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Assessment of selected properties of soils degraded by the mining industry: Case study of Lubelski Węgiel "Bogdanka" S.A.

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ABSTRACT

The aim of the study was to evaluate selected physicochemical properties of the soils located near the mining area of the Lubelski Węgiel "Bogdanka" S.A. mine, with particular emphasis on soil pH (pH_{KCl} and pH_{H2O}), total carbon (TOC) and inorganic carbon (IC) content, as well as salinity. Soil samples were collected from various land use types (arable land, meadows, forests, roadside areas, floodplains, and areas near a reservoir) and from two depths (0–20 cm and 20–40 cm). The results showed a wide variability in soil pH_{KCl}, ranging from strongly acidic to neutral. Total carbon content ranged from 1.54 to 27.90 g kg^{-1}, with the highest values recorded in the topsoils of floodplain and forest soils, and the lowest in meadow soils. Inorganic carbon was generally absent, except for isolated occurrences in arable soils and near a water body. Soil salinity was low throughout the study area, with the highest values observed in the floodplain soil. The results indicate that soil properties are primarily controlled by land use and hydrological conditions, rather than by direct salinization processes. However, the spatial variability of physicochemical parameters suggests that the hydrological changes induced by mining may indirectly affect soil properties in the study area.

Keywords: soil pH, total carbon, salinity, coal mine soil degradation, hydrological disturbances.

INTRODUCTION

Despite declining production, mines in Poland remain a significant component of the Polish energy sector. As of December 2024, there were 19 operating hard coal mines and 4 lignite mines in Poland (Instat, 2025). Hard coal mining in Poland accounts for approximately 96% of total coal production in the European Union, primarily due to mine closures in other EU countries (Siciński, 2024; Sulik-Górecka and Strojek-Filus, 2025). Hard coal deposits occur in Carboniferous rocks, forming three coal basins in Poland: the Upper Silesian Coal Basin (UZW), the Lublin Coal Basin (LZW), and the Lower Silesian Coal Basin (DZW). In LZW, hard coal deposits are documented in categories A–C2 and cover an area of approximately 1000 km², with their economic reserves accounting for over 21% of national reserves. To date, only one mine is operational – Lubelski Węgiel "Bogdanka" S.A.(Instat, 2025). One of the significant factors shaping the contemporary state of the environment is mining activity, particularly hard coal mining, which leads to multifaceted changes, known as mining damage. The lithosphere and hydrosphere remain most susceptible to such impacts, where geological structure and water relations are disrupted (Piech and Sobczyk, 2023). Hard coal mining has a significant negative impact on the environment, causing long-term and often irreversible changes in ecosystems

(Głowacki and Wojciech, 2013; Sulik-Górecka and Strojek-Filus, 2025). The impact of hard coal mining on the environment is both direct and indirect. Direct impacts include permanent changes to the land surface associated with the location of mining infrastructure (shafts, coal processing plants, administrative facilities) and the storage of mining waste (heaps, mine water settling ponds). These processes lead to the exclusion of agricultural, forest, and recreational land from current use, which causes long-term changes in the land use structure and landscape transformations (Głowacki and Wojciech, 2013). On the other hand Mocek (Mocek, 2022) emphasized the impact of excessive industrial noise on the working environment in hard coal mines. Indirect impacts encompass a wide range of structural and functional changes that develop over the long term. Their primary cause is the underground mining of coal seams, which generates voids in the rock mass. Downward movement of overburden rock masses leads to secondary transformations of the ground surface. These manifest themselves in the form of continuous and discontinuous subsidence (sinkholes, cracks) as well as secondary disturbances in the geological structure of the mining area (Głowacki and Wojciech, 2013; Strozik, 2016). A key aspect of mining impacts is hydrological disturbances resulting from the need to drain the rock mass during mining operations. The drainage process leads to the formation of depression cones, i.e., a lowering of the groundwater table in the mine and its vicinity. The consequences of this phenomenon include the drying up of wells and springs, the disappearance of surface watercourses, soil desiccation, and a decrease in groundwater resistance to pollution. Furthermore, surface deformations (fissures, cracks) increase the hydraulic conductivity of rock layers, leading to increased surface water infiltration into aquifers, changes in groundwater flow directions, and a direct hydraulic connection between surface water, groundwater, and mine water (Shepley et al., 2008; Strozik et al., 2016). Discharge of mine water to the surface from active underground mines is a key environmental problem in hard coal mining. Discharge of saline mine water containing chloride, sulfate, and heavy metals into surface as well as groundwater leads to increased salinity and decreased water quality. This process not only pollutes groundwater and surface water but also causes drying out of wells, springs, and soils, as well as, and changes in the hydrological regime (Harat et al., 2015). A particularly significant problem is the impact of mining on the physicochemical and biological properties of soils. Dust deposition, heavy metal accumulation, and changes in water conditions can lead to reduced enzymatic activity, disruption of element cycling, and reduced biological productivity. Elevated concentrations of elements such as cadmium, lead, and zinc are often observed in mining areas, posing a threat to both plants and soil organisms, and consequently to entire food chains (Ciarkowska et al., 2014; Marcisz et al., 2021; Shang et al., 2016). Coal mine operations have a strong negative impact on atmospheric air quality, resulting from the multistage process of extraction, transport, and processing of the raw material. The main sources of gas and dust emissions include the operation of mining machinery and equipment, coal transportation, as well as mechanical processing, such as crushing, sorting, and screening. Significant amounts of suspended particulate matter (PM10, PM2.5), heavy metals (cadmium, lead, zinc, mercury, chromium, arsenic), and organic compounds, including aromatic hydrocarbons and methane, are released into the atmosphere. Suspended particulate matter serves as a carrier for heavy metals and organic compounds, increasing their toxicity and potential for dispersal into the environment (Bhanot et al., 2025). Deep-sea coal mining causes significant surface deformation. These deformations have a significant negative impact on the stability of buildings, leading to damage to residential buildings, roads, communication networks, bridges, pipelines, power lines, and industrial facilities. In the regions with the highest degree of surface transformation, where deformations threaten the stability of buildings, it is sometimes necessary to relocate residents from the areas at risk of mining damage and construction disasters (Kowalski, 2020). The research by Przyłucka et al. (Przyłucka et al., 2022) in Upper Silesia showed that over 20 years of intensive mining operations (1992–2012), 521 km² of areas were identified as affected by mining activities, with significant damage to buildings and urban infrastructure. Coal mine operations negatively impact people's quality of life by reducing the tourist and recreational value of areas, environmental degradation, and contributing to a loss of landscape attractiveness. This also affects property values. Residents of mining areas lose or experience a reduction in their sources of income, resulting from the loss of land, homes, and livelihoods following relocation, as well as from lower income from tourism and recreation (Moyle et al., 2021; Ryszko, 2012). A comprehensive assessment of the impact of mining activities requires taking into account both direct and indirect effects, as well as conducting an analysis of long-term processes.

MATERIALS AND METHODS

Research area

The Lubelski Węgiel "Bogdanka" S.A. (LW) mine is located in the Central Coal Region (CRW), located in the northeastern, best-explored part of the Lublin Coal Basin (Figure 1). Geographically, CRW lies within the boundaries of the Polesie Lubelskie region, and only small fragments of it cover the Lublin Upland (Solon et al., 2018). Administratively, the LW mine is located in the Lublin Voivodeship, in the Puchaczów commune, Łęczna County, approximately 10 km north of the town of Łęczna (Report, 2024). The formation of the Lublin Coal Basin is associated with the Hercynian orogeny and the formation of a sedimentary depression, which favored the accumulation of organic matter and, consequently, the formation of coal deposits. The sedimentary basin had the shape of an elongated syncline, cut by faults as a result of intense mountain-forming movements (Figure 1). Currently, the Lubelski Węgiel "Bogdanka" S.A. mine operates within the "Puchaczów V" mining area, covering an area of approximately 73 km^2. Within this area, eight

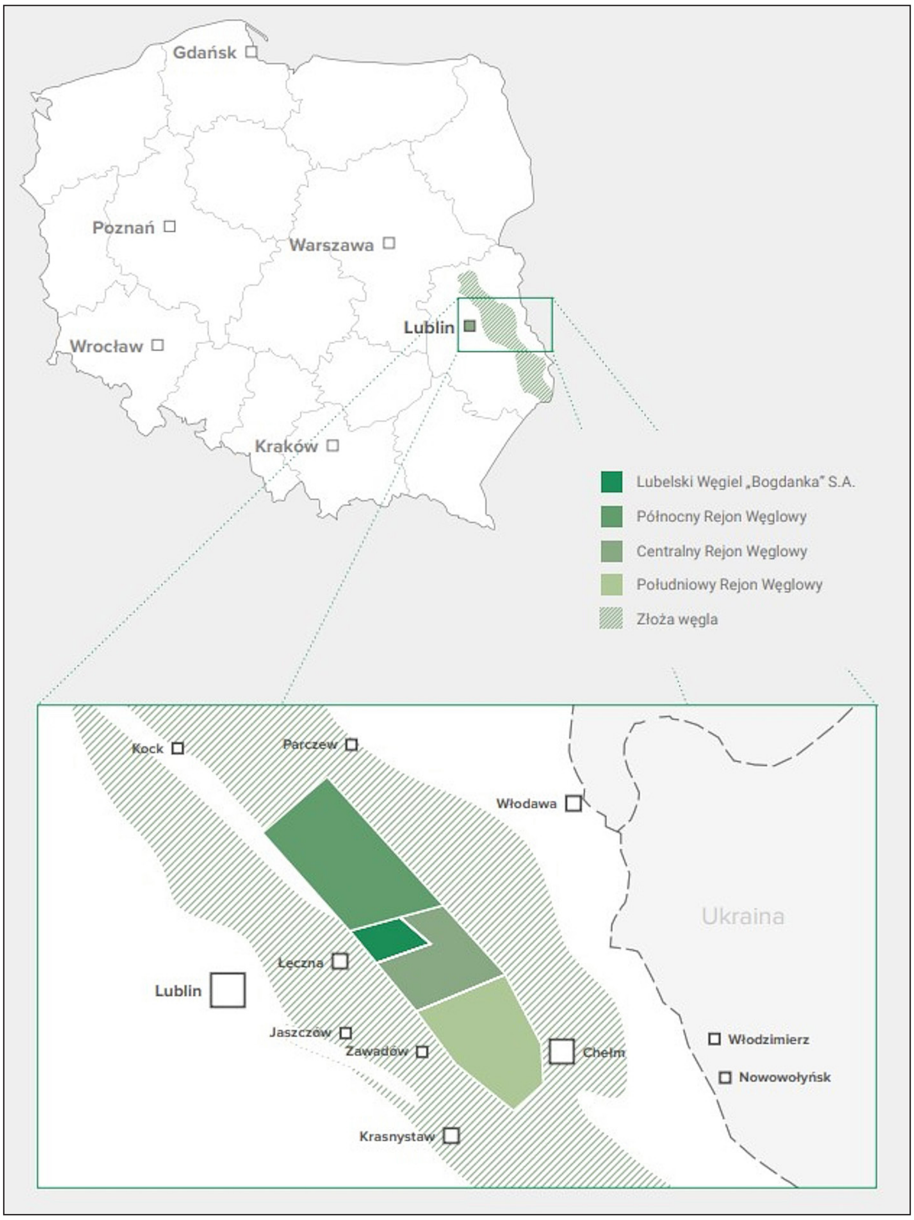

Figure 1. The location of LW in the context of the Lublin Coal Basin (Report, 2024)

of the 18 economic hard coal seams, located under overburden from 650 m to 730 m, have been selected for mining. The mine holds a concession for the extraction of only four seams of thermal coal, characterized by good quality and low sulfur content (Piech and Sobczyk, 2023; Raport, 2024; Zdanowski, 2019).

Research methodology

The soil samples for physicochemical analyses were collected from the area where hard coal mining is conducted by the Lubelski Węgiel "Bogdanka" S.A. mine. Soil material was collected from various land use types: arable land, meadows, forests, roadside areas, floodplains, and areas surrounding a water reservoir (Table 1).

The samples were collected from two depths: 0–20 cm and 20–40 cm. Basic physicochemical analyses were performed: pH in water (pH_{H2O}) and 1 mol.dm^{-3} KCl (pH_{KCl}) by potentiometric method (ISO 10390:2021), salinity (soil to water ratio 1:5) by conductometric method, and total organic carbon (TOC) and inorganic carbon (IC) content using a TOC-VCSH apparatus (Shimadzu Corp.; Kyoto, Japan) in accordance with the standard (PN-EN 15936:2013-02). Laboratory analyses were performed in triplicate.

Data analysis

Data are presented as means ± standard deviation (SD) of three independent experiments. The obtained results were subjected to statistical analysis, which included descriptive statistics (arithmetic means and standard deviation), one-way analysis of variance (ANOVA), and Tukey's least significant difference test. The assumed significance level was $p < 0.05$. A one-way analysis of variance was carried out at the $p = 0.05$ level to determine significant differences. Ward's cluster analysis was used to determine the similarity of the soils of the studied objects in terms of physicochemical properties (pH_{KCl}, pH_{H2O}, salinity, TOC, IC), and the results were presented in the form of a dendrogram. The results were analyzed using the Statistica v. 14.1 software (StatSoft, Kraków, Poland).

Table 1. Description of the soil sampling scheme from the LW coal mining area

No.	Methods of land uses
1	Arable land
2	Area next to a reservoir
3	Meadow
4	Area next to a road
5	Floodplain
6	Dry forest
7	Forest

RESULTS AND DISCUSSION

The analysis of the obtained results allowed the development of a conceptual model presenting the directions and mechanisms of the impact of the mining activities of the LW mine on the soil environment (Figure 2). This model takes into account both the direct effects of mining operations, such as surface transformations and changes in water conditions, as well as indirect processes affecting the physical, chemical, and biological properties of soils. The model was developed based on authors' own research results and literature data; it provides a synthetic approach to the relationship between mining operations and the state of the soil environment. The presented model can serve as a basis for identifying potential threats and determining the directions of monitoring and reclamation activities in the areas affected by hard coal mining.

The highest pH_{KCl} values were recorded in the surface horizon (0–20 cm) near the water body, where soils were neutral (pH_{KCl} = 6.98). The lowest pH values were recorded in forest soils (pH_{KCl} = 3.29), indicating strong acidification typical of forest ecosystems developed on acidic parent material and resulting from the decomposition of organic matter and the leaching of base cations (Högberg et al., 2011, Bik-Małodzińska et al. 2021). Agricultural soils were characterized by a slightly acidic pH (pH_{KCl} 6.37), which is generally considered optimal for crop production due to high nutrient availability and favorable microbiological activity (Penn and Camberato, 2019). Meadow and roadside soils were very acidic (pH_{KCl} 4.11 and 4.04), suggesting ongoing leaching processes and limited buffering capacity (Table 2).

In all samples, pH_{KCl} was consistently lower than pH_{H2O}, indicating the presence of exchangeable acidity and active soil acidification processes (Goulding, 2016, Żukowska et al. 2023). Close to the reservoir, a distinct vertical pH variation was observed, with the surface layer

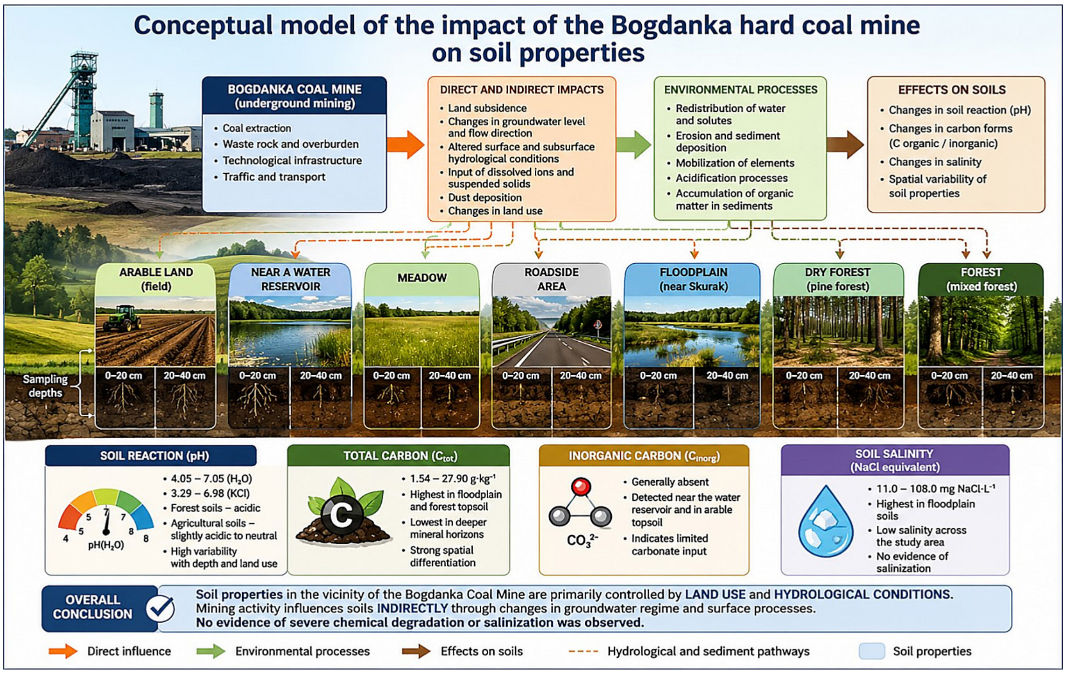

Figure 2. Diagram of the impact of hard coal mining in LW on soil [Own study based on IUSS Working Group WRB, 2022; Haering and Daniels, 2000; Younger et al., 2002]

(0–20 cm) characterized by a neutral pH (pH_{KCl} = 6.98), while the subsurface layer (20–40 cm) was very acidic (pH_{KCl} = 3.95) (Table 2). This may reflect changes in hydrological conditions, vertical migration of dissolved ions, and spatial heterogeneity of the parent material, potentially exacerbated by the changes in groundwater circulation caused by mining activities (Michalczyk et al., 2011). TOC content generally varied significantly between the study sites, ranging from 1.59 to 27.90 g·kg^{-1} (Table 3), indicating significant spatial variability depending on land use and soil layer. The highest TOC resources were found in the topsoil of floodplain soil (27.90 g·kg^{-1}) and forest soil (26.63 g·kg^{-1}), while the lowest values were found in meadow soil (7.61 g·kg^{-1}) (Table 3).

High carbon accumulation in floodplain soils is associated with periodic deposition of organic matter and sedimentation under hydromorphic

Table 2. Soil pH from the studied areas related to hard coal mining in LW

No.	Methods of land uses	Sampling depth	H_2O	KCl
1	Arable land	0–20	6.71	6.37
		20–40	6.17	5.45
2	Area next to a reservoir	0–20	7.05	6.99
		20–40	4.77	3,95
3	Meadow	0–20	4.86	4.11
		20–40	4.76	4.07
4	Area next to a road	0–20	5.04	4.04
		20–40	5.13	4.34
5	Floodplain	0–20	5.75	5.22
		20–40	6.00	5.74
6	Dry forest	0–20	6.05	6.01
		20–40	5.97	5.25
7	Forest	0–20	4.05	3.29
		20–40	4.23	3.51

conditions, which reduces the rate of decomposition (Lal, 2004). Similarly, increased carbon content in forest soils reflects the continuous supply of litter and limited mineralization in acidic environments (Jobbágy and Jackson, 2000, Żukowska et al. 2024). In turn, low TOC content in grassland soil reflects increased mineralization of organic matter. The subsurface layers (20–40 cm) of the soils of the studied sites were generally characterized by significantly lower TOC contents compared to the surface layer. No statistically significant differences were found only in the case of the meadow. A strong vertical gradient in carbon distribution is typical of mineral soils and those subject to natural leaching processes (Lal, 2004). IC was generally absent in most of the samples studied. Detectable amounts were found only in the topsoil layer of arable soil (0.27 g·kg^{-1}) and near a water body (3.47 g·kg^{-1}), suggesting local carbonate inputs or geochemical heterogeneity. In the regions affected by mining activities, such variability may also be related to hydrological disturbances and groundwater redistribution affecting carbonate mobility (Michalczyk et al., 2011).

Soil salinity, expressed as NaCl equivalent, ranged from 11.15 to 107.50 mg·dm^{-1}, indicating a generally low salinity of the soil environment in the study area. The highest salinity was recorded in floodplain soils (107.50 mg·dm^{-}3 surface layer), while the lowest values occurred in deeper layers near the reservoir (11.15 mg·dm^{-}3). The increased salinity of floodplain soils can be attributed to the episodic accumulation of dissolved ions transported by surface runoff and sediment deposition during floods. Floodplain environments often act as sinks for soluble salts and fine particles (Osman, 2012). However, the low salinity in deeper layers reflects leaching processes and limited ion accumulation.

Ward's cluster analysis based on pH, salinity, TOC, and IC confirmed that the soil properties in the coal mining area depended on land use (Figure 3). The diagram shows three clusters. The

Table 3. Average mean of total and inorganic carbon content and salinity in the soils covered by hard coal mining in LW

Description of the samples	Sampling depth	C total	C inorganic	salinity
		gkg^{-1}		mg NaCl·dm^{-1}
Arable land	0–20	16.13±0.17a	0.27±0.03a	69.30±0.30a
	20–40	7.14±0.21b	0.00±0.00b	32.00±0.60b
x̄		11.64±0.19A	0.14±0.02A	50.65±0.15A
Area next to a reservoir	0–20	10.31±0.09a	3.47±0.01a	49.60±0.40a
	20–40	1.59±0.05b	0.00±0.00b	11.15±0.15b
x̄		5.95±0.02B	1.74±0.00B	30.38±0.27B
Meadow	0–20	7.61±0.07a	0.00	17.00±0.10a
	20–40	7.03±0.15a	0.00	14.95±0.25b
x̄		7.32±0.04C	0.00	15.98±0.18C
Area next to a road	0–20	10.24±0.31a	0.00	18.00±0.10a
	20–40	3.38±0.01b	0.00	13.45±0.45b
x̄		6.81±0.16D	0.00	15.73±0.28C
Floodplain	0–20	27.90±0.03a	0.00	107.50±0.50a
	20–40	5.99±0.02b	0.00	26.50±0.10b
x̄		16.95±0.02E	0.00	67.00±0.20D
Dry forest	0–20	12.22±0.66a	0.14±0.02a	46.90±0.80a
	20–40	9.76±0.01a	0.00±0.00b	37.70±0.30b
x̄		10.99±0.36F	0.07±0.01C	42.30±0.55E
Forest	0–20	26.63±0.23a	0.00	28.20±0.30a
	20–40	5.71±0.05b	0.00	12.05±0.35b
x̄		16.17±0.09E	0.00	20.13±0.33F

Note: different lowercase letters (a–b) indicate statistically significant differences between layers, while different uppercase letters (A–F) indicate statistically significant differences between objects, at p≤0.05.

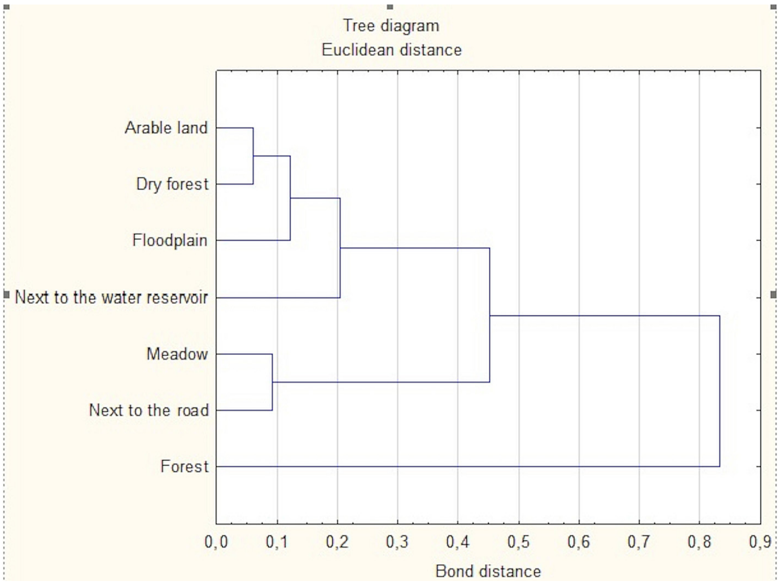

Figure 3. Tree dendrogram for the studied physicochemical properties of soils according to the type of use

first cluster contained one case (Forest), the second cluster contained two cases (Meadow + Next to the road), and the third cluster contained four cases (Arable land + Dry forest + Floodplain + Next to the water reservoir). Forest was the most distinct, joining the others only at the highest Bond distance value, suggesting a distinct nature of this land use in the analyzed set of features. In the second cluster, Meadow + Next to the road variants were very similar to each other. Arable land and Dry forest were the most similar, forming a compact cluster with a very short bond distance, suggesting a similar set of analyzed soil properties (Figure 3).

Despite local variability, none of the analyzed soils exhibited the salinity levels characteristic of saline or degraded soils, indicating that salinity is not a serious environmental problem in the study area. The obtained results indicate that the chemical properties of the soils near the LW are primarily determined by land use and natural hydrological conditions, rather than direct salinity or severe chemical degradation. Forest ecosystems were characterized by the strongest acidification and high carbon accumulation, reflecting natural pedogenetic processes. Agricultural soils maintained relatively favorable chemical conditions, likely due to agricultural practices such as liming and fertilization (Penn and Camberato, 2019, Bik-Małodzińska, 2024). Floodplain soils constituted the most dynamic system, characterized by the highest carbon content and salinity, which can be linked to periodic sediment deposition and hydrological connectivity. Such environments are particularly sensitive to the changes in water regime, which can be influenced by subsidence and groundwater redistribution associated with underground coal mining (Michalczyk et al., 2011).

CONCLUSIONS

The soils studied in the Lubelski Wegiel "Bogdanka" impact area do not show signs of significant chemical degradation, and their properties are determined to a greater extent by land use and hydrological conditions than by the direct impact of mining. Low soil salinity indicates that there is no need for remedial action in this regard, but local increases in salinity in floodplains should be periodically monitored. The potential indirect impact of mining activities through changes in water conditions justifies the need for long-term soil monitoring, encompassing both chemical and biological properties. Reclamation and conservation efforts should consider the specific characteristics of individual land uses, with particular emphasis on preserving the functions of forest and floodplain ecosystems as areas of high natural value. It is recommended to expand future studies to include biological indicators (e.g., enzymatic activity, microbial diversity), which may provide a more sensitive tool for assessing the early degradation changes in soils due to mining activities.

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