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CHEMICAL COMPOSITION OF LEACHATES FROM MUNICIPAL WASTE LANDFILLS IN SOUTHERN POLAND

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ABSTRACT

The aim of the study was the physicochemical characterization of leachates from two municipal waste landfills located in Upper Silesia (Tychy-Urbanowice and Świętochłowice). In the leachate samples from both locations, 19 key physicochemical parameters were determined. In order to assess the degree of contamination, the obtained concentrations were compared to the limit values for class III groundwater quality in Poland, calculating the Nemerow index for each parameter. The leachates are characterized by an alkaline reaction and a high value of specific electrolytic conductivity. The dominant pollutant in both cases is the ammonium ion, the concentration of which exceeds the class III standard by more than 900 times. Leachates from both tested landfills pose a threat to the environment, mainly due to the very high concentrations of ammonium ion and phosphates. The results of the index calculations emphasize the key role of the efficiency of landfill security systems and the need for constant monitoring to protect water resources.
Keywords: landfill leachate, municipal waste, water pollution, ammonium ion, phosphates, Nemerow index, Tychy, Świętochłowice.

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INTRODUCTION

Rapid population growth, progressive urbanization, and increasing consumerism are leading to a rise in the amount of municipal solid waste (MSW) generated. In 2016, global MSW production reached 2.01 billion tons, and forecasts indicate that it will increase to 3.4 billion tons by 2050 [1,2]. Landfilling remains the predominant form of waste disposal. It is estimated that approximately 70% of global waste management, especially in developing countries, consists of landfilling [3,4,5]. However, landfills pose a complex threat to the environment as they are a source of greenhouse gas emissions and also generate toxic landfill leachates.

Landfill leachates are multi-component substances formed as a result of the percolation of rainwater through the waste bed and as a consequence of complex biochemical processes occurring within it [6,7]. The chemical composition is related to the age of the landfill and the phases of anaerobic decomposition of organic matter [8]. In the initial period, leachates are characterized by a high content of volatile fatty acids (VFAs), high chemical oxygen demand (COD), and high biodegradability. As the landfill ages, humic substances begin to dominate in the leachates [9,10].

The threat from leachates is not limited to the aquatic environment. These substances, migrating from unsealed landfills, pose a serious risk to entire ecosystems. Infiltration of leachates into the soil leads to contamination, changing its physicochemical and biological properties, and also causing the bioaccumulation of heavy metals, among other things [18]. Numerous studies on the toxicity of leachates show a wide spectrum of negative effects on terrestrial organisms, including phytotoxicity and genotoxicity [18]. Contamination of groundwater and surface water is not only an environmental problem but also a health issue [12,13].

Emerging contaminants (ECs) are also identified in landfill leachates, including substances such as per- and polyfluoroalkyl substances (PFAS), microplastics, and pharmaceuticals and personal care products (PPCPs) [14,15]. These compounds can be present in leachates at various concentrations - from nanograms to micrograms per liter. It is worth emphasizing that they are characterized by high persistence in the environment, potential for bioaccumulation, and high toxicity. Particularly in the case of PFAS, it should be noted that they are practically non-removable in conventional treatment processes [14,15].

The chemical and toxicological complexity of these substances means that conventional methods for assessing leachate quality, based on summary physicochemical parameters (such as COD, BOD_5), may not be adequate for assessing environmental risk [16,17]. Legal requirements, such as the EU Landfill Directive 1999/31/EC, impose an obligation for long-term monitoring (the post-closure phase lasts 30 years), but this period may be insufficient to achieve full biochemical stabilization and the cessation of toxic substance emissions, especially in the context of persistent organic pollutants [18]. Unfortunately, such a broad spectrum of information about leachates is not always available, which is why assessments are based on typical physicochemical parameters [19]. Thanks to these parameters, it is possible to characterize the general potential contamination of the soil and water environment and decide on further research.

The aim of this article is to assess the quality of landfill leachates from two selected municipal waste landfills located in Upper Silesia (southern Poland). The values of the physicochemical parameters were compared to the applicable quality standards for groundwater, for which selected pollution indices were calculated.

STUDY AREA

Leachates were collected from municipal waste landfills located in Tychy-Urbanowice and Świętochłowice (southern Poland, Fig. 1). The landfill complex, managed by MASTER Sp. z o.o., is located in the eastern part of Tychy, in the Urbanowice district. The total area of the facility is 12.7 ha. The complex consists of a decommissioned, reclaimed landfill covering 3.5 ha and a newer, actively operated section comprising two sites (KW-1/1 and KW-1/2), a waste sorting plant, and a biogas recovery system [20]. The landfill area is characterized by a complex geological structure. The bedrock consists of Carboniferous formations (Łaziska strata), overlain by a complex of poorly permeable Miocene clays approximately 80 meters thick. This layer constitutes the key natural insulating barrier. Directly above the clays lie Quaternary sediments with a thickness of 12.5–17 m, developed mainly as various-grained sands and gravels. The groundwater table of the Quaternary aquifer is predominantly unconfined and stabilizes at a depth of 2 to 8 meters below ground level. The general direction of groundwater flow is southward, and the natural drainage base is the Gostynia River [21].

With regard to leachate migration prevention measures, the new sites were designed and constructed in accordance with current safety standards. Cell KW-1/1 (1994) features a double HDPE geomembrane liner and a triple drainage system (above-liner, inter-liner, and sub-liner). In KW-1/2 site, the base was sealed with a system consisting of a bentonite mat, an HDPE geomembrane, and a geotextile. Leachates from the new sites are collected by the drainage system and discharged to a wastewater treatment plant.

The Świętochłowice landfill was formed in 2001, with the end of operations planned for 2031. The geological profile includes Carboniferous, Triassic, and Quaternary formations. A key characteristic of this area is the high degree of environmental degradation caused by centuries of mining and industrial activity (metallurgical, chemical). Throughout the entire city, there is no natural, continuous insulating layer, which, combined with numerous surface contamination sources, creates a very high level of risk for groundwater. The aquifer horizons present here (Quaternary, Triassic, and Carboniferous) are significantly degraded and are not of utility character. No Major Groundwater Basins have been designated in the Świętochłowice area.

The primary barrier isolating the deposited waste from the subsoil is an advanced mineral-synthetic sealing system. In accordance with the permit, this structure consists of the following elements: an HDPE geomembrane with a thickness of 2 mm. To ensure stability on sloped surfaces, two types of geomembrane were used: smooth on the base and textured on the slopes. The geomembrane was laid on a suitably prepared, compacted subsoil with a levelling layer. It was covered

from above with a protective layer made of permeable (draining) materials, which protects it from mechanical damage. The drainage network was laid at the bottom of the sites. It was constructed from stoneware pipes and perforated PE and HDPE pipes laid with a 1% gradient towards the collection wells, ensuring gravitational flow of leachates (https://mpgk.eu/zaklad-gospodarki-odpadami#zgo-mapa).

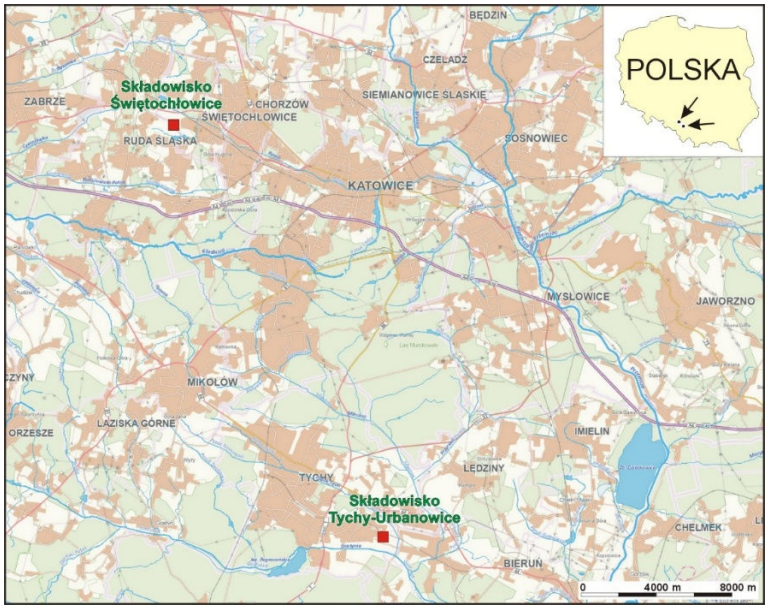


Fig. 1. Location of the study area.

METHODS

The quality analysis of the leachates was carried out on the basis of physicochemical tests for 19 parameters. The values considered were pH, conductivity, sulfates, chlorides, nitrates, ammonium ion, sulfur, calcium, sodium, potassium, magnesium, bicarbonates, phosphates, aluminum, copper, iron, manganese, nickel, and strontium. The degree of contamination was determined on the basis of the Nemerow Pollution Index [22]. As reference values for the calculations, the limit values for class III groundwater quality were used, based on the Regulation of the Minister of Maritime Economy and Inland Navigation of 11 October 2019 on the criteria and method of assessing the status of uniform bodies of groundwater (Journal of Laws 2019, item 2148). The choice of this quality class as the limit values was dictated by the fact that exceeding these values for groundwater results in their classification to class IV or V, which indicates poor chemical status.

The Nemerow Pollution Index (NPI) is calculated using the following formula:

$$NPI = \frac{C_i}{L_i}$$

where:
C*i* – measured value of the *i*-th parameter
L*i* – permissible value of the *i*-th parameter

An index value for a single parameter of < 1 suggests low contamination, a value from 1 to 3 indicates moderate contamination, a value from 3 to 6 indicates high contamination, and remaining values indicate very high contamination.

RESULTS AND DISCUSSION

Both leachate samples are characterized by an alkaline reaction, with pH values of 7.9 for Tychy and 8.4 for Świętochłowice, respectively. A common feature of both samples is also a very high specific electrolytic conductivity, reaching 12,000 µS/cm in the Tychy sample and 6,200 µS/cm in the Świętochłowice sample. The chemical composition of both leachates is typical of mature landfills. The dominant pollutant is ammonium nitrogen (NH_4), the concentration of which in the Tychy leachate is 990 mg/l, and in the Świętochłowice leachate 464.4 mg/l. Furthermore, very high concentrations of other ions were found in both samples, such as bicarbonates (HCO_3), potassium (K), sodium (Na), and chlorides (Cl). The Świętochłowice sample stands out from the Tychy sample with a tenfold higher concentration of phosphates (PO_4), amounting to 79 mg/l (Table 1).

Tab. 1

Summary of source data and calculated NPI index values.

Parameter	Unit	Boundary III class	Tychy	NPI Tychy	Class	Święt.	NPI Święt.	Class
pH	pH	6,5–9,5	7.9	0.07	I–III	8.4	0.27	I–III
EC	µS/cm	2500	12000	4.80	V	6200	2.48	V
SO4	mg/l	250	733	2.93	V	482	1.93	IV
Cl	mg/l	250	1800	7.20	V	950	3.80	V
PO4	mg/l	1	8	8.00	V	79	79.00	V
NH4	mg/l	1.0	990	990.00	V	464.4	464.40	V
NO3	mg/l	50	170	3.40	V	14.2	0.28	≤ III
HCO3	mg/l	500	5800	11.60	V	2500	5.00	V
Al	mg/l	0.2	0.89	4.45	IV	0.17	0.85	≤ III
Cu	mg/l	0.2	0.082	0.41	≤ III	0.01	0.05	≤ III
Fe	mg/l	5	3.6	0.72	≤ III	0.59	0.12	≤ III
Mn	mg/l	0.4	0.75	1.88	IV	0.67	1.68	IV
Mg	mg/l	100	200	2.00	V	200	2.00	V
Ni	mg/l	0.02	0.093	4.65	IV	0.08	4.00	IV
Ca	mg/l	200	180	0.90	≤ III	120	0.60	≤ III
K	mg/l	15	1000	66.67	V	470	31.33	V

Parameter	Unit	Boundary III class	Tychy	NPI Tychy	Class	Święt.	NPI Święt.	Class
Na	mg/l	200	1600	8.00	V	750	3.75	V

In the case of leachates from Tychy-Urbanowice, as many as 13 out of 16 analyzed parameters exceeded the permissible values. The greatest exceedance was recorded for the ammonium ion (NH_4), the concentration of which was 990 times higher than the standard. Very high indices were also obtained for potassium (66.7), bicarbonates (11.6), phosphates (8.0), and sodium (8.0). For the leachates from Świętochłowice, 11 out of 16 parameters exceeded the standards. In this case, the dominant pollutant also proved to be the ammonium ion, with an index of 464.4. High index values were also observed for phosphates (79.0). Significant exceedances were also recorded for potassium and bicarbonates. It is worth noting that in both samples, the concentrations of copper, iron, and calcium did not exceed the limit values for class III groundwater quality.

The ammonium ion is regarded as a major threat to the soil and water environment. It is also a significant problem when this ion migrates to surface waters due to its high toxicity and negative impact on living organisms. It is worth mentioning that nitrogen is a key nutrient. Its rapid influx into surface waters leads to intense algal and cyanobacterial blooms. The decomposition of dead organic matter from blooms consumes dissolved oxygen in the water, leading to the formation of anoxic zones in which aerobic life perishes [23].

Chlorides are identified as a typical indicator of groundwater contamination from municipal waste. They are classified among the most mobile ions in the aquatic environment. The main sources of chloride contamination beyond landfills include road salts used for winter road maintenance and agricultural fertilizers containing potassium chloride. An excess of chlorides in freshwater ecosystems, referred to as freshwater salinization, leads to a range of negative environmental consequences. Increased salinity disrupts the water-electrolyte balance of ecosystems, causing osmotic stress [24]. Chloride ions can also displace metal ions (e.g., cadmium, lead) bound to bottom sediments, increasing their bioavailability and toxicity.

In the case of phosphates in landfill leachates, detergents should be identified as the primary source. The most significant consequence of excess phosphates in water is eutrophication. An excessive influx of phosphates causes algal and cyanobacterial blooms, a decrease in dissolved oxygen concentration (hypoxia) or its complete disappearance (anoxia), especially in the near-bottom zone, which leads to mass die-offs of aerobic organisms such as fish and invertebrates, and may also lead to the release of other toxins [25].

Municipal waste also includes spent batteries, electronics, paints, accumulators, and metal packaging. Such waste is a source of heavy metals that are leached into the leachate. These metals include lead, cadmium, mercury, nickel, zinc, and copper. The analysis of the described samples did not cover all of these components; however, previous studies conducted at the Tychy-Urbanowice landfill did not indicate significant exceedances for these parameters [20,21].

The pH values of both tested samples fall within the range typical of leachates from landfills in the methanogenesis phase [18]. However, the electrolytic conductivity (EC) of both samples is clearly higher than the values reported in the literature for Polish landfills. The conductivity exceeds the maximum values reported for active Lower Silesian landfills (up to 11,370 μS/cm) [26]. The NH_4^+ concentration in the Tychy sample is considerably higher compared to values for other landfills in Poland. For example, at landfills located in the Lower Silesian Voivodeship, this value did not exceed 800 mg/l [26]. The European average for this parameter is 526 mg/l [27]. Chloride values are typical for municipal landfills. Active landfills generate leachates with chloride content in the range of 853–2,670 mg/l [28].

CONCLUSIONS

The analyzed leachate samples from both landfills allow for a preliminary assessment of the potential threat to the aquatic environment. The chemical composition of both samples is typical of leachates from mature, long-standing landfills in the methanogenesis phase, as confirmed by the alkaline reaction and high conductivity values. Comparing the concentrations of individual parameters to the limit values for class III groundwater quality revealed exceedances of the standards for the majority of the analyzed indicators. The key and dominant pollutant in both cases proved to be the ammonium ion. A comparison of the obtained results with literature data for other landfills in Poland and Europe confirmed that the studied leachates are among the more contaminated ones. It is worth noting, however, that both facilities have a leachate collection system, which directs the leachates to treatment.

In further research, attention should be paid to other parameters, such as per- and polyfluoroalkyl substances, microplastics, and pharmaceuticals and personal care products, the content of which may help to determine more effective methods of leachate treatment.

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