SOIL SCIENCE ANNUAL
2025, 76(2), 207802

https://doi.org/10.37501/soilsa/207802

Influence of reclamation and slope aspect on the selected properties of constructosols developed on a reclaimed landfill in Czmoń. Part I: basic physical and chemical soil properties

Wiktor Michnej-Zakrzewski[1]*, Łukasz Mendyk[2], Marta Molińska-Glura[3], Agnieszka Mocek-Płóciniak[2]

[1] District Chemical-Agricultural Station in Poznań, Laboratory Department, Unit for Microelements and Trace Elements in Soils, Sieradzka 29, 60-163 Poznań, Poland
[2] Poznań University of Life Sciences, Faculty of Agriculture, Horticulture and Biotechnology, Department of Soil Science and Microbiology, Szydłowska 50, 60-656 Poznań, Poland
[3] Poznań University of Life Sciences, Faculty of Forestry and Wood Technology, Department of Forest Economics and Engineering, Wojska Polskiego 71c, 60-625 Poznań, Poland

* Corresponding author: Wiktor Michnej-Zakrzewski, wiktor.zakrzewski92@wp.pl, ORCID iD: https://orcid.org/0009-0004-1661-7141

Received: 2025-03-27
Accepted: 2025-07-02
Published online: 2025-07-02
Associated editor: Stephan Glatzel

Keywords:

Landfill reclamation
Physicochemical soil properties
Waste management
Constructosols
Technosols
Degraded land management

Abstract

The dynamic development of civilization and the increase in municipal waste generation in Poland have necessitated effective landfill management and reclamation. This study analyzes the impact of slope aspect, position on the slope, and the time elapsed since reclamation on selected physicochemical properties of surface soil layers in a reclaimed landfill in Czmoń, Wielkopolskie Voivodeship. The research included soil analyses of the surface (0–10 cm) and subsurface (10–20 cm) layers in different parts of the landfill. Parameters such as grain size distribution, pH, organic carbon (OC) content, calcium carbonate ($CaCO_3$) content, and cation exchange capacity (CEC) were determined. Statistical analysis of the obtained results indicated that these factors influenced soil properties depending on landfill age and slope orientation. The texture was expected to be the result of the specific technical reclamation process, which was confirmed. The newer part of the landfill exhibited higher pH, CEC, and $CaCO_3$ content, whereas the older part had a higher C:N ratio. A relationship was also observed between the exposure of analyzed slopes (N-S) and selected soil properties. These findings highlight the importance of well-designed reclamation activities that ensure the biological function of soils formed on such landfills and minimize the negative impact on the environment. These studies make a significant contribution to advancing knowledge on the long-term effects of landfill reclamation.

1. Introduction

The dynamic development of civilization in recent years has led to a significant increase in waste production and changes in its composition. Currently, the annual municipal waste production in Poland amounts to approximately 13,448 thousand tons, translating to an average waste accumulation rate of 357 kg per capita per year (Statictics Poland, 2024). The majority of waste should ideally be subjected to secondary processing for reuse. However, waste disposal, neutralization, and management still primarily rely on landfill storage (Kaczorek and Ledakowicz, 2005; Ważny, 2015). Therefore, a key issue is the design, construction, and maintenance of landfills with minimal environmental impact (Jamróz, 2012), while also ensuring that hazardous and non-hazardous waste landfills cannot be located on soils valued as Class I–III or organic soils, according to the Polish land bonitation classification (Journal of Laws, 2022). In the 1990s, many municipal waste landfills in Poland did not meet basic safety standards (Wota and Woźniak, 2006). The lack of appropriate legal regulations was one of the primary reasons for this issue (Górecka and Koda, 2010; Mamak and Kicińska, 2016). These facilities were often located in areas previously used for the exploitation of natural aggregates such as sand, gravel, or clay (e.g., former sandpits and gravel pits), or on low-quality soils. As a result, numerous landfills did not comply with regulations, requiring closure and reclamation efforts (Adamczyk et al., 2015). According to data from the Central Statistical Office, the number of active municipal waste landfills has decreased in recent years from 803 in 2009 to 347 in 2015, and 254 in 2023 (Statistics Poland 2010; 2016; 2024). Nevertheless, closed and reclaimed landfill sites should be monitored, including assessments of soil quality both below and on the surface, as well as in the surrounding areas (Regulation of the Minister of the Environment, 2013).

The reclamation of waste landfills is the process of restoring areas previously designated for waste disposal to a usable state (Ważny, 2015). A landfill reclamation project is an integral part of landfill planning and should consider all stages, from construction and operation to closure. The responsibility for reclamation lies with the investor. It should be emphasized that reclamation is not merely the execution of specific technical and biological activities that conclude with construction work but also involves continuous monitoring for many years until the area can be deemed permanently and safely repurposed according to its new intended use (Ważny, 2015).

A particularly significant aspect is assessing the impact of stored waste on the environment, especially concerning potential contamination that may arise from waste accumulation (Jamróz, 2012).

Upon the completion of waste disposal operations, hazardous waste landfills are sealed to prevent the infiltration of rainwater. The sealing consists of three layers: a barrier layer (mineral and synthetic insulation), a drainage layer (gravel-sand with a drainage system), and a topsoil layer (at least 1 m thick) that enables plant growth. For non-hazardous and inert waste landfills, the requirements for top sealing are more lenient and less stringent (Jamróz, 2012). One method of technical soil reclamation involves covering contaminated areas with a layer of soil materials. Heavy (clayey and loamy) soils, particularly those with high organic matter content exhibit the greatest resistance to chemical degradation. Light, sandy soils with low organic matter content have significantly lower buffering capacity. As a result, in chemically resistant soils, the effects of fertility decline emerge more gradually but are also more difficult to mitigate (Jakubiak, 2010).

Current legal regulations concerning land protection, reclamation, and management, particularly regarding soil, are characterized by a significant degree of generality and fragmentation. There are considerable gaps in regulatory coherence, making them difficult to understand and apply uniformly. Additionally, the lack of technical standards constitutes a major shortcoming, leading to the flexible interpretation of legal provisions in the design, implementation, management, and evaluation of reclamation processes (Siuta, 2007).

There are limited reports and publications addressing the impact and outcomes of reclamation on the properties of the surface soil layer in landfill areas. Technosols, soils formed or heavily modified as a result of human activity, are currently among the most intensively studied soil groups. They are primarily found in urbanized, industrial, and post-mining areas, and their composition is highly heterogeneous, often containing artifacts such as construction debris, ash, or slag, which influence their physicochemical properties and pedogenic processes. In Poland, research on technosols has gained significant attention in the 21st century, focusing on their classification, transformation dynamics, and the potential for reclaiming degraded lands (Kabała et al., 2020; Uzarowicz et al., 2020).

The aim of this study was to determine the basic physicochemical properties and to assess the influence of slope aspect, slope position, and the time elapsed since reclamation on selected parts of a reclaimed non-hazardous and inert waste landfill in Czmoń, Wielkopolskie Voivodeship. These findings will serve as a baseline for monitoring the development of constructosols in the coming years. The obtained results may hold significant cognitive and practical value in the broader field of waste management.

2. Materials and methods

2.1. Study area

The subject of the research was a reclaimed municipal waste landfill located in Czmoń, Kórnik commune, Poznań County, in the Wielkopolskie Voivodeship (Fig. 1).

According to the geographical regionalization of Poland (Solon et al., 2018), Kórnik commune is situated in the Wielkopolska Lakeland macroregion (315.5) and the Poznań Lakeland mesoregion (315.51). Based on the Köppen-Geiger climate classification, this part of Poland belongs to the temperate warm fully humid climate zone, characterized by warm summers (Kottek et al., 2006). The average air temperature remains at 8.3°C. This region experiences the lowest annual precipitation in Poland (Pająk, 2022), which can locally amount to 500 mm per year (Dudziński, 2021). Additionally, an increase in the annual average air temperature and changes in precipitation patterns have been observed, with precipitation becoming more intense, shorter, and irregular (Pająk, 2022). The surface geological structure of Kórnik commune, including the Czmoń, is primarily associated with Pleistocene deposits (Bajorek et al. 2005; Detailed Geological Map of Poland, sheet No. 508). The dominant formations include glacial tills, as well as silt-sand deposits formed by glacial meltwater (Głowacka, 2023).

The landfill is situated approximately 30 km southeast of Poznań, adjacent to a forested area managed by the Babki Forestry Management to the north and agricultural fields to the south. The site covers approximately 8.36 ha (Technical and Biological Reclamation Project, 2014).

The reclamation project was based on the decision of the Marshal of the Wielkopolska Voivodeship dated March 14, 2014, granting approval for the official closure of the landfill (Decision No. DSR-II.2.7241.1.28.2013, 2014). The landfill operated from 1995 to 2005, receiving waste from various parts of Poland, with approximately 50–70% of the total waste mass originating from Poznań. The facility is managed by "SATER KÓRNIK" Sp. z o.o. The reclamation process was carried out with a meadowland objective, transforming the former landfill site into meadows with some tree and shrub plantings (Technical and Biological Reclamation Project, 2014).

The schedule of technical and partially biological reclamation work, excluding tree and shrub planting, included preparatory work such as a geotechnical assessment of landfill slopes, pumping out the leachate reservoirs, evaluating reservoir conditions and testing soil contamination beneath leachate areas. The second stage involved dismantling unnecessary technical infrastructure. Subsequently, new perimeter ditches and an evaporative surface reservoir for rainwater were constructed. The next phase involved shaping the waste heap while maintaining slopes, inclinations, and elevation levels, as well as redistributing waste to form a technological road. Additionally, the stabilization of the base, slopes, and the construction of a relief slope on the sealed area were carried out.

The next step involved shaping the summit slopes while taking precautions around existing gas wells, followed by the installation of a leveling layer, sand, and soil on the slopes and summit. The waste heap was sealed with a bentonite mat up to

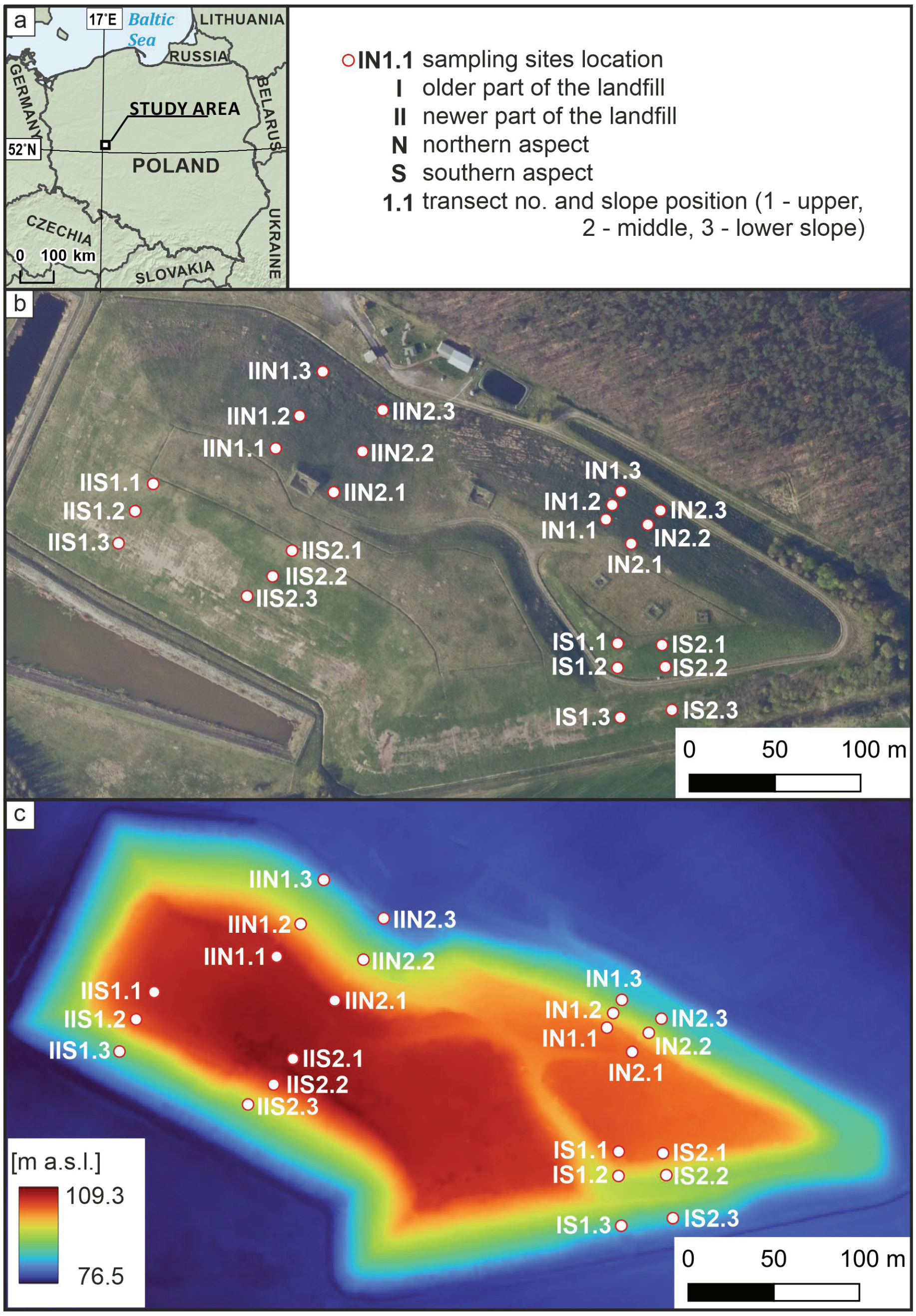

Fig. 1. Location of the study area (a) and the distribution on the sampling sites within the landfill (b)

a height of 5 meters, and above that with natural material- clay and anchoring ditches were installed. The final stage of technical reclamation included the application of a 0.5 m thick protective-drainage layer of coarse sand on the summit and slopes. In the following step, a 0.4 m thick layer of soil, known as the reclamation cover, was applied to the summit. Then, a 0.2 m thick humus layer was placed on the summit and slopes, followed by sod placement from the surface of the summit. The final stage involved the application of fertilizers, grass seed mixtures, and subsequent maintenance and agronomic activities (Technical and Biological Reclamation Project, 2014).

The final form of the landfill is more than 25 meters high, with an elevation of 109.3 m a.s.l at the highest point within the plateau-like summit and 79.0 m a.s.l. at the bottom of the slopes (Fig. 1).

2.2. Field works

As part of the field research, a total of eight transects were established – two on the north-facing (N) and two on the south-facing (S) slopes within the older part (I) of the landfill (reclaimed in 1996), and two on the north-facing and two on the south-facing slopes in the newer part (II) of the landfill (reclaimed in 2015). In each transect, three soil sampling locations were designated, positioned at the upper (1), middle (2), and lower (3) sections of the slopes (Fig. 2). In total, 24 study sites were sampled, from which two samples were collected at each site – one from the surface layer (0–10 cm) and another from the subsurface layer (10–20 cm). These locations were precisely determined using Garmin GPSMap 60 CSx receiver with an accuracy of <1,5 m.

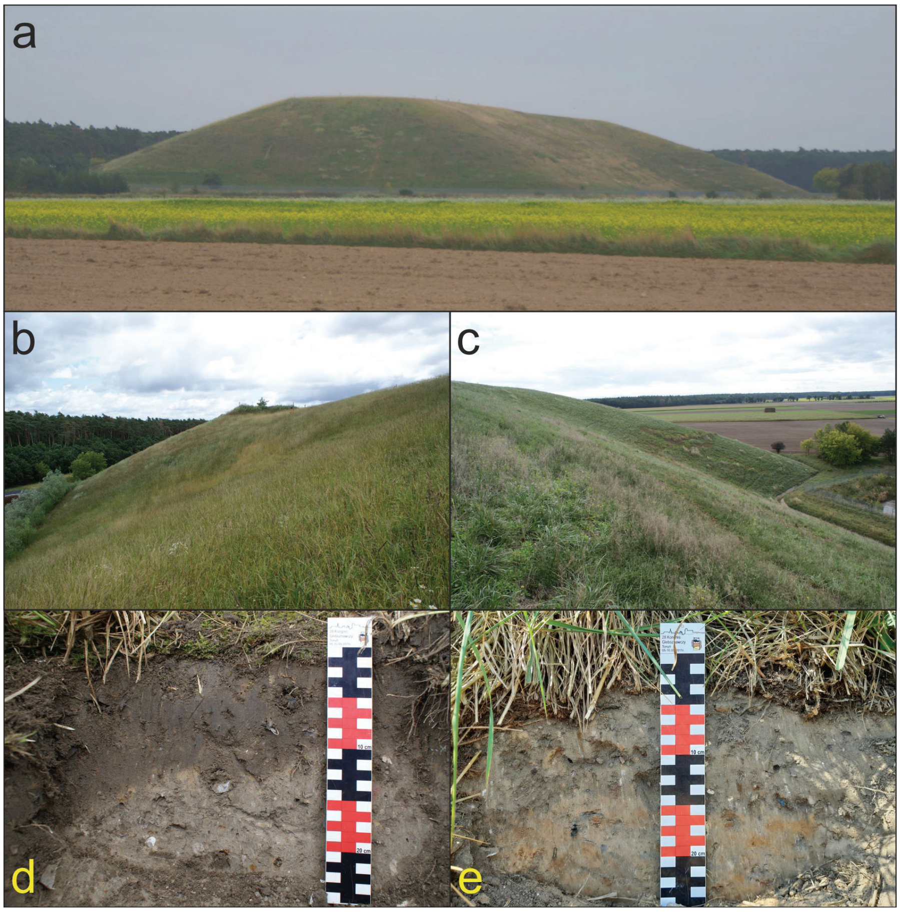

Fig. 2. Landfill in Czmoń, wiev from the southestwest (a), the northern (b) and the southern (c) slopes of the landfill, examples of the morphology of the studied soils: profile IN3 (d) and IIN1 (e)

In total, 48 disturbed soil samples were collected in polyethylene bags, and 144 undisturbed samples were obtained using steel cylinders with a volume of 100 cm^3 in June, 2023. All studied soils were classified as constructosols according to the Polish Soil Classification (PSC, 2019) or as Linic Technosols according to WRB (IUSS Working Group WRB, 2022). Soil color in both dry and wet states was described using the Munsell Soil Color Charts (2009).

2.3. Analytical methods

The following soil properties were determined in the collected samples: bulk density by the oven-dry method; solid particle density according to Marcinek and Spychalski (1987) for the needs of calculating total porosity; total porosity on the basis of bulk density and solid particle density; particle size distribution was determined using the Mastersizer 2000 (Malvern, UK) laser diffractometer, and the names of the texture classes were given in line with the USDA (Soil Survey Division Staff, 1993). The total carbon (TC) and total nitrogen (TN) content were measured using a Vario MaxCube CN Elementar analyser in steel cylinders using standard procedure recommended by the Soil Science Society of Poland (PSC, 2019); pH at a soil-to-solution ratio of 1:5 using 1 M KCl and H_2O as the suspension medium (PN-EN ISO 10390:2022-09, 2022) and content of carbonates by the Scheibler volumetric method using standard procedure recommended by the Soil Science Society of Poland (PSC, 2019) for calculation of the total organic carbon (TOC), the TC values were adjusted (inorganic carbon content from carbonates was subtracted from TC content). Content of exchangeable cations of sodium, potassium, calcium and magnesium was determined using the extraction of ammonium acetate of 7.0 pH (PSC, 2019), hydrolytic acidity was determined using the Kappen method (PSC, 2019).

The cation exchange capacity (CEC) was estimated as the sum of exchangeable cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and hydrolytic acidity (Hh), in accordance with standard practice recommended by the Soil Science Society of Poland (PSC, 2019). No direct measurement of CEC was performed.

2.4. Statistical methods

Statistical analyses were preceded by the verification of data to confirm a normal distribution via the Kolmogorov–Smirnov test, whereas homoscedasticity was tested using the Box–Cox transformation. Next, a one and two-way analysis of variance (ANOVA) was performed for the main effects and interaction which made it possible to determine the effects of the location within the older (I) and the newer (II) part of the landfill, as well as the slope aspect and sampling depth on the selected newer (II) part od landfill, as well as properties such as: texture – represented by the content of silt fraction, the total porosity representing the physical properties, pH H_2O and KCl, TOC content, C:N ratio values, $CaCO_3$ content and base saturation. When significant differences were found, they were identified using the post hoc Tukey test for multiple comparisons. The assumed significance level was p < 0.05. Calculations and analyses were performed via the Statistica 13.3 statistical packages (StatSoft Polska).

3. Results and discussion

In the newer part of the landfill, the studied soils were predominantly of loamy sand texture (22), while two samples were identified as sandy loams. The average content of earth fractions was 79% sand, 19% silt, and 2% clay (Table 1).

In the older part of the landfill, the studied soils were also primarily of loamy sand texture (17), with several samples identified as sand (6), and one sample as sandy loam. The average content of individual fractions was 83% sand, 15% silt, and 2% clay.

Due to the negligible clay content and the observed inverse relationship between sand and silt fractions, only silt content was subjected to statistical analysis as the finer fraction. The silt content was significantly higher (p= 0.000) in the newer part of the landfill compared to the older part (Fig. 3). No significant differences in silt content were observed between samples collected from north- and south-facing slopes in either the older (p = 0.247), or newer (p = 0.123) sections of the landfill. In both the older (p = 0.247) and newer (p = 0.155) sections, higher silt values were observed in the subsurface layer; however, these differences were not statistically significant (Fig. 4 and Fig. 5).

The presented results are consistent with those obtained for soils formed on other reclaimed landfills (Siuta, 2004; Obianefo et al., 2017).

Table 1
Statistical characteristics (arithmetic mean ± standard deviation, median, range) of selected physical properties of soils from the reclaimed waste landfill in Czmoń

Depth	Sand [%]	Silt [%]	Clay (%)	PD [g cm^{-3}]	BD [g cm^{-3}]	TP [%]
			I N			
a	86±1.32	13±1.21	1±0.22	2.60±0.00	1.40±0.03	46.22±1.22
	86	13	1	2.60	1.41	45.86
	85–88	11–14	1–1	2.60–2.60	1.35–1.43	44.94–48.02
b	83±7.04	16±6.09	2±0.89	2.61±0.01	1.42±1.31	46.14±1.80
	84	14	1	2.61	1.42	45.69
	68–91	8–28	1–4	2.60–2.62	1.31–1.48	43.60–49.61
			I S			
a	83± 2.67	16± 2.17	2± 0.43	2.62±0.01	1.47±0.03	43.74±1.25
	83	15	2	2.62	1.48	43.69
	78–86	13–20	1–2	2.61–2.62	1.43–1.53	41.53–45.19
b	81± 2.69	17± 2.11	2± 0.49	2.63±0.01	1.51±0.04	42.57±1.47
	81	17	2	2.63	1.52	42.32
	77–85	14–20	1–3	2.61–2.64	1.42–1.55	41.24–45.62
			II N			
a	79±1.96	19±1.51	2±0.24	2.62± 0.00	1.52±0.12	41.69±4.48
	79	19	2	2.62	1.56	40.50
	75–81	17–22	2–3	2.61–2.63	1.28–1.64	37.44–51.02
b	77±4.77	21±4.23	3±0.88	2.63±0.01	1.47±0.08	44.05±3.14
	78	19	3	2.63	1.46	44.50
	70–82	16–27	2–4	2.62–2.63	1.36–1.58	40.01–48.39
			II S			
a	81±2.80	17±2.14	2±0.68	2.61±0.01	1.42±0.05	45.79±1.64
	82	17	1	2.61	1.42	45.83
	76–85	14–21	1–3	2.59–2.62	1.34–1.47	43.64–48.55
b	70±3.01	19±2.50	2±0.57	2.60±0.03	1.38±0.09	46.87±3.70
	79	19	2	2.61	1.38	47.70
	73–83	16–24	1–3	2.55–2.63	1.29–1.53	39.93–50.51

Explanations: Part of the landfill: I – older part of the landfill; II – newer part of the landfill. Slope aspect: N – north; S – south. Sampling depth: a – 0–10 cm; b – 10–20 cm.

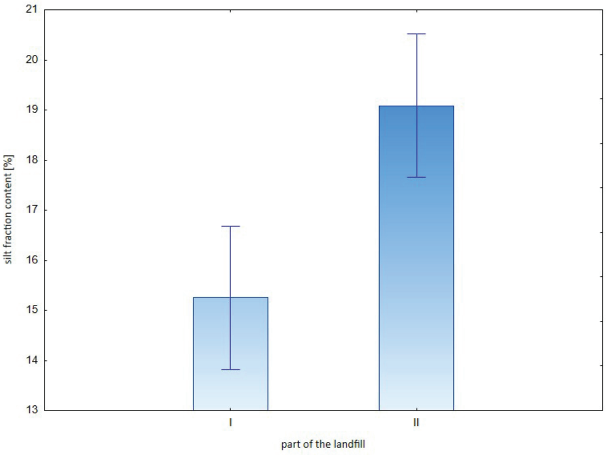

Fig. 3. The effect of the location within the older (I) and the newer (II) part of the landfill on the silt fraction content (mean value of silt fraction and ± 95% confidence interval)

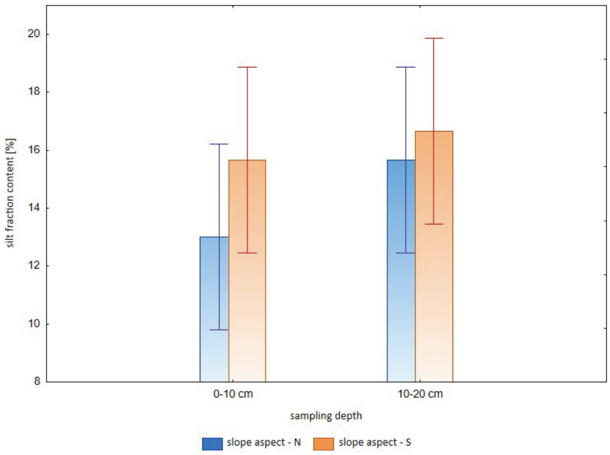

Fig. 4. The effect of the location within the northern (N) and southern (S) slopes of the older part of the landfill and the sampling depth on the silt fraction content (mean value of silt fraction and ± 95% confidence interval)

The texture of the surface layer is directly dependent on the original characteristics of the soil materials used during reclamation. Project documentation indicates that primarily loamy sand and sandy loam were used, which is reflected in the obtained research results (Technical and Biological Reclamation Project, 2014).

The analyzed soils exhibited bulk density values ranging from 1.28 to 1.64 g cm^{-3} (average 1.45 g cm^{-3}) in the newer part of the landfill and from 1.31 to 1.55 g cm^{-3} (average 1.45 g cm^{-3}) in the older section (Table 2). The surface layers (0–10 cm) in the newer section had slightly higher bulk density values compared to the subsurface layers (10–20 cm). Total porosity values ranged from 37.44% to 51.02% (average 44.60%) in the newer part of the landfill and from 41.24% to 49.61% (average 44.67%) in the older section. The surface layers (0–10 cm) in the newer section of the landfill exhibited slightly lower porosity values compared to the deeper layers (10–20 cm). However, this trend was not observed in the older section.

The probable causes of the obtained total porosity results align with the previously described factors affecting bulk density, which may be a result of the reclamation work conducted (compaction due to the passage of heavy machinery such as excavators). In the older section, this trend was not visible, suggesting that plant root growing since almost 30 years in the formed soil contributed to the equalization of bulk density values in these layers.

However, statistical analyses did not indicate significant differences in total porosity values between the surface and subsurface layers ($p = 0.474$). Additionally, there were no significant differences in total porosity (TP) between the older and newer sections of the landfill ($p = 0.947$). The only statistically significant differences were observed between north- and south-facing slopes in both sections (older $p = 0.000$, newer $p = 0.005$), while, surprisingly, higher TP values were recorded in the older section on the northern slope, whereas in the newer section, they were higher on the southern slope (Fig. 6).

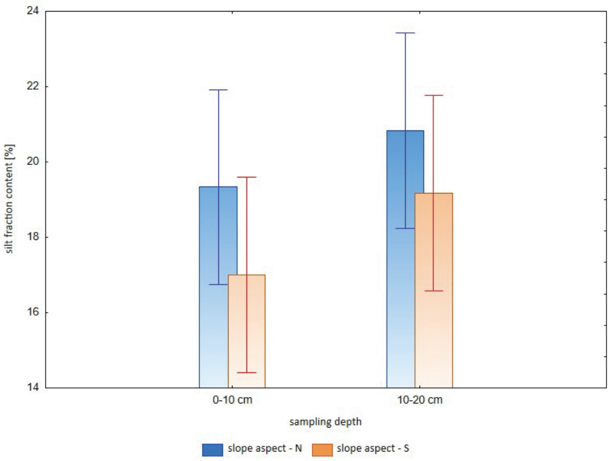

Fig. 5. The effect of the location within the northern (N) and southern (S) slopes of the newer part of the landfill and the sampling depth on the silt fraction content (mean value of silt fraction and ± 95% confidence interval)

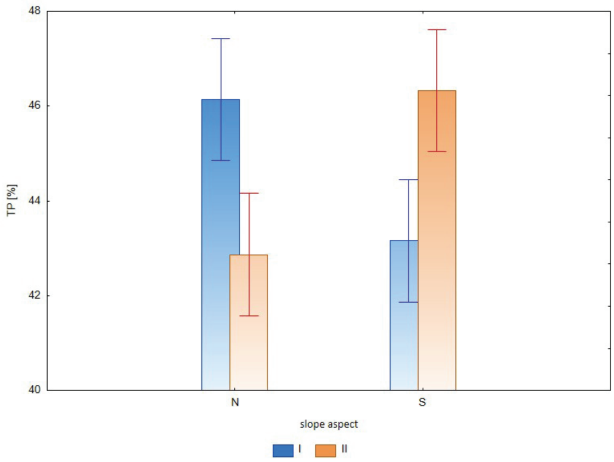

Fig. 6. The effect of the location within the northern (N) and southern (S) slopes of the older (I) and the newer (II) part of the landfill on the total porosity values (mean value of total porosity and ± 95% confidence interval)

Weeks et al. (1992) indicated no significant differences in porosity between surface and subsurface layers in soils formed within the reclaimed landfills, similarly to our observations. Lins et al. (2020) highlighted the influence of north vs south exposure on physical properties, which was also observed in our study. Nevertheless the difference in trends of TP values within the older and newer section is hard to explain. Higher total porosity values in the northern parts of the older landfill may result from more favorable moisture conditions that, over time, facilitated vegetation growth and microbial activity, leading to soil loosening. In the newer landfill sections, higher total porosity in the southern slopes may be an effect of greater solar exposure, which intensifies organic matter decomposition processes, including humification, and thereby improves soil structure. Although no direct statistical comparison was made, organic matter content is known to influence bulk density and total porosity, a relationship observed qualitatively in this study. Additionally, the intensity of reclamation activities might have varied depending on exposure. In the more sunlit southern areas, reclamation activities such as planting vegetation with extensive root systems or mechanical loosening of the soil to improve aeration may have been more concentrated to compensate for faster moisture loss and maintain suitable conditions for vegetation growth.

The studied soils exhibited pH values measured in water solution (pH in H_2O) ranging from 7.28 to 8.11 (average 7.87) in the newer part of the landfill and from 6.64 to 7.96 (average 7.64) in the older section (Table 2). Meanwhile, pH measured in a 1-molar KCl (pH in KCl) solution varied from 7.36 to 7.92

Table 2

Statistical characteristics (arithmetic mean ± standard deviation, median, range) of selected chemical properties of soils from the reclaimed waste landfill in Czmoń

Depth	pH		TOC [g kg^{-1}]	TN [g kg^{-1}]	C/N	$CaCO_3$ [g kg^{-1}]
	H_2O	KCl				
			I N			
a	7.67±0.11	7.54±0.05	14.24±0.86	0.88±0.06	16.25±0.53	5.48±1.03
	7.73	7.56	14.51	0.87	16.29	5.43
	7.48–7.79	7.45–7.59	12.9–15.1	0.8–1.0	15.40–16.88	4–7
b	7.87± 0.08	7.75± 0.07	11.99± 2.41	0.68± 0.22	19.18± 5.07	6.40± 1.41
	7.87	7.74	12.29	0.71	17.27	6.46
	7.73–7.96	7.66–7.85	7.3–14.5	0.2–0.9	15.15–30.10	4–8
			I S			
a	7.57±0.15	7.45±0.17	9.74±1.52	0.68±0.08	14.23±1.04	3.39±1.28
	7.57	7.51	9.36	0.71	13.96	3.74
	7.37–7.80	7.21–7.63	8.0–11.8	0.6–0.8	12.91–15.74	2–5
b	7.43±0.41	7.23±0.67	6.73±2.89	0.47±0.21	14.71±2.22	4.48±3.84
	7.5	7.48	6.64	0.51	15.06	3.78
	6.64–7.91	5.81–7.80	3.2–11.0	0.2–0.8	11.78–17.90	1–12
			II N			
a	7.92± 0.12	7.77± 0.06	8.31± 1.41	0.61± 0.11	13.75± 0.44	11.35± 0.65
	7.92	7.80	8.25	0.62	13.69	11.47
	7.70–8.08	7.63–7.81	6.4–10.4	0.4–0.7	13.26–14.52	10–12
b	7.98±0.11	7.83±0.04	6.49±1.93	0.48±0.13	13.65±1.81	12.44±2.72
	8.03	7.83	6.37	0.47	14.12	12.47
	7.84-8.11	7.76-7.89	4.2-8.9	0.3-0.7	10.06-15.27	9–17
			II S			
a	7.82±0.10	7.74±0.07	11.35±2.96	0.87±0.26	13.23±0.77	7.80±1.35
	7.85	7.72	11.06	0.85	13.1	8.19
	7.65–7.94	7.64–7.85	7.7–16.6	0.5–1.3	12.41–14.39	5–9
b	7.74±0.28	7.72±0.19	13.04±8.45	1.21±0.93	12.04±2.01	10.09±1.27
	7.86	7.78	10.25	0.80	12.49	9.77
	7.28–8.04	7.36–7.92	4.5–30.2	0.3–3.0	8.81–14.38	9–12

Explanations: Part of the landfill: I – older part of the landfill; II – newer part of the landfill. Slope aspect: N – north; S – south. Sampling depth: a – 0–10 cm; b – 10–20 cm (average 7.77) in the newer landfill section and from 5.81 to 7.85 (average 7.49) in the older section.

The pH in H_2O in the newer landfill section is significantly higher ($p = 0.025$) than in the older section (Fig. 7). The pH in KCl values are statistically significantly higher ($p = 0.003$) in the newer section of the landfill (Fig. 8). The differences in pH are statistically significant between the north- and south-facing slopes in both the older and newer sections of the landfill ($p = 0.027$). However, no statistically significant differences were found between the surface and subsurface layers ($p = 0.949$).

The obtained results are consistent with findings from other studies investigating soil pH in reclaimed landfills. Saritha et al. (2014) reported a pH range of 6.5 to 8.0.

The average pH values in both landfill sections may result from variations in soil mineral composition, microbial activity intensity, and processes occurring within the waste material.

In the older section of the landfill, the leaching of alkaline ions by precipitation may lead to a gradual decrease in pH. Simultaneously, organic decomposition products from vegetation covering the reclaimed landfill, such as organic acids, may contribute to localized soil acidification in the older sections.

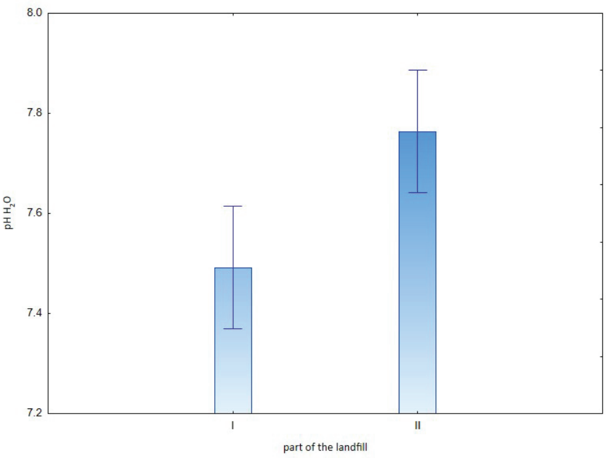

Fig. 7. The effect of the location within the older (I) and the newer (II) part of the landfill on the pH in H_2O (mean value of pH in H_2O and ± 95% confidence interval)

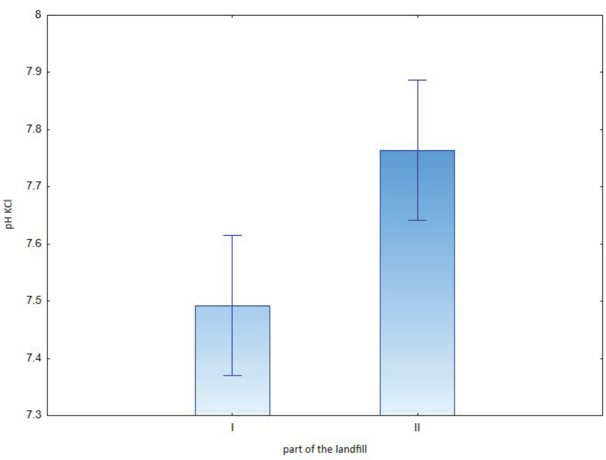

Fig. 8. The effect of the location within the older (I) and the newer (II) part of the landfill on the pH in KCl (mean value of pH in KCl and ± 95% confidence interval)

An important factor influencing soil pH is the presence of calcium carbonate ($CaCO_3$). The detected levels of $CaCO_3$ in the studied soils indicate a buffering effect, particularly in layers with higher concentrations. Calcium carbonate dissolves in the presence of acidic compounds, leading to the release of calcium (Ca^{2+}) and bicarbonate (HCO_3^-) ions. These ions react with hydrogen ions (H^+), reducing their concentration and thus mitigating acidification. Through this mechanism, $CaCO_3$ contributes to the stabilization of soil pH, and its buffering capacity may explain why pH fluctuations – though present – remain within a relatively narrow range (Gonet et al., 2015).

Differences between north- and south-facing slopes align with observations by Tudor (2023), who highlighted that environmental factors such as sunlight exposure and precipitation influence the rate of organic matter decomposition and microbial activity. Microbial activity, modulated by oxygen availability, moisture, and nutrient content, plays a crucial role in shaping soil pH.

The variation in pH between surface and subsurface layers is limited, which may indicate uniform chemical and biological processes throughout the vertical soil profile. However, as noted by Saritha et al. (2014), deeper soil layers may exhibit greater pH stability due to reduced oxygen availability and limited microbial activity.

The TOC content in the studied soils of the newer landfill section ranged from 4.2 to 30.2 g kg^{-1} (average 9.8 g kg^{-1}), with similar values in both the 0–10 cm and 10–20 cm layers (Table 2). In the older landfill section, the TOC content varied from 3.2 to 15.1 g kg^{-1} (average 10.7 g kg^{-1}), with slightly higher values in the surface layer (0–10 cm).

The total nitrogen content in the soil of the newer landfill section ranged from 0.3 to 3.0 g kg^{-1} (average 0.8 g kg^{-1}), with similar values in both the 0–10 cm and 10–20 cm layers. In the older landfill section, the total nitrogen content varied from 0.2 to 1.0 g kg^{-1} (average 0.7 g kg^{-1}), with slightly higher values in the surface layer (0–10 cm).

There are no significant differences ($p = 0.348$) in organic carbon content between the older and newer landfill sections. However, significant differences were observed between the north- and south-facing slopes in both sections (Fig. 9), with higher values recorded on the northern slope in the older section ($p = 0.000$) and on the southern slope in the newer section ($p = 0.001$). In the older section, the differences between the 0–10 cm and 10–20 cm layers were statistically significant ($p = 0.000$), whereas in the newer section, these values did not differ significantly ($p = 0.958$).

In the older section of the landfill, the higher total organic carbon (TOC) and total nitrogen (TN) content in the surface layer is likely due to the longer period accumulation of organic matter. Similar results were obtained by Ogbonna et al. (2009) in their study of soils in Port Harcourt, where higher TOC values were recorded in the upper soil layers within landfill influence zones.

Significant differences in TOC content between the north- and south-facing slopes in both the older and newer landfill sections may be linked to landfill section age and the slope aspect.

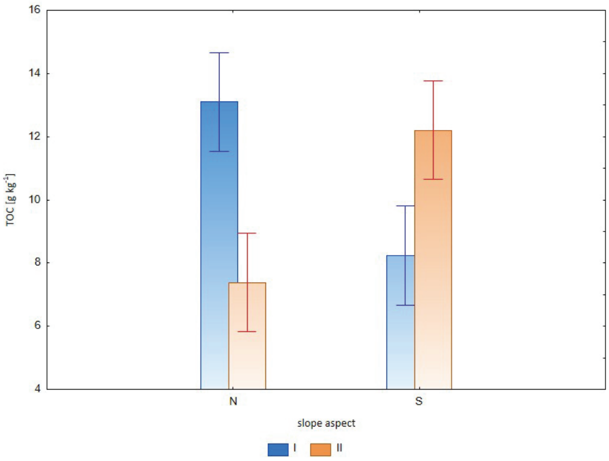

Fig. 9. The effect of the location within the northern (N) and the southern (S) slopes of the older (I) and the newer (II) part of the landfill on the TOC content (mean value of TOC content and ± 95% confidence interval)

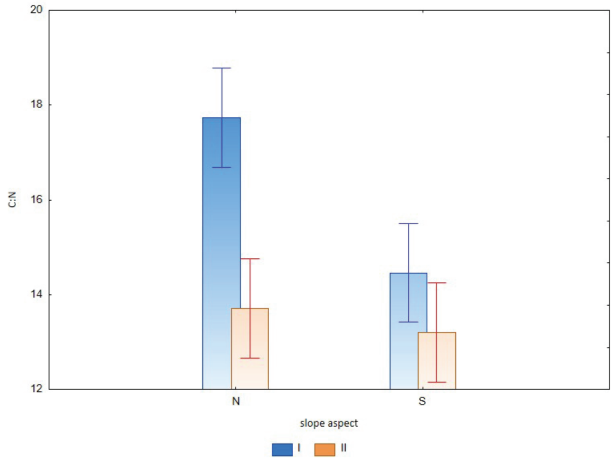

Fig. 10. The effect of the location within the northern (N) and the southern (S) slopes of the older (I) and the newer (II) part of the landfill on the C:N ratio (mean value of C:N and ± 95% confidence interval)

In the older section, the higher TOC content in the northern slopes may result from long-term soil stabilization processes, such as humification and humus compound formation, as well as protection from direct sunlight exposure. These findings align with the study by Mhaiske and Jain (2019), who demonstrated that older waste deposits exhibit higher organic matter content due to reduced moisture loss and slower mineralization in shaded areas.

Di Trapani et al. (2013) analyzed the influence of slope inclination and landfill age on methane emissions and organic compound dynamics, indicating that southern slopes in older landfills are characterized by faster mineralization and organic matter loss.

The opposite situation observed within the newer landfill section may be attributed a greater input of fresh waste, releasing organic compounds through rapid biodegradation, which also explains the higher TOC values in this area or the original differences in material used for the reclamation activities. As indicated by de Medeiros Engelmann et al. (2018), older landfills are characterized by soil stabilization and a reduction in organic carbon content due to prolonged biodegradation processes. Similarly, Zhao et al. (2017) highlight that these changes are often more intense in older landfill areas, where higher nitrogen losses occur due to ammonia volatilization and denitrification processes.

The carbon-to-nitrogen ratio (C:N) in the newer landfill section ranged from 8.81 to 15.27 (average 13.45), with higher values in the surface layer. In the older section, the C:N ratio varied from 11.78 to 30.10 (average 16.09), with higher values in the subsurface layer (Table 2).

The C:N ratio values in the older landfill section were significantly different (higher, $p = 0.000$) compared to the newer landfill section. Differences between north- and south-facing slopes were also statistically significant ($p = 0.001$) in both the older and newer landfill sections, with higher values observed in samples collected from north-facing slopes (Fig. 10). In the newer landfill section, the differences in C:N ratio between the surface and subsurface layers were statistically significant ($p = 0.015$), whereas in the older section, these differences were not statistically significant ($p = 0.055$; Fig. 11, Fig. 12, respectively).

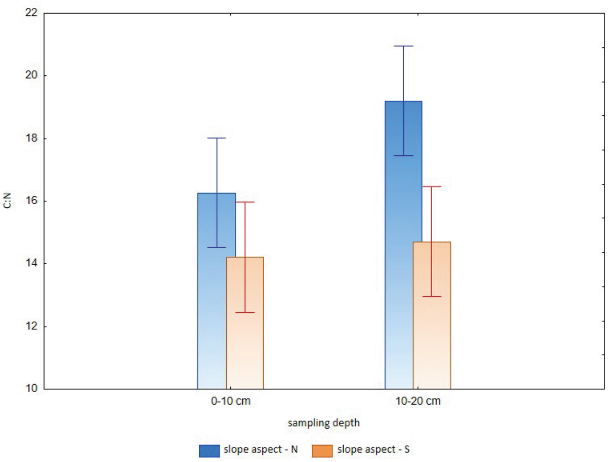

Fig. 11. The effect of the location within the northern (N) and southern (S) slopes of the older part of the landfill and the sampling depth on the C:N ratio (mean value of C:N and ± 95% confidence interval)

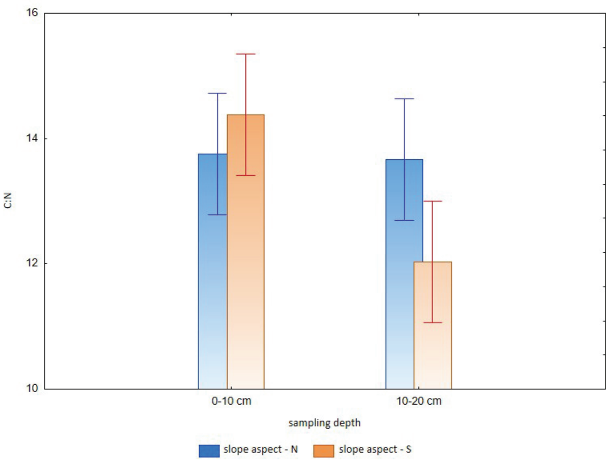

Fig. 12. The effect of the location within the northern (N) and southern (S) slopes of the newer part of the landfill and the sampling depth on the C:N ratio (mean value of C:N and ± 95% confidence interval)

The high C:N ratio in the surface layer of the newer landfill section may be due to the addition of fresh organic matter, which is rich in carbon but low in nitrogen. In the older section, the higher C:N ratio in the subsurface layer may be a result of slower mineralization (limited oxygen availability) or lower microbial activity.

Differences in the C:N ratio between north- and south-facing slopes may be attributed to microclimatic conditions. In the north, where organic matter decomposition occurs at a slower rate, the C:N ratio is higher. In the south, more intense sunlight exposure accelerates the decomposition of organic matter, reducing the C:N ratio.

According to Zhou et al. (2019), high C:N values in fresh organic matter can limit nitrogen availability to plants, as microorganisms compete for this element during the decomposition process. As mineralization progresses, the C:N ratio stabilizes, promoting the accumulation of organic carbon. Additionally, biological diversity and climatic conditions play a crucial role in these processes.

Wick et al. (2009), in their study of reclaimed soils in sandy-loamy post-mining areas, focused on the influence of soil structure on carbon and nitrogen content. The authors highlighted that mineralization processes and soil aggregate structure are crucial for maintaining an appropriate C:N ratio. They also noted that the presence of fresh organic matter in reclaimed soil can lead to high C:N values.

The $CaCO_3$ content in the soil of the newer landfill section ranged from 5 to 17 g kg^{-1} (average 11 g kg^{-1}), with slightly higher values in the subsurface layer (10–20 cm). In the older section, the $CaCO_3$ content ranged from 1 to 12 g kg^{-1} (average 5 g kg^{-1}), also with slightly higher values in the subsurface layer (Table 2).

In the newer landfill section, $CaCO_3$ content was statistically significantly higher ($p = 0.000$) than in the older section, which explains the previously analyzed higher pH values (Fig. 13). Differences between north- and south-facing slopes were statistically significant ($p = 0.000$) in both landfill sections, with higher values recorded on north-facing slopes. In the newer section, values in the subsurface layer were statistically significantly higher ($p = 0.020$) than in the surface layer, whereas no such differences were observed in the older section ($p = 0.102$).

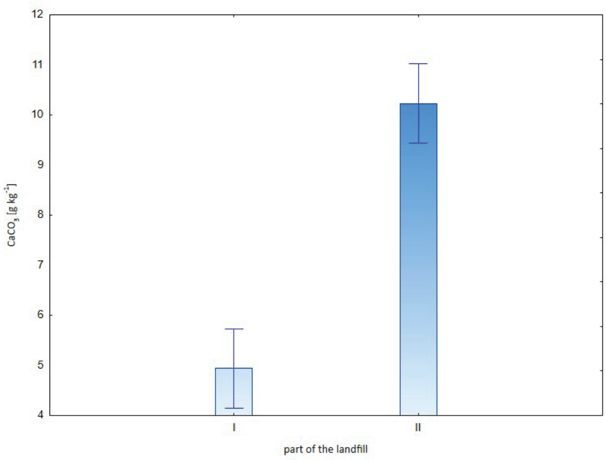

Fig. 13. The effect of the location within the older (I) and the newer (II) part of the landfill on $CaCO_3$ content (mean value of $CaCO_3$ content and ±95% confidence interval)

Higher $CaCO_3$ content in the subsurface layer may result from the natural migration of calcium carbonate within the soil profile. In the newer landfill section, the higher $CaCO_3$ content is most probably related to the original properties of the soil material used during reclamation. In the older section, higher values in the deeper layers may be a consequence of prolonged downward movement of $CaCO_3$ within the soil profile.

The calcium carbonate content on the northern side of the landfill is higher (average 9 g kg^{-1}) what could be the result of lower solar radiation and cooler temperatures, which slow down chemical processes, promoting long-term accumulation of this mineral in the soil. Conversely, on the southern side, where temperatures are higher and solar radiation is more intense, chemical reactions occur more rapidly, facilitating the breakdown of calcium carbonate, resulting in lower content (average 6 g kg^{-1}). The present findings align with those of Peng and Liu (2019), who investigated the influence of temperature on microbially induced calcium carbonate precipitation in soil. Their results indicate that lower temperatures promote greater calcium carbonate precipitation. Differences in slope exposure may also stem from the original properties of the soil materials used for reclamation.

Similar carbonate contents were recorded by Kutyna and Nieczkowska (2009), who studied technogenic soils (0–25 cm) with texture of sands and loamy sands. They concluded that the primary determinant of carbonate content is its presence in the skeletal components of the soil. Additionally, Chodorowski et al. (2024) reported that technogenic soils typically contain this chemical compound.

The cation exchange capacity (CEC) in the newer landfill section ranged from 8.93 to 13.92 cmol kg^{-1} (average 10.94 cmol kg^{-1}), with slightly higher values in the subsurface layer (10–20 cm). In the older landfill section, CEC varied from 3.26 to 11.24 cmol kg^{-1} (average 7.24 cmol kg^{-1}), with similar values in both layers (Table 3).

These CEC values are consistent with those obtained by Fijałkowski and Kacprzak (2009), who analyzed CEC content in degraded soils and partially align with results reported by Bielińska and Mocek (2010) analyzing the soils subjected to varying degrees of anthropogenic pressure.

The base saturation (BS) in the newer landfill section ranged from 90.78% to 97.63% (average 95.90%), with slightly higher values in the subsurface layer (10–20 cm). In the older landfill section, BS values ranged from 63.54% to 95.59% (average 90.73%, Table 3). BS values were significantly higher ($p = 0.000$) in the newer landfill section compared to the older section (Fig. 14). However, it should be noted that differences in BS values between the surface and subsurface layers in the newer section were not statistically significant ($p = 0.260$).

The above BS values are consistent with the results obtained by Bielińska and Mocek (2010).

It should be noted that the values of exchangeable bases (Ca^{2+}, Mg^{2+}, K^+, Na^+) and hydrolytic acidity (Hh) presented in Ta-

Table 3
Statistical characteristics (arithmetic mean ± standard deviation, median, range) of exchangeable base cations (K^+, Na^+, Ca^{2+}, Mg^{2+}) content, total exchangeable bases, hydrolytic acidity, cation exchange capacity and base saturation of soils from the reclaimed waste landfill in Czmoń

Depth	K^+	Na^+	Ca^{2+}	Mg^{2+}	TEB [cmol kg^{-1}]	Hh [cmol H$^+$ kg^{-1}]	CEC [cmol kg^{-1}]	BS [%]
	cmol kg^{-1}							
				I N				
a	0.68±0.09	0.05±0.01	5.15±0.69	0.60±0.08	6.48±0.82	0.61±0.04	7.09±0.80	91.27±1.32
	0.67	0.06	4.85	0.64	6.19	0.62	6.81	90.81
	0.58–0.80	0.03–0.07	4.52–6.39	0.44–0.66	5.60–7.85	0.53–0.65	6.22–8.45	89.92–93.19
b	0.54±0.06	0.06±0.02	6.74±0.68	0.47±0.03	8.22±1.19	0.49±0.03	8.71±1.18	94.32±0.92
	0.54	0.06	6.67	0.48	7.95	0.48	8.41	94.51
	0.44–0.62	0.03–0.08	5.62–7.71	0.43–0.51	6.79–10.40	0.45–0.54	7.29–10.88	93.14–95.59
				I S				
a	0.57±0.07	0.04±0.01	4.83±1.28	0.58±0.11	6.03±1.42	0.59±0.08	6.62±1.35	90.40±3.29
	0.57	0.04	5.24	0.58	6.49	0.61	7.09	91.51
	0.46–0.68	0.03–0.06	3.06–6.20	0.40–0.74	3.95–7.55	0.45–0.68	4.63–8.12	85.30–94.26
b	0.41±0.09	0.05±0.02	5.06±3.00	0.40±0.07	5.91±3.09	0.62±0.26	6.53±2.94	86.92±10.99
	0.42	0.05	4.53	0.41	5.33	0.52	5.88	90.12
	0.26–0.52	0.03–0.09	1.17–9.71	0.31–0.54	2.07–10.70	0.42–1.19	3.26–11.24	63.54–95.43
				II N				
a	0.45± 0.04	0.18± 0.08	9.19± 1.13	0.58± 0.10	10.39± 1.26	0.44± 0.06	10.83± 1.20	95.83± 1.04
	0.45	0.23	9.17	0.59	10.43	0.42	10.85	96.13
	0.39–0.51	0.06–0.27	7.36–10.57	0.40–0.69	8.51–11.97	0.38–0.53	9.04–12.35	94.13–96.92
b	0.48±0.07	0.23±0.10	9.88±1.47	0.57±0.11	11.15±1.58	0.40±0.06	11.55±1.53	96.46±0.96
	0.45	0.26	9.67	0.59	11.08	0.39	11.47	96.64
	0.41–0.63	0.08–0.36	8.10–12.35	0.36–0.72	8.98–13.57	0.33–0.50	9.48–13.92	94.72–97.49
				II S				
a	0.48±0.04	0.21±0.17	8.14±0.75	0.74±0.22	9.56±1.07	0.44±0.03	10.00±1.05	95.54±0.63
	0.49	0.16	8.8	0.67	9.34	0.45	9.80	95.35
	0.42–0.52	0.04–0.50	7.24–9.58	0.54–1.20	8.52–11.79	0.38–0.48	8.93–12.17	94.91–96.88
b	0.44±0.05	0.40±0.33	9.36±1.79	0.74±0.14	10.93±1.45	0.46±0.18	11.39±1.28	95.77±2,31
	0.47	0.41	9.29	0.79	10.82	0.39	11.20	96.56
	0.35–0.50	0.04–0.76	6.25–11.71	0.55-0.91	8.27–12.77	0.30–0.84	9.11-13.12	90.78–97.63

Explanations: Part of the landfill: I – older part of the landfill; II – newer part of the landfill. Slope aspect: N – north; S – south. Sampling depth: a – 0–10 cm; b – 10–20 cm. TEB – total exchangeable bases; Hh – hydrolytic acidity; CEC – cation exchange capacity; BS – base saturation

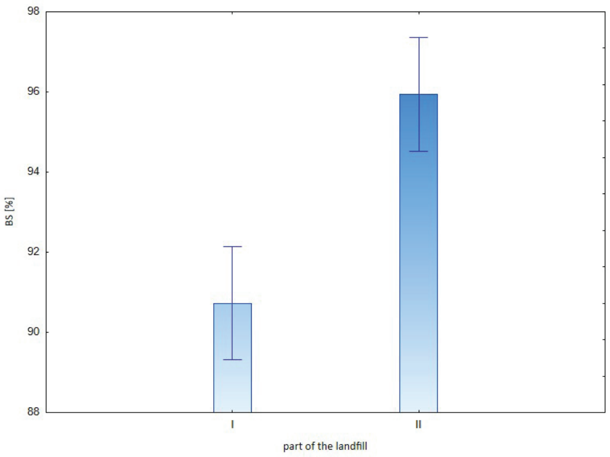

Fig. 14. The effect of the location within the older (I) and the newer (II) part of the landfill on the base saturation (mean value of BS and ±95% confidence interval)

ble 3 were used to calculate the total exchangeable bases (TEB) and subsequently the cation exchange capacity (CEC) and base saturation (BS). TEB was calculated as the sum of exchangeable cations, while CEC was derived by summing TEB and Hh. These parameters were not discussed separately due to their auxiliary role in these calculations; however, they are included in the table for transparency. Their presence provides clarity regarding the source values used in deriving the final CEC and BS values.

Solly et al. (2020), who conducted studies on CEC and organic carbon content in forest soils in Switzerland, reported that higher pH promotes an increase in CEC, as a higher pH enhances cation exchange capacity. Additionally, higher organic matter content in the soil is known factor enhancing cation exchange capacity (Gonet et al., 2015).

Similar mechanisms may explain the differences in CEC and BS across various landfill areas. Higher values of these parameters may result from the higher pH in the newer landfill section. Conversely, in the older landfill section, where pH is lower, both CEC and BS are reduced.

5. Conclusions

The time elapsed since the completion of the reclamation process (27 and 8 years, respectively), as well as the slope exposure at the landfill site, influenced the selected properties of the studied constructosols.

Different factors influenced the variability of different properties. The texture was expected to result solely from the technical reclamation process, which was confirmed by this study. We also anticipated lower values of pH, CEC, and carbonate content in the older section of the landfill, mainly due to longer exposure to precipitation, which was also consistent with the obtained results. Additionally, the slope aspect influenced these parameters; however, the outcomes were opposite to our expectations, as we assumed that the more humid northern slopes would have lower pH values.

Regarding organic carbon content, differences in its distribution across slopes with different aspects were observed between the older and newer landfill sections. This suggests that 27 years is sufficient time for the stabilization of organic matter accumulation processes, whereas after 8 years, the original properties of the reclamation materials or the influence of the waste itself may still contribute to its variability. This was also confirmed by the C:N ratio values, which differed in an expected manner across slopes with different aspects.

Nearly 30 years after reclamation, the differentiation of soil properties within this morphological form appears to be only beginning to resemble that of natural processes. The properties of the materials used for reclamation still supposed to have a strong influence on soil variability. Nevertheless, the outcomes of this study provide a solid starting point for further monitoring of the site and the evolution of technogenic soils developing within the studied landfill.

Acknowledgments

The authors would like to express their gratitude to Mr. Maksymilian Sułkowski, President of the Management Board of Sater Kórnik Sp. z o.o., the company managing the landfill site in Czmoń, for his kind support and for granting permission to conduct the research on site. The authors also thank the Reviewers for their valuable comments and suggestions on the manuscript.

Conflict of interest

The authors declare no conflict of interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This research did not involve human or animal subjects.

Author Contributions

Wiktor Michnej-Zakrzewski - Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Writing – original draft. **Łukasz Mendyk** – Conceptualization, Data curation, Supervision, Writing – review & editing. **Marta Molińska-Glura** – Data curation, Validation, Visualization, Writing – review & editing. **Agnieszka Mocek-Płóciniak** – Conceptualization, Data curation, Supervision, Writing – review & editing. All authors read and approved the final manuscript.

References

Adamczyk, I., Różańska, B., Sobczyk, M., 2015. Infrastruktura komunalna w 2014 r. Główny Urząd Statystyczny, Warszawa, 1–33.

Bajorek, J., Bojakowska, I., Dusza, A., Piaseczna, A., Tomassi-Morawiec, H., Wodyk, K., Woliński, W., 2005. Objaśnienia do Mapy Geośrodowiskowej Polski, arkusz Kórnik (508). Państwowy Instytut Geologiczny.

Bielińska, E.J., Mocek, A., 2010. Sorption properties and enzymatic activity of municipal park soils in regions of varying impact of anthropologic pressure. Journal of Research and Applications in Agricultural Engineering 55(3), 20–23.

Chodorowski, J., Bartmiński, P., Plak, A., Dębicki, R., 2024. Soil cover of the city of Lublin (Eastern Poland). Annales Universitatis Mariae Curie-Skłodowska Lublin – Polonia 79, Sectio B, 69–85. https://doi.org/10.17951/b.2024.79.0.69-85

De Medeiros Engelmann, P., Dos Santos, V.H.J.M., Barbieri, C.B., Augustin, A.H., Ketzer, J.M.M., Rodrigues, L.F., 2018. Environmental monitoring of a landfill area through the application of carbon stable isotopes, chemical parameters and multivariate analysis. Waste Management 76, 591–605. https://doi.org/10.1016/j.wasman.2018.02.027

Decision of the Marshal of the Greater Poland Voivodeship of March 14, 2014 (No. DSR-II.2.7241.1.28.2013) regarding the approval for the administrative closure of a landfill for non-hazardous and inert waste in the village of Czmoń, Kórnik municipality.

Di Trapani, D., Di Bella, G., Viviani, G., 2013. Uncontrolled methane emissions from a MSW landfill surface: Influence of landfill features and side slopes. Waste Management 33(10), 2108–2115. https://doi.org/10.1016/j.wasman.2013.01.032

Dudziński, J., 2021. Prognoza oddziaływania na środowisko dotycząca projektu miejscowego planu zagospodarowania przestrzennego w obrębie geodezyjnym Konarskie w rejonie ulic Huby i Prawdziwkowej, gmina Kórnik. Poznań, 21 lipca 2021 r.

Fijałkowski, K., Kacprzak, M., 2009. The influence of sewage sludge addition on selected physico-chemical parameters of degraded soils. Environmental Science, 12, 133–141.

Głowacka, M., 2023. Prognoza oddziaływania na środowisko na potrzeby miejscowego planu zagospodarowania przestrzennego dla wsi Radzewo, gmina Kórnik – etap I. Kórnik.

Gonet, S., Smal, H., Chojnicki, J., 2015. Chapter 6. Właściwości chemiczne gleb (Chemical properties of soils). Mocek, A. (ed.), Gleboznawstwo (Soil Science), Wydawnictwo Naukowe PWN, Warsaw

Górecka, A., Koda, E., 2010. Analysis of possibilities to reduce the risks of groundwater pollution resulting from operating of the modernized sanitary landfill. Przegląd Naukowy Inżynieria i Kształtowanie Środowiska 19(3), 49.

IUSS Working Group WRB, 2022. World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps. 4th edition. International Union of Soil Sciences (IUSS), Vienna, Austria.

Jakubiak, M., 2010. Zastosowanie stymulacji laserowej wybranych gatunków roślin w celu zwiększenia ich przydatności dla rekultywacji terenów zasolonych. Praca doktorska. Akademia Górniczo-Hutnicza im. Stanisława Staszica (Kraków). http://winntbg.bg.agh.edu.pl/rozprawy2/10242/full10242.pdf (data dostępu: 18.10.2015r.).

Jamróz, A., 2012. Proper Construction, Maintenance and Reclamation of Municipal Landfills in Accordance with Polish Legislation. Environment. Technical Journal 4, 88-100.

Journal of Laws of the Republic of Poland, 2022. Dz.U. 2022.1902 consolidated text. Binding act, version effective from September 9, 2022.

Kabała, C., Greinert, A., Charzyński, P., Uzarowicz, Ł., 2020. Technogenic soils–soils of the year 2020 in Poland. Concept, properties and classification of technogenic soils in Poland. Soil Science Annual, 71(4), 267–280. https://doi.org/10.37501/soilsa/131609

Kaczorek, K., Ledakowicz, S., 2005. Analiza pracy składowiska odpadów z punktu widzenia inżynierii bioreaktorowej. Biotechnologia 2(69), 69–87.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World Map of the Köppen-Geiger Climate Classification Updated. Meteorologische Zeitschrift 15, 259–263. https://doi.org/10.1127/0941-2948/2006/0130

Kutyna, I., Nieczkowska, M., 2009. Natural characteristics of the area of the former university of Agriculture in Szczecin situaded in Słowackiego and Papieża Pawła VI Streets and the information concerning the aim and methods of the research on the flora in this area. Folia Pomeranae Universitatis Technologiae Stetinensis. Agricultura, Alimentaria, Piscaria et Zootechnica 271 (10), 11–22.

Lins, E.A.M., Jucá, J.F.T., Mota, C.M., Lins, S., Mariana, M.O.H., 2020. Relationship of field capacity with geotechnical parameters in an urban solid waste landfill. American Scientific Research Journal of Engineering, Technology and Science 71(1), 99–122.

Mamak, M., Kicińska, A., 2016. The closing and remediation of the nonregulated landfills non-conforming with legal requirements after the joining of Poland to EU, on the example of a selected landfill at the territory of Nowy Sącz district. Zeszyty Naukowe Uniwersytetu Zielonogórskiego, Inżynieria Środowiska 162(42), 139–154.

Marcinek, J., Spychalski, M., 1987. The influence of organic matter content in hydromorphic soils on their physical properties Roczniki Akademii Rolniczej w Poznaniu. Melioracje 7, 19–33.

Mhaiske, V.M., Jain, A., 2019. Effect of tree plantations on soil organic carbon in Wardha coalfields of Maharashtra, India. International Journal of Farm Sciences 9(2), 65–71. https://doi.org/10.5958/2250-0499.2019.00045.4

Munsell Color, 2009. Munsell Soil Color Charts. Revised Edition. Grand Rapids, Michigan: Munsell Color, X-Rite, Inc.

Obianefo, F.U., Agbagwa, I.O., Tanee, F.B.G., 2017. Physicochemical characteristics of soil from selected solid waste dump sites in Port Harcourt, Rivers State, Nigeria. Journal of Applied Sciences and Environmental Management 21(6), 1153–1156. https://dx.doi.org/10.4314/jasem.v21i6.27

Ogbonna, D.N., Kii, B.L., Youdeowei, P.O., 2009. Some physico-chemical and heavy metal levels in soils of waste dumpsites in Port Harcourt Municipality and Environs. Journal of Applied Sciences and Environmental Management 13(4), 65–70. https://doi.org/10.4314/jasem.v13i4.55414

Pająk, W., 2022. Prognoza oddziaływania na środowisko Programu Ochrony Środowiska dla miasta i gminy Kórnik na lata 2022-2026. Dokumentacja Środowiskowa. Miasto i Gmina Kórnik, Plac Niepodległości 1, 62-035 Kórnik.

Peng, J., Liu, Z., 2019. Influence of temperature on microbially induced calcium carbonate precipitation for soil treatment. PLoS One 14(6), e0218396. https://doi.org/10.1371/journal.pone.0218396

PN-EN ISO 10390:2022-09. Soil quality - Determination of pH.

Polish Soil Classification, 2019. Polskie Towarzystwo Gleboznawcze, Komisja Genezy Klasyfikacji i Kartografii Gleb. Wydawnictwo Uniwersytetu Przyrodniczego we Wrocławiu, Polskie Towarzystwo Gleboznawcze, Wrocław - Warszawa.

Regulation of the Minister of the Environment of April 30, 2013, on waste landfills. https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20130000523

Saritha, V., Vuppala, N.S., Prashanthi, K., Anjum, A., 2014. Soil properties governed by municipal solid waste - contemporary and enduring. Agriculture and Soil Sciences 1, 42–49.

Siuta, J., 2004. Rekultywacja i zagospodarowanie terenu wysypiska odpadów komunalnych w Kawęczynie. Inżynieria Ekologiczna 9, 67–76.

Siuta, J., 2007. Odpady w rekultywacji gruntów. Inżynieria Ekologiczna 19, 59–78.

Soil Survey Division Staff, 1993. Soil Survey Manual. Soil Conservation Service. U.S. Department of Agriculture Handbook, 18.

Solly, E.F., Weber, V., Zimmermann, S., Walthert, L., Hagedorn, F., Schmidt, M.W., 2020. A critical evaluation of the relationship between the effective cation exchange capacity and soil organic carbon content in Swiss forest soils. Frontiers in Forests and Global Change 3, 98. https://doi.org/10.3389/ffgc.2020.00098

Solon, J., Borzyszkowski, J., Bidłasik, M., Richling, A., Badora, K., Balon, J., Brzezińska-Wójcik, T., Chabudziński, Ł., Dobrowolski, R., Grzegorczyk, I., Jodłowski, M., Kistowski, M., Kot, R., Krąż, P., Lechnio, J., Macias, A., Majchrowska, A., Malinowska, E., Migoń, P., Myga-Piątek, U.Z., Nita, J., Papińska, E., Rodzik, J., Strzyż, M., Terpiłowski, S., Ziaja, W., 2018. Physicogeographical mesoregions of Poland: Verification and adjustment of boundaries on the basis of contemporary spatial data. Geographia Polonica 91(2), 143–170. https://doi.org/10.7163/GPol.0115

Statistics Poland, 2010. Environmental Protection. Warsaw. https://stat.gov.pl/obszary-tematyczne/srodowisko-energia/srodowisko/ochrona-srodowiska-2010-r,1,9.html

Statistics Poland, 2016. Environmental Protection. Warsaw. https://stat.gov.pl/obszary-tematyczne/srodowisko-energia/srodowisko/ochrona-srodowiska-2016,1,17.html

Statistics Poland, 2024. Environmental Protection. Warsaw. https://stat.gov.pl/obszary-tematyczne/srodowisko-energia/srodowisko/ochrona-srodowiska-2024,1,25.html

Technical and Biological Reclamation Project of a Landfill for Non-Hazardous and Non-Inert Waste in Czmoń, Kórnik Municipality. As-Built Documentation, 2014.

Tudor, B.D., 2023. Studies and Research on Soil Analysis in a Derelict Area, where there Was a Landfill. The Annals of "Dunarea de Jos" University of Galati. Fascicle IX, Metallurgy and Materials Science 46(1), 41–46. https://doi.org/10.35219/mms.2023.1.07

Uzarowicz, Ł., Charzyński, P., Greinert, A., Hulisz, P., Kabała, C., Kusza, G., Kwasowski, W., Pędziwiatr, A., 2020. Studies of technogenic soils in

Poland: past, present, and future perspectives. Soil Science Annual, 71(4), 281–299. https://doi.org/10.37501/soilsa/131615

Ważny, K., 2015. Posadowienie składowiska odpadów inne niż niebezpieczne i obojętne w warunkach niekorzystnych. Rozprawa doktorska. https://www.dbc.wroc.pl/dlibra/publication/33379/edition/30242?language=pl

Weeks, O.L., Mansell, R.S., McCallister, S.W., 1992. Evaluation of soil topcover systems to minimize infiltration into a sanitary landfill: A case study. Environmental Geology and Water Sciences 20(2), 139–151.

Wick, A.F., Stahl, P.D., Ingram, L.J., 2009. Aggregate-associated carbon and nitrogen in reclaimed sandy loam soils. Soil Science Society of America Journal 73(6), 1852–1860. https://doi.org/10.2136/sssaj2008.0011

Wota, A., Wozniak, A., 2006. Logistyczne aspekty składowania odpadów komunalnych w województwie małopolskim. Infrastruktura i Ekologia Terenów Wiejskich 3(2).

Zhao, R., Gupta, A., Novak, J.T., Goldsmith, C.D., 2017. Evolution of nitrogen species in landfill leachates under various stabilization states. Waste Management 69, 225–231. https://doi.org/10.1016/j.wasman.2017.07.041

Zhou, G., Xu, S., Ciais, P., Manzoni, S., Fang, J., Yu, G., Chen, X., 2019. Climate and litter C/N ratio constrain soil organic carbon accumulation. National Science Review 6(4), 746–757. https://doi.org/10.1093/nsr/nwz045

Wpływ procesu rekultywacji oraz wystawy stoków na wybranie właściwości gleb na zrekultywowanym składowisku odpadów komunalnych w Czmoniu. Część I: podstawowe fizyczne i chemiczne właściwości gleb

Słowa kluczowe

Rekultywacja składowisk odpadów
Właściwości fizykochemiczne gleby
Gospodarka odpadami
Konstruktosole
Technosols
Zarządzanie terenami zdegradowanymi

Streszczenie

Dynamiczny rozwój cywilizacyjny i wzrost ilości odpadów komunalnych w Polsce wymusiły konieczność efektywnego zarządzania składowiskami odpadów oraz ich rekultywacji. W artykule przeanalizowano wpływ wystawy stoków, położenia na stoku i czasu jaki upłynął od zakończenia rekultywacji na wybrane właściwości fizykochemiczne powierzchniowych poziomów glebowych na zrekultywowanym składowisku w miejscowości Czmoń, w województwie wielkopolskim. Badania obejmowały analizy gleby w warstwach powierzchniowej (0–10 cm) i podpowierzchniowej (10–20 cm) w różnych częściach składowiska. Oznaczono między innymi uziarnienie, odczyn, zawartość węgla organicznego (TOC) i węglanu wapnia ($CaCO_3$) oraz pojemność sorpcyjną gleby (CEC). Na podstawie analizy statystycznej uzyskanych wyników, stwierdzono, że wymienione czynniki wpłynęły na zróżnicowanie właściwości gleby w zależności od wieku składowiska i orientacji stoków. Zgodnie z oczekiwaniami uziarnienie badanych gleb było związane bezpośrednio z działaniami rekultywacyjnymi. Gleby w obrębie nowej części składowiska charakteryzowały się wyższymi wartościami pH, CEC i zawartością $CaCO_3$. Gleby w obrębie starszej części składowiska cechowały się szerszym stosunkiem C/N. Stwierdzono także zależność pomiędzy ekspozycją badanych stoków (N – S), a wybranymi właściwościami gleb. Badania te podkreślają znaczenie dobrze zaprojektowanych działań rekultywacyjnych, które pozwalają na spełnienie funkcji biologicznej gleby utworzonej na tego typu składowiskach oraz ograniczenie negatywnego wpływu na środowisko. Badania te stanowią istotny wkład w rozwój wiedzy na temat długoterminowych efektów rekultywacji składowisk odpadów.