota, the average zinc content in the soil of the sample taken in the area exceeded the values of permissible concentrations of the element according to the national regulations [Journal of Laws 2016] for arable land (land group II-2) (<500 $mg \cdot 10^{-3} \cdot kg^{-1}$ DM). In pot experiments for the sewage sludge sample, the average zinc content amounted to 1350 $g \cdot 10^{-3} \cdot kg^{-1}$. It complied with the ministerial requirements [Journal of Laws 2015] for agriculture and land reclamation for agricultural purposes (<2500 $g \cdot 10^{-3} \cdot kg^{-1}$), for land reclamation for non-agricultural purposes (<3500 $g \cdot 10^{-3} \cdot kg^{-1}$) and for land adaptation for land development plans (LDPs), compost crops and crops not intended for food and fodder production (<5000 $g \cdot 10^{-3} \cdot kg^{-1}$).

The analysis of the above data shows that fertilisation with doses of 50, 100 and 200 $Mg \cdot ha^{-1}$ changed the zinc content, the soil after sludge application exceeded the national standards. Curzydło [1995] pointed out that the distance from emission sources of zinc pollution is not important for the accumulation of the metal in soils.

Table 7. Reclamation costs for sewage sludge of light soil category II at the dose of 50 Mg·ha^{-1}

Light soil - category II soil - sewage sludge 50 Mg·ha^{-1}								
No.	Specification of labour, materials and machinery	Unit	Qantity	Price PLN	L (labour)	M (material)	E (Equipment)	Total cost
1	KNR 2-21 - Table 0208 - Manure spreading (sewage sludge analogy)							
2	Gardeners - Group I (analogy)	r-g	49.67	27	1341.09			3,293.62
3	Stabilised sewage sludge – dose of 50 Mg·ha^{-1} - transport within 50km (analogy) KNR 201 0207-B	kg	50 000	22.94		0 (free of charge)	1 147.24	
4	Manure spreader 10.5m^3 (without tractor)	m-g	4.16	85.5			355.68	
5	Wheeled tract (1)	m-g	4.92	83			408.36	
6	Harrow (without tractor)	m-g	0.75	55			41.25	
7	KNR 2-21 - Table 0207 - Ploughing with a trailed cultivator and mechanical harrowing and cultivating before ploughing							
8	Gardeners - Group I	r-g	188.14	27	5 079.78			6,208.67
9	Wheeled tractor 25-30 KM (1)	m-g	3.02	83			250.66	
10	Rototiller (without tractor)	m-g	3.02	85.5			258.21	
11	Harrow (without tractor)	m-g	4.06	55			223.3	
12	Cultivator (without tractor)	m-g	4.64	85.5			396.72	
Total								9,502.3

Table 8. Reclamation costs for light soil category II sludge at the dose of 100 Mg·ha^{-1}

No.	Specification of labour, materials and machinery	Unit	Qantity	Price PLN	L (labour)	M (material)	E (Equipment)	Total cost
1	KNR 2-21 - Table 0208 - Manure spreading (sewage sludge analogy)							
2	Gardeners - Group I (analogy)	r-g	113.67	27	3069.09			6,009.12
3	Stabilised sewage sludge – dose of 100 Mg·ha^{-1} - transport within 50km (analogy) KNR 201 0207-B	kg	100 000	21.35		0 (free of charge)	2 134.74	
4	Manure spreader 10.5m^3 (without tractor)	m-g	4.16	85.5			355.68	
5	Wheeled tract (1)	m-g	4.92	83			408.36	
6	Harrow (without tractor)	m-g	0.75	55			41.25	
7	KNR 2-21 - Table 0207 - Ploughing with a trailed cultivator and mechanical harrowing and cultivating before ploughing							
8	Gardeners - Group I	r-g	188.14	27	5 079.78			6,208.67
9	Wheeled tractor 25-30 KM (1)	m-g	3.02	83			250.66	
10	Rototiller (without tractor)	m-g	3.02	85.5			258.21	
11	Harrow (without tractor)	m-g	4.06	55			223.3	
12	Cultivator (without tractor)	m-g	4.64	85.5			396.72	
Total								12,218

Table 9. Reclamation costs for light soil category II, sewage sludge at the dose of 200 Mg·ha^{-1}

Light soil - category II soil - sewage sludge 200 kg·ha^{-1}								
No.	Specification of labour, materials and machinery	Unit	Qantity	Price PLN	L (labour)	M (material)	E (Equipment)	Total cost
1	KNR 2-21 - Table 0208 - Manure spreading (sewage sludge analogy)							
2	Gardeners - Group I (analogy)	r-g	241.67	27	6 525.09			11,440.12
3	Stabilised sewage sludge – dose of 200 Mg·ha^{-1} - transport within 50km (analogy) KNR 201 0207-B	kg	20 0000	20.55		0 (free of charge)	4,109.74	
4	Manure spreader 10.5m^3 (without tractor)	m-g	4.16	85.5			355.68	
5	Wheeled tract (1)	m-g	4.92	83			408.36	
6	Harrow (without tractor)	m-g	0.75	55			41.25	
7	KNR 2-21 - Table 0207 - Ploughing with a trailed cultivator and mechanical harrowing and cultivating before ploughing							
8	Gardeners - Group I	r-g	188.14	27	5 079.78			6,208.67
9	Wheeled tractor 25-30 KM (1)	m-g	3.02	83			250.66	
10	Rototiller (without tractor)	m-g	3.02	85.5			258.21	
11	Harrow (without tractor)	m-g	4.06	55			223.3	
12	Cultivator (without tractor)	m-g	4.64	85.5			396.72	
Total								17,649

Soils contaminated with zinc may be located at different distances from the emitter, not necessarily in the nearest zone of its influence. Zinc is a very abundant element in the topsoil and its content is usually between 30 and 125 g·10^{-3}·kg^{-1} DM [Kabata-Pendias 2002]. As Curzydło [1995] noted in his study, the distance from sources of zinc pollution is not directly related to the accumulation of the metal in soils.

In the villages of Karniowice and Lgota, the average content of copper in the soil of the samples taken in the area did not exceed the permissible concentrations of the element (<150 g·10^{-3}·kg^{-1}DM) according to the national regulations [Journal of Laws 2016] for arable land (land group II-2). For the sample of sewage sludge collected, the average copper content was 163.0 g·10^{-3}·kg^{-1}. This value complied with the ministerial requirements [Journal of Laws 2015] for agriculture and land reclamation for agricultural purposes (<1000 g·10^{-3}·kg^{-1}), for land reclamation for non-agricultural purposes (<1200 g·10^{-3}·kg^{-1}) and for land adaptation for land development plans (LDPs), compost crops and crops not intended for food and fodder production (<2000 g·10^{-3}·kg^{-1}). The analysis of the above data shows that fertilisation with doses of 50, 100 and 200 Mg·ha^{-1} did not change the copper content in soil solutions of both villages and after sewage sludge application; it did not exceed national standards. According to [Karczewska 2002], copper toxicity is a sporadic phenomenon in natural conditions, and the exceedance of this element is limited to areas degraded by mining and metallurgical industries, mainly in the Lower Silesia Voivodship. This issue was also addressed by [Ibragimov et al. 2010] and [Bojakowska and Sokolowska 1998]. Their analyses of samples from current and former river floodplains showed that significant amounts of heavy metals, including copper, are transported by rivers and other smaller watercourses.

Table 10. Reclamation costs for light soil category II - chicken, cattle, horse and pig manure at the dose of 200 Mg·ha^{-1}

Light soil - category II soil - sewage sludge 200 kg·ha^{-1}								
No.	Specification of labour, materials and machinery	Unit	Qantity	Price PLN	L (labour)	M (material)	E (Equipment)	Total cost
1	KNR 2-21 - Table 0208 - Manure spreading (sewage sludge analogy)							
2	Gardeners - Group I (analogy)	r-g	241.67	27	6 525.09			
3.a	Chicken manure – dose of 200 Mg·ha^{-1} - transport within 50 km (analogy) KNR 201 0207-B	kg	200 000	20.55		65*		17,110.00
3.b	Cattle manure – dose of 200 Mg·ha^{-1} - transport within 50km (analogy) KNR 201 0207-B	kg	200 000	20.55		60*		16,110.00
3.c	Horse manure – dose of 200 Mg·ha^{-1} - transport within 50 km (analogy) KNR 201 0207-B	kg	200 000	20.55		65*		17,110.00
3.d	Pig manure – dose of 200 Mg·ha^{-1} - transport within 50km (analogy) KNR 201 0207-B	kg	200 000	20.55		57*		15,510.00
4	Manure spreader 10.5m3 (without tractor)	m-g	4.16	85.5			355.68	
5	Wheeled tract (1)	m-g	4.92	83			408.36	
6	Harrow (without tractor)	m-g	0.75	55			41.25	
7.a	Total (Chicken manure) KNR 2-21 - Table 0208 - Manure spreading							24,440.38
7.b	Total (Cattle manure) KNR 2-21 - Table 0208 - Manure spreading							23,440.38
7.c	Total (Horse manure) KNR 2-21 - Table 0208 - Manure spreading							24,440.38
7.d	Total (Pig manure) KNR 2-21 - Table 0208 - Manure spreading							22,840.38
8	KNR 2-21 - Table 0207 - Ploughing with a trailed cultivator and mechanical harrowing and cultivating before ploughing							
9	Gardeners - Group I	r-g	188.14	27	5 079.78			6,208.67
10	Wheeled tractor 25-30 KM (1)	m-g	3.02	83			250.66	
11	Rototiller (without tractor)	m-g	3.02	85.5			258.21	
11	Harrow (without tractor)	m-g	4.06	55			223.3	
13	Cultivator (without tractor)	m-g	4.64	85.5			396.72	
Total (Chicken manure)								30,649.05
Total (Cattle manure)								29.649,05
Total (Horse manure)								30.649,05
Total (Pig manure)								29.049,05

Note: * Source: www.notowania.kpodr.pl Kuyavian-Pomeranian Agricultural Price Quotations, access: 02.07.2023.

ANALYSIS OF THE DIRECT COSTS OF LAND RECLAMATION WITH THE USE OF SEWAGE SLUDGE

The cost of using direct sewage sludge for land reclamation is an aspect often overlooked in sludge management. In the course of the research, the necessary expenditures related to soil reclamation with sewage sludge were calculated on the basis of cost estimation for the execution of the necessary works for the doses used (Table 7–9). The estimated costs ranged from PLN 9,502.30 to PLN 17,649.00 per 1 ha for doses from 50 to 200 Mg per ha. Direct costs were defined as the sum of labour, materials and equipment required to achieve the objective, i.e. to fertilise the area of agricultural use. The eligible labour costs included those directly related to preparing the soil for sewage sludge application, i.e. transporting the material, distributing the sludge on a unit area of the soil, and mixing the soil by subsoiling, followed by harrowing and surface tillage. The use of sewage sludge was assumed as a direct material cost. At the same time, the sludge was considered to be treated as waste and handed over free of charge by its producer (sewage treatment plant) as part of its management. The costs of transport (hire, depreciation) of sludge by self-unloading lorries with a maximum permissible transport weight of 20 Mg, as well as the hire and working time of equipment, including fuel costs for wheeled tractors and combined spreaders, tillers, harrows and cultivators, were classified as direct equipment labour costs. The cost of the activity is the mass of sewage sludge required for management. The cost calculation was based on KNR (National Contractors Estimator) No. 2–21 Tereny Zieleni (Green Areas) for soil category III and current prices from BRZ Sekocendbud's Bulletin of Prices for Earthworks and Engineering Works, 5/2023 (2145), 1st quarter 2023 (Table 7–9). Due to the type of soil in Karniowice and Lgota and the high sand content, soil category II was included in the cost estimate according to KNR.

The cost of fertilising with stabilised sewage sludge for category II land was relatively low. The cost difference between the lowest sludge application dose of 50 $Mg \cdot ha^{-1}$ and the highest application dose of 200 $Mg \cdot ha^{-1}$ amounted to 85%. Therefore, the optimum cost is to use the highest possible sludge dose per unit area. In recent years, the problem of the availability of natural fertilizers, including chicken, cattle, horse and pig manure, and the related significant increase in prices have been known. Comparing the obtained results with the available market data on prices of manure (Table 10) for the highest dosage, it is possible to observe the competitiveness of sewage sludge, which is cheaper than manure in application by an average of 39 to 42%. Due to the physical and chemical properties of sewage sludge, after meeting the normative requirements, they can replace manure, while being recycled.

CONCLUSIONS

The concentrations of cadmium, zinc and lead in the soils sampled for the pot experiments in the village of Karniowice exceeded the levels permitted by the Regulation, indicating the historic mining past of the area, which continues to have a negative impact on the topsoil despite the absence of mining for many years. In addition, the application of sewage sludge caused a significant increase in the concentration of the aforementioned heavy metals in the soil, especially at the dose of 100 Mg·ha-1. This confirms the hypothesis presented in the literature about the effect of the heavy metal content on the increase of the metal content in the soil after mixing with sewage sludge. However, no copper contamination of the soil was found, despite an obvious increase in the content of this metal after sludge application. No heavy metal contamination was found in the soils of the village of Karniowice before and after mixing with municipal sewage sludge.

The application of sewage sludge to the soil resulted in a slight increase in soil pH after mixing, both for pH in H_2O and pH in KCl tests in Karniowice and Lgota. For soils with high sand content, the cost of using sewage sludge as a fertilizer is relatively low due to more favourable agrotechnical conditions for sludge application (e.g. easier mixing of sludge with the soil). The application of sewage sludge increased the electrolytic conductivity (salinity) of the soil after mixing with municipal sewage sludge, but the value was insignificant (with no effect on erosion properties). This aspect requires further in-depth analysis of the effect of salinity on soil properties after mixing over a multi-year period. The difference in total costs at current unit prices between the lowest sludge application dose of 50 $Mg \cdot ha^{-1}$ and the highest application dose of 200 $Mg \cdot ha^{-1}$ amounted to 85%. However, when the value of total cost is related to the weight of sludge applied, a reduction in unit cost of 53.6% was observed between the lowest sludge dose of 50 $Mg \cdot ha^{-1}$ and the highest dose of 200 $Mg \cdot ha^{-1}$. Thus, the optimum in terms of estimated costs is to use the highest possible sewage sludge dose per unit area. Given the four times higher sludge application dose for the 200 $Mg \cdot ha^{-1}$ value, the optimum in terms of cost is therefore to apply the highest possible sludge dose per unit area. The estimated total costs ranged from PLN 9,502.3 to PLN 17,649.0 $\cdot ha^{-1}$ for doses from 50 to 200 $Mg \cdot ha^{-1}$. The cost of fertilising with stabilised sewage sludge increased with the dose of sludge per unit area. The competitiveness of the use of sewage sludge in relation to manure was observed, which in the event of an increase in manure prices can supplement the shortage of raw material on the market, being its cheaper alternative.

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