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Effect of Coal Mining Waste and Its Mixtures with Sewage Sludge and Mineral Wool on Selected Properties of Degraded Anthropogenic Soil

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ABSTRACT

The aim of the study was to evaluate the effect of coal mining waste and its mixtures with municipal sewage sludge and waste rock wool from cover crops on the formation of selected properties of degraded anthropogenic soil. Under the conditions of a pot experiment, coal mining waste and its mixtures with 2.5 and 5% sewage sludge and mixtures supplemented with 1% addition of waste rockwool from cover crops were introduced (in a ratio of 1:1) into the degraded anthropogenic soil. White mustard was grown on the substrates in the first year and maize in the second year. The pH, EC, and sorption properties were determined in soil samples taken before of the plants and after their harvest. The results showed that the addition of coal mining waste and its mixtures with municipal sewage sludge and waste rock wool improved the soil pH and sorption properties. The management of coal mining waste and waste optimising its properties for the production of fertilizing agents can be an effective strategy within a circular economy, which at the same time will increase the efficiency of the management of degraded and poor-quality soils.

Keywords: soil, pH, sorption properties, coal mining waste, sewage sludge, waste rock wool, circular economy.

INTRODUCTION

In Poland, approximately 35% are light soils. These soils are characterised by strong acidity, very low and low organic matter and nutrient abundance, and defective sorption properties, which results into low production potential. In addition, more than 70.000 hectares are degraded and devastated land, which, in accordance with the current legal regulations [Dz.U. 2013 poz. 21, Dz.U. 2016 poz. 1395], must be reclaimed. The poor quality of soils in Poland, the commonly recorded processes of their degradation, including the loss of humus, and the need for reclamation of degraded and devastated soils, fully justify the requirement for natural management of waste with valuable fertilising properties [Bik-Małodzińska et al., 2021, Łabętowicz, 2019].

Wastes characterised by good fertilising properties are produced in many sectors of the economy, including municipalities, the agri-food sector, and the mining industry, and the use of their fertilising potential would significantly improve the balance of organic matter and nutrients in soils [Arias et al., 2022, Pham et al., 2021].

Coal mining wastes are characterised by very good properties of a fertilising nature. They are composed of quartz dust, feldspars, carbonate minerals, and significant amounts of clay minerals from the kaolinite and illite groups [Chandra et al., 2017, Firpo et al., 2021].

The properties of coal mining waste are dependent on the characteristics of the deposit, the particular mining system, and the coal treatment technology [Chugh and Behum 2014, Pyssa 2016]. Mining waste from the Lubelski Węgiel

Bogdanka S.A. mine is a waste rock consisting of fragments of roof, floor, and overgrowth rocks of the Lublin strata coal seams. In the roof and overgrowth of these seams, there are siltstone sediments with fossils of plants and lake environment siltstone. The floor is composed of soils containing clayey siderites and siderite oolites [Bzowski and Dawidowski 2013].

Carboniferous mining waste from the Lubelski Węgiel Bogdanka S.A. mine is a petrographically natural fossil characterised by an average content of 85% clay shale, siltstone (4.9%), sandstone (6.3%), and clayey siderites and spherosiderites [Bzowski and Dawidowski, 2013]. The grain composition of these wastes is as follows: coarse-grained fraction (20-200 mm) 40-50%, fine-grained fraction (0.5-20 mm) 30-40%, silty-laden fraction (<0.5 mm) about 20%. The mineralogical composition is as follows: 50-60% clay minerals (kaolinite, illite, chlorite), 10-35% quartz and muscovite, 7-10% organic matter, 2-5% siderite and traces of feldspar and pyrite. The waste is characterised by a neutral reaction, and significant potassium, magnesium, and calcium content. Heavy metal content does not exceed levels acceptable for cultivated soils [Bzowski et al., 2010, Bzowski and Dawidowski, 2013, Dz.U. 2011 nr 175 poz. 1048].

The properties of Carboniferous mining wastes from the Lubelski Węgiel Bogdanka S.A. mine indicate that they represent potential mineral resources that can be used in environmental management. The application of Carboniferous mining wastes to soil translates into an improvement of soil mineral abundance, as the application of 100 $Mg \cdot ha^{-1}$ of these wastes will introduce into the soil about $Mg \cdot ha^{-1}$: 1.2 CaO, 1.2 MgO, 2.1 K_2O, and 0.2 P_2O_5 and will increase the share of clay fraction by 4% and organic carbon by 0.7%.

One option for the recovery of coal mining waste is to use it to produce soil-like substrates or fertilizing agents [Firpo et al., 2015, Weiler et al., 2020, Amaral et al., 2020]. Fertilizing agents based on coal mining waste should provide nutrients for plants and soil biota; however, the quality of fertilisers depends on interrelated and optimally shaped physical, chemical, and biological properties [Lal 2015]. Therefore, when producing fertilizing agents that ensure optimal properties, it is advisable to associate coal mining waste with other wastes. Municipal sewage sludge or rockwool from cover crops, among others, can be used for this purpose. These wastes, proven in fertiliser and environmental remediation [Baran et al., 2008a, Baran et al., 2008b, Baran et al., 2008c, Wójcikowska-Kapusta et al., 2012], can effectively optimise the properties of coal mining waste-based mixtures. The application of sewage sludge is one such strategy to rapidly enrich soils with organic matter, nitrogen, and phosphorus [Darmody et al., 2009, Liu and Lal 2014, Watkinson et al., 2016, Moreno-Barrigaet et al., 2017]. Passive, inactive, and chemically inert, mineral wool has a high water-holding capacity and very good capillary properties. When used together with sewage sludge in the reclamation of degraded soils, it optimises physical and aqueous properties and organic matter transformation processes, which creates conditions for the initiation of the soil-forming process and proper mineral nutrient management, reflected in plant yields [Baran et al., 2006, Baran et al., 2008c, Baran et al., 2012, Żukowska et al., 2014, Kołodziej et al., 2020].

The aim of the study was to evaluate the effect of coal mining waste and its mixtures with municipal sewage sludge and waste rockwool from cover crops on shaping selected properties of degraded anthropogenic soil.

MATERIAL AND METHODS

In the study, coal mining waste generated during the enrichment of hard coal and mixtures with municipal sewage sludge and waste rockwool from cover crops were used.

Carboniferous mining waste – fine-grained and silt-laden fraction (code 01 04 12) [Dz.U. 2020 poz. 10], from the Lubelski Węgiel Bogdanka S.A. mine, was the main material used for the mixtures, acting as a mineral material (component). The properties of coal mining waste were optimised by enriching it with organic matter and nutrients, the source of which was sewage sludge (code 19 08 12) [Dz.U. 2020 poz. 10] from the municipal sewage treatment plant in Lublin. Waste rockwool from cover crops (code 02 01 83) [Dz.U. 2020 poz. 10] from the Horticultural Enterprise in Niemce near Lublin, was added to optimise water and air properties. The properties of the materials used in the study are shown in Table 1.

A total of 5 fertilizing agents were evaluated in the study:

- M_1 coal mining waste – 100%,
- M_2 coal mining waste 97.5% + sewage sludge 2.5%,

Table 1. Selected soil properties and materials used. Average values [Żukowska et al., 2023]

Property	Unit	Coal mining waste	Sewage sludge	Mineral wool	Soil
Reaction	pH H_2O	7.30	6.45	6.72	4.48
	pH 1 mol·dm $^{-3}$ KCl	7.10	6.15	652	4.08
Hydrolytic acidity (HA)	cmol(+)·kg^{-1}	0.61	4.74	0.23	2.70
Exchangeable base cations (BC)		11.47	29.15	23.22	3.38
Cation exchange capacity of the soil (CEC)		12.08	33.89	23.45	6.08
Degree of saturation of the sorption complex with basic cations (V)	%	94.9	86.1	99.0	55.6
TOC	g·kg^{-1}	6850	207.50	n.o.	7.50
TN		2.36	38.10	n.o.	0.88
C/N	-	29.0	5.6	n.o.	8.5
Salinity	gNaCl·kg^{-1}	1.80	286	0.06	0.11
P available	mg·kg^{-1}	1.6	742.5	632.2	18.2
K available		208.4	13.68	1249.2	3.,0
Mg available		180.0	135.0	54.,2	17.1
Pb		47.5	39.8	38.3	27.5
Zn		45.8	874.5	44.9	24.8
Cu		45.5	301.5	26.5	20.1
Cd		1.04	3.54	1.05	0.36
Cr		33.9	89.3	11.4	19.6
Ni		35.9	37.6	22.6	5.8
Hg		0.029	0.984	0.006	0.035
Ba		308.0	110.5	27.5	41.5

Note: TOC – total organic carbon, TN – total nitrogen content, C/N – ratio.

- M_3 coal mining waste 95% + sewage sludge 5%,
- M_4 coal mining waste 96.5% + sewage sludge 2.5% + mineral wool 1%,
- M_5 coal mining waste 94% + sewage sludge 5% + mineral wool 1%.

The proportion (%) of each waste in the mixtures was expressed as % w/w and s.m.

The study was conducted in a strict pot experiment. Pots of 12 dm^3 capacity were filled (10 kg air-dry weight) with degraded anthropogenic soil with the addition of the mixtures in a 1:1 ratio (Table 2). The control objects were: unfertilized soil, soil fertilized with NPK in doses recommended for cultivated plants and soil with 1% of manure. All variants of the experiment were carried out in three repetitions (a total of 24 vases).

After preparation of the pots, samples were taken from the entire depth of the vessels for laboratory tests – the beginning of the experiment - 1st test date. In the first growing season, white mustard of the Borowska C/1 variety was sown at

Table 2. Schematic of the pot experiment

Symbol	Objects
C_1	Soil
C_2	Soil + NPK
C_3	Soil + manure
SM_1	Soil + coal mining waste – 100%
SM_2	Soil + coal mining waste 97.5% + sewage sludge 2.5%
SM_3	Soil + coal mining waste 95% + sewage sludge 5%
SM_4	Soil + coal mining waste 96.5% + sewage sludge 2.5% + mineral wool 1%
SM_5	Soil + coal mining waste 94% + sewage sludge 5% + mineral wool 1%

a rate of 0.2 g/pot. Harvesting was carried out at the flowering stage and soil samples were taken for laboratory tests – 2nd test date. In the following year, the contents of the pots were mixed, fertilisation was applied at the control site C_2, and 20 seeds/pot of maize cv. KB 1903 C/1 were sown. Harvesting was carried out at the cob setting stage and soil samples were taken for laboratory analyses – 3rd test date.

Laboratory analyses

The pH_{KCl} was determined by the potentiometric method in a 1 $mol \cdot dm^{-3}$ KCl (1:2.5) solution [ISO 2005]. Electrical conductivity (EC) was analyzed in a 1:5 substrate-water suspension with a HI 2316 EC-meter from Hanna Instruments (Nusfalau, Romania). The hydrolytic acidity (HA) and exchangeable base cations (BC) were determined with Kappen's method [Soil Survey Investigation Report 1996]. The cation exchange capacity of the soil (CEC) was calculated according to the following formula:

$$CEC = HA + BC \tag{1}$$

Exchangeable cations (Na, K, Ca, Mg) were analysed by the Inductively Coupled Plasma Atomic Emission Spectroscopy, Shimadzu Japan (ICP-AES) after extraction with 1 $mol \cdot dm^{-3}$ $AcNH_4$.

The results obtained were statistically processed by analysis of variance using the Tukey test. Ward's cluster analysis method was used to assess the similarities of the evaluated research variants. Statistical calculations were performed using the StatSoft STATISTICA 10 programme.

RESULTS

The pH of the unfertilised (C_1) and NPK-fertilised (C_2) soil was strongly acidic at the beginning of the experiment, while that of the manure-fertilised soil was acidic (C_3) (Table 3). In these soils, the pH in 1 $mol \cdot dm^{-3}$ KCl had values of 3.9 (C_1), 4.2 (C_2), and 4.6 (C_3), respectively. A change in soil pH to acidic and slightly acidic was recorded in the subsequent test dates, after the white mustard harvest (term II) and in the following year of maize (term III). The highest pH value in 1 $mol \cdot dm^{-3}$ KCl (5.8) at the end of the study (term III) within the control sites was characterised by manure-fertilised soil.

The fertilisation (in a 1:1 ratio) of the strongly acidic soil with coal mining waste, which had a neutral reaction (Table 3), changed the reaction of this soil to slightly acidic (Table 3). At the end of the study, the soil of the (SM_1) showed a slight reduction (by 0.2) of pH in 1 $mol \cdot dm^{-3}$ KCl. In soil SM_2, fertilised (in a 1:1 ratio) with a mixture of mining waste with 2.5% sludge addition, and in soil SM_3, to which a mixture of coal mining waste with 5% sludge addition was introduced, there was an improvement in the pH, but it was given a slightly acidic pH (Table 3). The extent of this improvement was proportional to the proportion of sludge in the mixture. Soil fertilisation with mixtures extended with mineral wool (SM_4 and SM_5) further improved the soil reaction to neutral, especially in the soil of object SM_5 (mixture with 5% share of sludge and 1% share of mineral wool).

Table 3. Soil pH and electrical conductivity (EC)

Objects	pH		pH		pH		EC			
	H_2O	KCl	H_2O	KCl	H_2O	KCl	$mS \cdot cm^{-1}$			
	I		II		III		I	II	III	Average
C_1	4.4	3.9	4.8	4.3	5.4	4.9	0.11	0.10	0.08	0.10
C_2	4.8	4.2	4.9	4.4	6.0	5.3	0.11	0.11	0.10	0.11
C_3	5.1	4.6	5.3	4.9	6.5	5.8	0.12	0.11	0.10	0.11
SM_1	7.3	6.8	7.1	6.7	7.0	6.6	0.38	0.31	0.60	0.43
SM_2	6.9	6.6	6.8	6.5	6.7	6.4	0.70	0.52	0.48	0.57
SM_3	7.5	7.0	7.3	6.9	7.0	6.7	0.71	0.58	0.49	0.59
SM_4	7.3	6.8	7.2	6.6	7.1	6.5	0.71	0.48	0.40	0.53
SM_5	7.5	7.1	7.3	6.8	7.2	6.7	0.72	0.56	0.45	0.58
Average							0.45	0.34	0.34	0.38
NIR ** significant differences at p = 0.01			for the object				0.29**			
			for the term				0.15			
			for object x term				0.61			

Table 4. Sorption properties

Objects	HA				BC				CEC			
	cmol(+)·kg^{-1}											
	Term			Average	Term			Average	Term			Average
	I	II	III		I	II	III		I	II	III	
C_1	2.70	2.80	2.50	2.67	3.38	3.79	4.65	3.94	6.08	6.49	7.15	6.57
C_2	2.25	2.70	2.13	2.36	3.40	4.40	5.00	4.27	5.65	7.10	7.13	6.63
C_3	2.15	2.25	2.00	2.13	4.20	5.20	5.80	5.07	6.35	7.45	7.80	7.20
SM_1	1.06	0.92	0.85	0.94	7.43	8.12	7.97	7.84	8.49	9.07	8.72	8.76
SM_2	0.96	0.91	0.79	0.89	9.65	9.10	10.15	9.63	10.61	10.01	10.94	10.52
SM_3	0.92	0.85	0.77	0.85	11.01	10.68	11.08	10.92	11.93	11.53	11.85	11.77
SM_4	0.94	0.89	0.83	0.89	10.62	10.44	11.70	10.92	11.56	11.53	12.53	11.87
SM_5	0.84	0.77	0.68	0.76	11.02	11.15	11.58	11.25	11.86	11.92	12.26	12.01
Average	1.40	1.56	1.28	1.41	7.59	7.86	8.49	7.98	8.99	9.51	9.85	9.45
NIR ** significant differences p = 0.01 * significant differences p = 0.05	for the object			0.66**	1.34**				1.52**			
	for the term			0.32	0.61**				0.70*			
	for object x term			1.37	2.78				3.18			

Note: HA – hydrolytic acidity, BC – exchangeable base cations; CEC – cation exchange capacity.

The averaged soil EC values of the control sites ranged between 0.10 (C_1) and 0.11 mS·cm^{-1} (C_2 and C_3) (Table 3), indicating that this was a non-saline soil (Karczewska, 2008). The EC of soil SM_1 averaged 0.43 mS·cm^{-1} during the study period and was 4.3 times higher compared to soil C_1 (Table 3). Soil enriched with coal mining waste mixtures with 2.5 and 5% sewage sludge (SM_2 and SM_3) had, compared to the soil of object SM_1, a not-significantly higher EC, by 32% (SM_1) and 37% (SM_3), respectively, and in soil with mineral wool mixtures, by 23% (SM_4) and 35% (SM_5) (Table 3). There was a significant reduction in soil EC under the evaluated mixtures over the study period.

The hydrolytic acidity (HA) in the soil of the control soils, averaged over the evaluated period, ranged in value from 2.13 cmol(+)·kg^{-1} (C_3) to 2.67 cmol(+)·kg^{-1} (C_1). The HA of the soil with coal mining waste in a 1:1 ratio (SM_1) was 2.8 times lower than that of the control soil without fertilisation, and that of the soil fertilised with NPK and manure was 2.5- and 2.3-fold lower, respectively (Table 4, Figure 1).

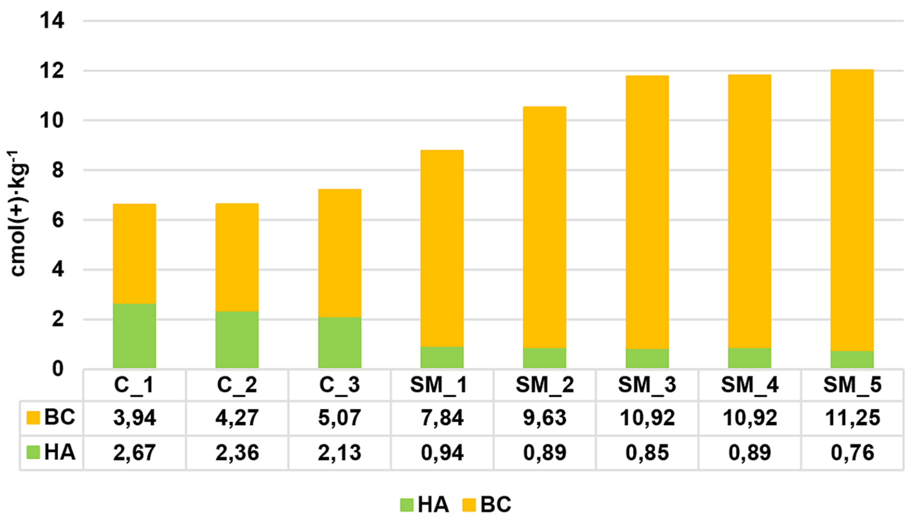

Figure 1. Average values of total sorption capacity (CEC) soil fertilized with the assessed mixtures (Designations as in Table 2; HA – hydrolytic acidity, BC – exchangeable base cations)

Fertilisation of the degraded anthropogenic soil with mixtures of mining waste + sludge of 2.5% and 5%, compared to the soil of object SM_1, resulted in a non-significant reduction in HA, by 7% (SM_2) and 13% (SM_3), respectively, while fertilisation with mixtures with a composition extended by rockwool reduced HA by 5% (SM_4) and 20% (SM_5). A non-significant decrease in HA was found in the soil with the addition of the evaluated mixtures during the study period.

In the soil of the control, at the beginning of the study – term I, the content of exchangeable base cations (BC) was low and ranked in order: C_3 5.10 cmol(+)·kg^{-1} > C_2 4.27 cmol(+)·kg^{-1} > C_1 3.94 cmol(+)·kg^{-1} (Table 4, Figure 1). In the soil of these object, an increase in BC was recorded at successive dates, significant between the beginning and end of the study. The BC content of the soil of the SM_1 was about 99% higher than that of the soil (C_1), and that of the soil fertilised with NPK and manure was 84% (C_2) and 54% (C_3) higher, respectively (Table 4, Figure 1). The fertilisation of degraded anthropogenic soil with mixtures significantly increased BC, by 23% in the soil of SM_2, 39% in the soil of SM_3 and SM_4, and 43% in SM_5, respectively. During the study period, non-significant trends of BC increase were found in soil with the addition of the evaluated mixtures, more pronounced in mixtures with rockwool.

In the control soil, the sorption capacity (CEC), assessed based on the average values of the three dates, was: C_3 7.20 cmol(+)·kg^{-1} > C_2 6.63 cmol(+)·kg^{-1} > C_1 6.57 cmol(+)·kg^{-1} (Table 4, Figure 1). A systematic improvement in the soil CEC of the control object was observed over the study period. The introduction of coal mining waste into the low CEC soil improved this property. In the soil of this (SM_1), the CEC was 33% higher than in the unfertilised soil (C_1), (Table 4, Figure 1). In the soil of SM_2 and SM_3, compared to SM_1, there was a significant increase in CEC; 20% and 34%, respectively. A further increase in CEC of 36% was found in the soil of SM_4 and SM_5. In the soil of fertilised with mixtures containing sewage sludge, there was a trend towards an increase in CEC during the study period evaluated, more pronounced under the influence of mixtures whose composition was expanded with mineral wool.

It is noteworthy that the discussed increase in CEC of soil fertilised with mining waste and its mixtures with sludge and wool was due to a higher content of base cations. In the soil of the evaluated objects, different contents of Ca^{++}, Mg^{++}, K^+, and Na^+ cations were recorded. In the soil of the control sites, the average content of base exchangeable cations ((+)·kg^{-1}) over the evaluated study period formed a series: Ca^{++} (3.45) > Mg^{++} (0.74) > K^+ (0.25) > Na^+ (0.19). In the soil of SM_1, the base cations formed the series: Ca^{++} (4.88) > Mg^{++} (1.60) > Na^+ (1.02) > K^+ (0.44), (Table 5).

The application of mixtures to the soil resulted in a significant increase in exchangeable calcium content, by 42% (SM_2) and 63% (SM_3), and by 48% (SM_4) and 66% (SM_5), respectively, compared to the soil of SM_1. An increase in exchangeable calcium content was found in the soil fertilised with the evaluated mixtures during the study period, significant between all dates (Table 5).

Compared to the exchangeable magnesium content found in the soil of object SM_1, the exchangeable Mg content was higher by about 12% in the soil of object SM_2 and 16% in SM_3, while SM_4 and SM_5 were higher by 11 and 20%. During the study period, a reduction in exchangeable magnesium content was found, significant between the 1st and 3rd study dates, in soil with sludge and sludge-wool mixtures, and a stabilisation in soil fertilised with mining waste only (Table 5).

The impact of coal mining waste mixtures with 2.5 and 5% sludge increased, compared to the soil of SM_1, the content of exchangeable potassium by 23 (SM_2) and 25% (SM_3), respectively, and mixtures with sludge and rock wool by 14 and 41%, respectively. During the study period, there was a significant reduction in exchangeable potassium content in soil with mixtures (SM_2 - SM_5) and a decreasing trend in soil with coal mining waste (SM_1) (Table 5).

Compared to the exchangeable sodium content in soil SM_1, there was a reduction of approx. -6 and -17, respectively, in the soil of sites SM_2 and SM_3, and by -4 and -14%, respectively, in SM_4 and SM_5 (Table 5). A reduction in exchangeable sodium content was found in soil with the addition of the evaluated mixtures during the study period, significant for the 1st and 3rd test dates.

Table 5. The content of basic exchangeable cations

Objects	Ca^{++}				Mg^{++}			
	cmol(+)·kg^{-1}							
	Term			Average	Term			Average
	I	II	III		I	II	III	
C_1	2.30	3.40	3.70	3.13	0.62	0.82	0.65	0.70
C_2	2.38	3.20	4.60	3.39	0.60	0.85	0.79	0.75
C_3	2.82	3.95	4.70	3.82	0.68	0.92	0.80	0.80
SM_1	4.29	4.89	5.46	4.88	1.58	1.62	1.59	1.60
SM_2	6.09	6.95	7.75	6.93	1.86	1.85	1.65	1.79
SM_3	7.50	7.69	8.74	7.98	2.00	1.95	1.63	1.86
SM_4	6.05	7.95	9.44	7.28	1.87	1.79	1.57	1.74
SM_5	7.23	8.08	9.05	8.12	1.96	1.94	1.85	1.92
Average	4.83	5.76	6.68	5.76	1.40	1.47	1.32	1.39
NIR * significant differences p = 0.05 ** significant differences p = 0.01	for the object			1.16**	0.36**			
	for the term			0.53**	0.17**			
	for object x term			2.41	0.74			
Objects	K^{+}				Na^{+}			
	cmol(+)·kg^{-1}							
	Term			Average	Term			Average
	I	II	III		I	II	III	
C_1	0.18	0.16	0.16	0.17	0.18	0.20	0.20	0.19
C_2	0.26	0.22	0.16	0.21	0.18	0.21	0.20	0.20
C_3	0.42	0.38	0.30	0.37	0.19	0.18	0.18	0.18
SM_1	0.48	0.45	0.39	0.44	1.12	1.18	0.77	1.02
SM_2	0.60	0.54	0.47	0.54	1.10	1.04	0.74	0.96
SM_3	0.60	0.56	0.49	0.55	1.02	0.83	0.69	0.85
SM_4	0.62	0.48	0.39	0.50	1.18	1.04	0.72	0.98
SM_5	0.70	0.62	0.53	0.62	1.15	0.84	0.65	0.88
Average	0.48	0.43	0.36	0.42	0.77	0.69	0.52	0.66
NIR * significant differences p = 0.05 ** significant differences p = 0.01	for the object			0.14**	0.48**			
	for the term			0.07**	0.22**			
	for object x term			0.28	0.98			

Note: Ca^{++} – exchangeable calcium, Mg^{++} – exchangeable magnesium, K^{+} – exchangeable potassium, Na^{+} – exchangeable sodium.

DISCUSSION

The current trends of population growth and economic development are putting significant strain on the earth's natural resources and the environment. This has drawn attention to issues of resource efficiency, including waste and material management policies, resulting in the promotion of a circular economy paradigm (circular economy) [OESD 2019]. The circular economy is modelled on the natural environment, in which the remains of one organism are simultaneously food for many others, whose remains are used as food by the next, which is repeated until the cycle is fully closed, i.e., a state of homeostasis is reached. In line with this, a circular economy is inherently self-regulating [Ellen MacArthur Foundation 2013]. In the Fertiliser Regulations published in 2019, the European Commission indicates that the protection of primary raw materials should include the introduction of secondary raw materials for the production of fertilisers and soil conditioners in the EU. This is to enable the introduction of recycled fertilisers and plant aids (compost, digestate, biocarbon, organic-mineral and mineral fertilisers) [Chojnacka et al., 2020].

In a two-year vegetation pot experiment, the possibility of using Carboniferous mining wastes and mixtures of these wastes with varying proportions of sewage sludge and rockwool to shape the properties of degraded anthropogenic soil was assessed.

The soil under study was characterised by a strongly acid reaction and mineral fertilisation with NPK and manure had little effect on changing this. The soil of the control object showed a slight improvement in reaction over the duration of the experiment, to an acidic and slightly acidic reaction in the manure-fertilised soil. Soil reaction plays an important role in regulating plant nutrient transformation processes, including the processes of nutrient mobilisation and immobilisation, and thus in shaping the production potential of ecosystems [Filipek and Skowrońska 2013]. The application of neutral coal mining waste to a highly acidic soil improved its pH to slightly acidic, with a tendency to decrease pH at the end of the study period. The observed reduction in pH should be associated with weathering of the coal mining waste [Patrzałek and Nowińska 2013]. Soil fertilisation with the assessed mixtures increased soil pH to a slightly greater extent than mining waste applied alone. The soil pH was more favourably affected by mixtures with a 5% share of sewage sludge and mixtures whose composition was supplemented with rockwool. The results obtained indicate the possibility of shaping the pH of soils by mixtures of mineral waste with the addition of sludge and rock wool refer to the study by Kujawska and Pawłowska [2020], who showed that the combined application of drilling waste and sewage sludge effectively improves the pH of acidic soils.

When waste is introduced into soils, especially post-mining waste, there is a risk of increasing the salinity of those soils. Fertilisation of the soil with coal mining waste and the mixtures evaluated resulted in a non-significant increase in EC, which is a measure of salinity; however, according to Jackson's classification [FAO 2006], the soil was classified as non-saline. Significant reductions in EC were found in the soil during the study period under the influence of the mixtures evaluated. The recorded reduction in EC over the subsequent study dates is consistent with the observed changes in this value in reclaimed waste rock dumps and technosols constructed from coal waste and biowaste [Klatka et al., 2017, Fabbri et al., 2021].

Coal mining waste and its mixtures with sewage sludge and rockwool had a significant effect on improving the sorption properties of the soil. The sorption capacity of the soil of SM_1 was 33% higher than that of soil without fertilisation. Fertilisation of degraded anthropogenic soil with mixtures including sewage sludge at a rate of 2.5 and 5% (SM_2 and SM_3), compared to SM_1, significantly increased its sorption capacity by 20 and 34%, respectively, while fertilisation with SM_4 and SM_5 increased its sorption capacity by 35% (SM_4) and 37% (SM_5). This is supported by the study of Firpo et al. [2016], who showed that carbonaceous waste composites with 5% sewage sludge can be used to shape the sorption properties of soils. The observed improvement in soil sorption properties under the influence of coal mining wastes, especially their mixtures with sewage sludge and rock wool, indicates that these mixtures can be used to improve the properties of poor-quality soils or soils restored in degraded areas. This is due to the important role of sorption, which determines the bioavailability of micro- and macro-nutrients. Sorption properties regulate the leaching of nutrients from the soil and have a protective function against the excessive flow of undesirable substances [Adrian 2001].

The fact that an increase in sorption capacity was associated with an increase in the content of basic cations should be regarded as a favourable influence of the assessed mixtures on the formation of soil sorption properties. In the soil of SM_1, the content of base cations ($cmol(+)\cdot kg^{-1}$) formed a series as follows: Ca^{++} (4.88) > Mg^{++} (1.60) > Na^{+} (1.02) > K^{+} (0.44), and these contents were higher than in the control soil. Consequently, the sum of exchangeable base cations in the soil of with SM_1 was 99% greater than in the soil without fertilisation, and when fertilised with NPK and manure was 84% and 54% greater, respectively. The application of SM_2 and SM_3 mixtures to the soil increased the content of base cations by 23% and 39%, respectively, compared to their content in the soil of the SM_1. The most favourable influence on the content of base cations in the soil was exerted by mixtures whose composition was supplemented with mineral wool. The results obtained are confirmed by studies indicating that the properties of technosols constructed from coal mining waste depend on the addition of materials rich in organic matter, which increases the content of base cations [Kujawska and Pawłowska 2020, Ruitz et al., 2020, Kacprzak et al., 2022]. Patrzałek and Nowińska [2013] report that the content of alkali cations in

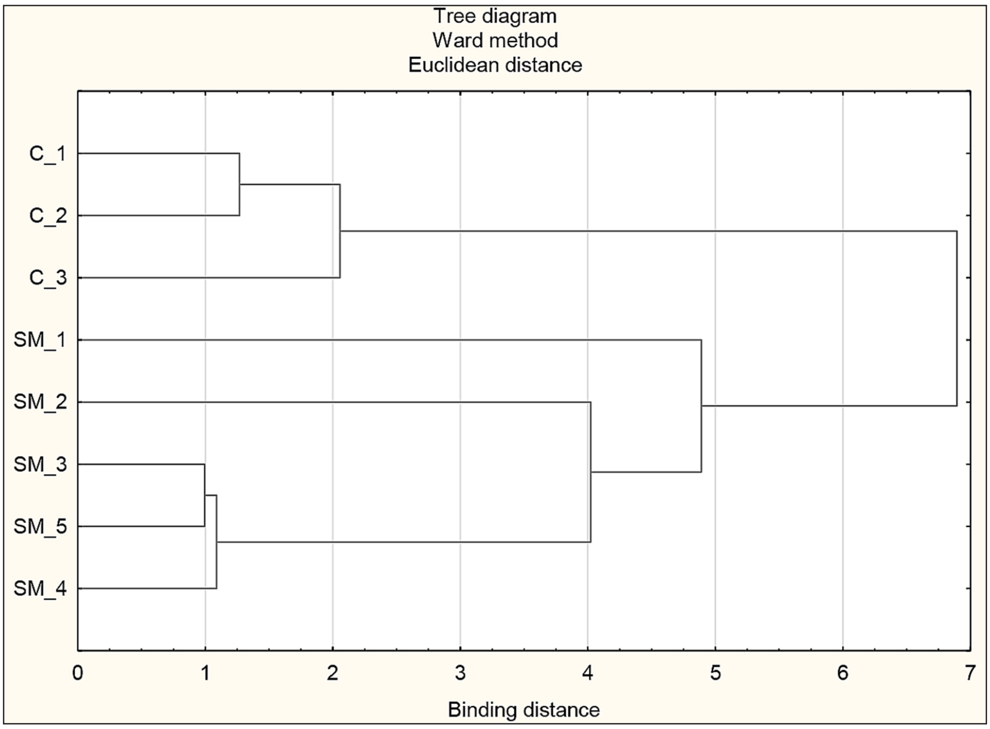

Figure 2. Ward cluster analysis

Carboniferous mine wastes is lower than the organic carbon content would indicate and that it increases with the 'ageing' of the wastes, which explains the increase in the content of alkali cations observed in their study on successive study dates. Ward's cluster analysis confirmed that mixtures with sewage sludge and rockwool had the most beneficial effect on shaping the sorption properties and that the extent of the observed improvement was proportional to the proportion of sewage sludge in the mixture (Figure 2).

This is confirmed in the study by Filho et al., [2020], who showed that a mixture of family soil degraded with coal mining waste when compared to a control soil, had significantly better sorption properties, and that supplementing the mixture composition with compost or sewage sludge further improved those sorption properties.

CONCLUSIONS

The results obtained confirmed the hypothesis that the addition of coal mining waste and its mixtures with municipal sewage sludge and waste rock wool to the soil optimises its properties. Evaluation of the properties of degraded anthropogenic soil fertilised with the evaluated mixtures showed that:

1. The application of Carboniferous mining wastes to degraded anthropogenic soil (at a ratio of 1:1), significantly improved the pH, from strongly to slightly acidic, and the sorption properties.
2. Mixtures of carbonaceous tailings with 2.5 and 5% sludge produced a further significant improvement in pH and sorption properties.
3. The addition of rockwool to the mixtures of coal mining waste and sewage sludge (2.5 and 5.0%) had a more favourable effect on soil properties in the sites with a higher (5%) share of sewage sludge compared to the soil fertilised with the mixture of coal mining waste + sludge.
4. The management of carbonaceous mining waste and waste optimising its properties for the production of fertilisers can be an effective strategy within a closed-loop economy, which at the same time will increase the efficiency of the management of degraded and poor-quality soils.

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