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A comparative analysis of leachate quality from municipal solid waste landfills: case studies from Poland and the Czech Republic

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ABSTRACT

This study presents a comprehensive analysis of quality of leachate generated in selected municipal solid waste (MSW) landfills located in Poland and the Czech Republic, differing in terms of technical management and site conditions. On the basis of a long-term monitoring period, the leachate samples were characterized regarding their basic physico-chemical parameters and variations in time. Moreover, the leachate contamination potential was assessed using leachate pollution index (LPI). The results demonstrated that the leachate characteristics can vary widely depending on the sampling location and the landfill age. The effect of landfill age was indicated by the relationships between Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) parameters. Statistical analyses were also performed in order to track existing relationships between monitored parameters of leachate quality. This study proved that it is justified to evaluate physico-chemical characteristics of landfill leachate during different seasons in a monitoring period to assess reliably their possible impact on the environment. Finally, the suggestions and recommendations were delineated regarding the possible treatment of leachate and their management in aspect of environmental protection needs.

Keywords: leachate, waste management, environmental assessment, leachate pollution index

1 INTRODUCTION

The landfills are found as objects, which, even properly designed and managed, may cause negative impact on the environment. As found by Madon et al. (2019), after a long-term operation of a sanitary landfill, the deterioration of isolation layers and failure of the drainage system may occur, resulting in the release of contaminants to the environment. The major hazard related to landfilling is leachate, produced mainly as an effect of percolation of rainfall through the landfill body and biochemical reactions in waste layers. The leachate is a wastewater with significant content of organic and inorganic pollutants. All of the leachate constituents may negatively impact the environment, as most of them are toxic, persistent and able to degrade components of the natural environment. The composition of leachate is influenced by several factors, i.e. types and morphology of wastes, moisture content of wastes, climatic conditions, techniques of landfill operation and landfill age (Ololade et al., 2019). It was also reported that the landfill and its effluents may induce ecological and health risk toward ecosystems (Li et al., 2010). A comprehensive assessment of leachate quality is required for the purpose of their proper treatment. Moreover, to protect the environment and human health, the knowledge of physical, chemical and biological features of the leachate is crucial for its further management (Siddiqi et al., 2022). Considering the complexity of the landfilling and its side effects, it must be highlighted that there is a real need for scientific research worldwide dedicated to the assessment of characteristics of the leachate and their polluting potential in aspect of a sustainable landfills and waste management.

In relation to the above, the presented research aimed to investigate: a) characteristics of leachate from selected landfills in Poland and the Czech Republic, b) changes of the leachate parameters over time, c) polluting potential of the leachate, d) interrelationships between the leachate parameters.

2 MATERIALS AND METHODS

2.1 Study areas

The Radiowo landfill (52°16′37″ N, 20°52′45″ E) is located in the commune Stare Babice and partially in Warsaw, Poland. The landfill covers an area of approximately 16 ha, and its altitude is approximately 60 m. The landfill is surrounded by Forest Park Bemowo and Nature Reserves from the south and east sides. From the north side, the landfill is adjacent to a composting plant located in the Warsaw–Bielany District. On the west side, in the vicinity of the landfill slope, there are industrial facilities (Fig. 1). The landfill was constructed in the early 1960s when no legal restrictions, regarding location and environmental issues, were taken into consideration. The Radiowo landfill was utilized for disposal of the municipal wastes from Warsaw in the period 1962–1991. Since 1992, the landfill has become a technological facility for the storage of the so-called ballast wastes from the Radiowo composting plant. At that time, plastics, foils, textiles, metal scraps and organic wastes (approximately 5%) were disposed at the landfill. Initially, the protection system against the contamination was not applied at the landfill site. Since 1994, the reclamation works have been implemented. The solutions of stability improvement were introduced, and also the mineral capping, planting of slopes, and installation of drainage and recirculation systems were applied. One of the most important solutions introduced at the landfill, as part of reclamation works, was the installation of bentonite cut-off wall. The function of the cut-off wall was to minimize the spread of contaminants to the soil–water environment. The cut-off wall of a width 0.6 m was installed at a depth of 2 m below the top of the clayey soils, at the level 3.5–22 m below the surface. The permeability of the vertical barrier was below 10^{-9} m/s (Podlasek et al., 2021). The landfill has been finally closed in 2018 after technical reclamation (Koda et al., 2022).



Figure 1. *Location of the tested landfills and their neighbourhood.*

The Petrůvky landfill (49°10’03.4” N 15°54’04.8” E) is located in the south to southeast part of Vysočina region, 8 km from Třebíč, Czech Republic (Lichovníková et al., 2015). From the southwest and west side the landfill is surrounded by the meadow. There is also an unpaved road formed between the boundary of the landfill and the meadow. At the north and northeastern side the landfill is adjacent to the forest (Fig. 1). The landfill started its operation in 1994, and is classified as S-OO3 (receives “other wastes” with significant content of biodegradable compounds). The area of the Petrůvky landfill is around 7.2 ha. The total amount of wastes stored at that landfill is 31,000 Mg·year^{-1}, and the total volume of the landfill is 600,000 m^3. The landfill was designed with eight cells for waste storage, serving an area of 118,000 inhabitants. The landfill was constructed with the aim to be used for 17 years. The landfill is divided into sections. Currently, storage has started on the eighth section with an area of 1.9 ha, the capacity of which is 260,000 m^3, thus extending the life of the landfill until 2024. The Petrůvky landfill was designed as a sanitary landfill with base sealing system and top cover systems consisting of several protective layers, including HDPE geomembrane and soil layers (Podlasek et al., 2022, Vaverkova et al., 2022). At present, five sections have already been reclaimed, the reclamation of sections sixth and seventh is being prepared. Reclamation works consist of shaping the landfill slopes, laying a drainage layer, geotextile, sealing geomembrane, drainage layer, geotextile, and top layer of soil. Landfill gas from reclaimed sections is used for the needs of a cogeneration unit that supplies electricity to the power grid.

2.2 Sampling and chemical analysis

The scope of the monitoring and analysed leachate parameters was based on the requirements presented in the legal acts. The analysis of the quality of leachates from the Radiowo landfill was based on the results of tests carried out for samples collected four times a year in the period 2015-2017 and twice a year in the period 2018-2019. The measurements in 2015-2017 were conducted in spring (March/May), late summer (September) and autumn (November). The measurements in 2018-2019 were conducted in late spring or early summer (June) and in autumn (November). The leachate tests from the Petrůvky landfill were carried out twice a year, in spring (March/April) and in late summer or autumn (September/October). The leachate from the Radiowo landfill was taken for the analysis from the west pumping station, whereas the leachate from the Petrůvky landfill was collected from the leachate pond. In the Radiowo landfill, the following indicators were measured: electrical conductivity (EC), pH, lead (Pb), cadmium (Cd), copper (Cu), zinc (Zn), chromium VI (Cr^{6+}), mercury (Hg), total organic carbon (TOC), polycyclic aromatic hydrocarbons (PAHs), ammonium (NH_4^+), chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), chlorides (Cl^-) and sulphates (SO_4^{2-}). In the Petrůvky landfill, the monitoring indicators were: pH, EC, cyanides (CN^-), phenol index (PI), arsenic (As), Cd, total chromium (Cr_{tot}), nickel (Ni), Pb, selenium (Se) and Hg. The samples were collected in accordance with the technical guidelines presented in PN-ISO 5667-10 (2021). For the current study each set of the monitoring data represents the mean of several measurements performed in the monitoring points. Chemical analyses of selected indicators were performed in accordance with the procedures applied by the external accredited laboratory. The quality of leachate was assessed regarding permissible values of pollution indicators reported in the Announcement of the Ministry of Infrastructure and Construction (2016), the Regulation of the Ministry of Marine Economy and Inland Navigation (2019) and guidelines for effluent limitations reported by United States Environmental Protection Agency (US EPA, 2022) (Table 1).

Table 1. *Limit values for the leachate discharge.*

Source	Announcement of the Ministry of Infrastructure and Construction (2016)[a]	Regulation of the Ministry of Marine Economy and Inland Navigation (2019)[b]	US EPA (2022)[c]
Parameters:			
pH	6.5-9.5 or 8-10[d]	6.5-9.5	6-9[e, f]
Pb	1.0	0.5	-
Cd	0.4[g]	0.4[g]	-
Cu	1.0	0.5	-
Zn	5.0	2.0	0.2[e] or 0.11[f]
Cr^{6+}	0.2	0.1	-
Hg	0.06[g]	0.06[g]	-
TOC	[h]	30.0	-
PAH	0.2	-	-
NH_4^+	100[i] or 200[j]	10.0	10[e] or 4.9[f]
COD	[h]	125.0	-
BOD_5	[h]	25.0	140[e] or 375[f]
Cl^-	1,000.0	1,000.0	-
SO_4^{2-}	500.0	500.0	-

[a] Limit values of pollution indicators for some substances particularly harmful to the aquatic environment in industrial wastewater discharged into sewage devices, [b] Limit values of pollutants for wastewater and rainwater or meltwater discharged into water and soil, [c] Effluent limitations regarding non-hazardous waste landfill, [d] Applies to wastewater containing cyanides and sulphides, [e] Daily maximum, [f] Maximum monthly average, [g] Daily average, [h] The values of the indicators should be determined on the basis of the permissible load of these pollutants on the treatment plant, [i] Applies to wastewater discharged to treatment plants for agglomerations with an equivalent number of inhabitants <5000, [j] Applies to wastewater discharged to treatment plants for agglomerations with an equivalent number of inhabitants ≥5000. Concentrations of indicators expressed in mg/L, with the exception of pH (unitless).

2.3 Leachate Pollution Index

For assessing the leachate pollution potential of analysed landfill, the Leachate Pollution Index (LPI) was applied. The approach of LPI calculation was adopted from Kumar and Allapat (2005), using the formula:

$$LPI = \sum_{i=1}^{m} w_i \times p_i / \sum_{i=1}^{m} w_i \quad (1)$$

where m is parameter of leachate quality, w_i is weight of the leachate parameter, p_i is sub-index score.

2.4 Statistical analysis

The results of leachate quality from both landfills were subjected to statistical analysis using Statistica 12 software (StatSoft Inc., Tulsa, OK, USA). To determine the relationships between the parameters of the leachate, the Pearson's correlation coefficients (r) were calculated. Following the scale presented by Schobber et al. (2018), the interpretation included: negligible correlation (r = 0.00–0.09), weak correlation (r = 0.10–0.39), moderate correlation (r = 0.40–0.69), strong correlation (r = 0.70–0.89), very strong correlation (r = 0.90–1.00).

3 RESULTS AND DISCUSSION

The results of performed analysis indicate that for the Radiowo landfill, the pH of leachate is quite stable in time (Figure 2).

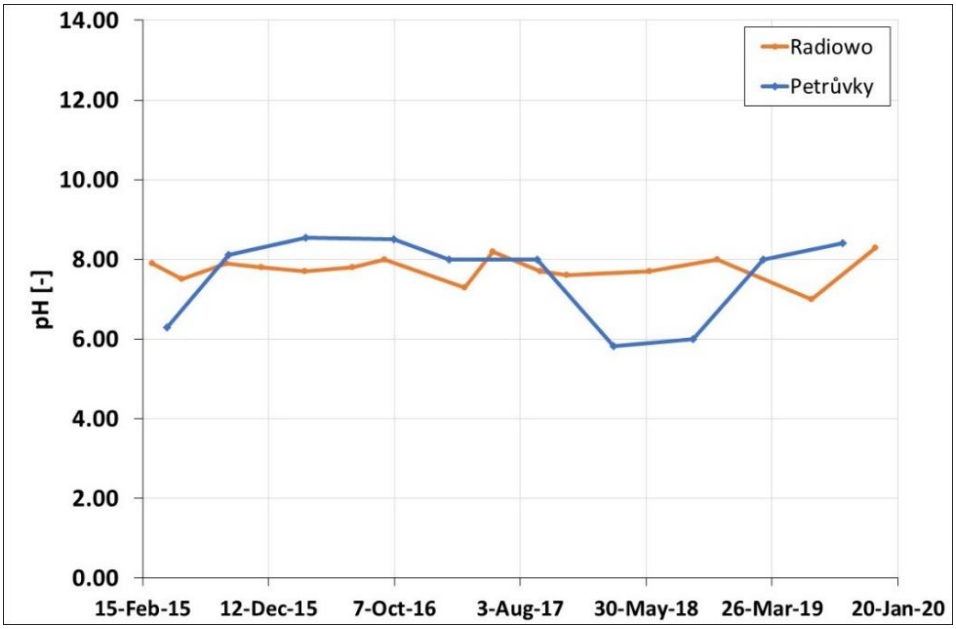


Figure 2. *Temporal changes of pH in the leachate.*

The minimum, maximum and average value of pH were 7.0, 8.3, and 7.8, respectively. Regarding these values, it can be concluded that in terms of pH, the leachate from the Radiowo landfill is in range accepted for the discharge into sewage devices, water and soil, and also meets the criteria set for the effluent limitations from non-hazardous waste landfills. For the Petrůvky landfill, the minimum, maximum, and average values of pH were 5.8, 8.6, 7.6, respectively. The average value of pH measured in the leachate during the monitoring period was in accordance with the requirements presented in environmental standards (Table 1). The average values of pH measured for analyzed landfills were similar and indicated alkaline character of the leachate. It may also suggest that for both landfill, the wastes are in mature stage (Podlasek et al., 2023). Similar observations were presented by Bhalla et al. (2013) who found that leachate of an old landfill has pH higher than 7.5.

The results presenting the changes of EC in leachate over time indicate that this parameter was highly variable for both monitored landfills (Figure 3).

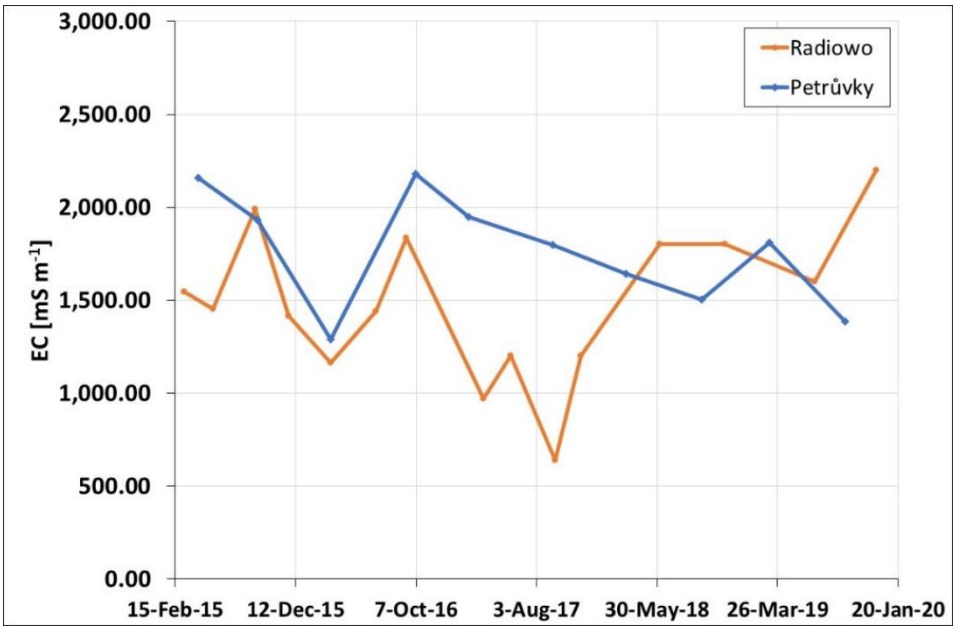


Figure 3. *Temporal changes of EC in the leachate.*

The minimum, maximum, and average values of EC for the Radiowo landfill were 1290 mS/m, 2180 mS/m and 1484 mS/m, respectively. For the Petrůvky landfill, the minimum, maximum, and average values of this parameter were 640 mS/m, 2200 mS/m, and 1765 mS/m. The ranges of observed values of EC parameter are consistent with the EC values reported for municipal solid waste landfills (Guérin et al., 2004). High levels of EC measured in the leachate from both landfills may be correlated with the presence of calcium (Ca), sodium (Na), magnesium (Mg) and potassium (K) ions (Li et al., 2010).

In terms of the Pb concentrations in the leachate, it was found that for both analysed landfills, observed values are lower than the limits presented in environmental law (Table 1). For both landfills, also the stabilization of Pb concentrations is visible during the last three years of monitoring period (Figure 4). Also for Cd (Figure 5), the concentrations measured in the leachate samples were very low and stabilized in recent years of monitoring.

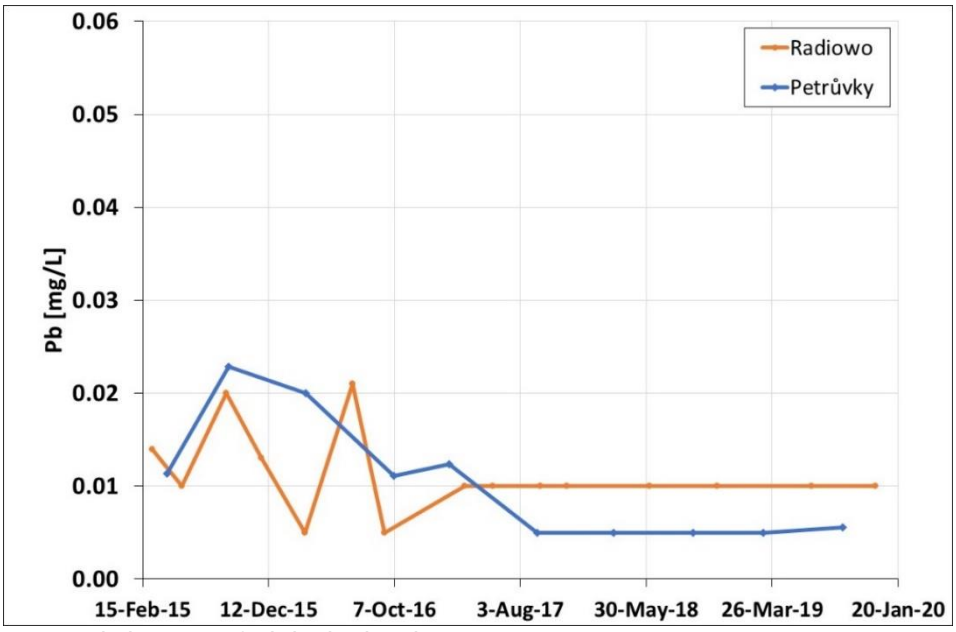


Figure 4. *Temporal changes of Pb in the leachate.*

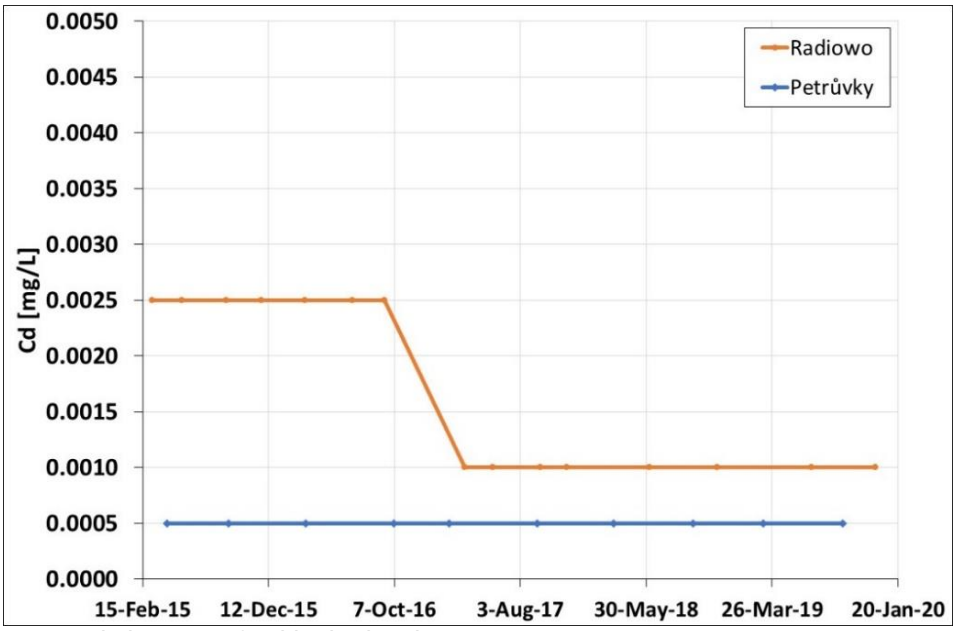


Figure 5. *Temporal changes of Cd in the leachate.*

For the Radiowo landfill, it was observed that the concentrations of Hg in leachate had increasing trend and then stabilized (Figure 6). For the Petrůvky landfill, the concentrations of Hg were stable in time. For both landfills, observed vales were substantially lower than the limits sets for the discharge of the leachate to the sewage systems, water and soil. In the presented research, low values of heavy metals in the leachate may indicate the methanogenic phase of the landfill (Kulikowska and Klimiuk, 2008). Low concentrations of heavy metals measured in the Radiowo and Petrůvky are typical for later stage of the waste decomposition (Bhalla et al., 2013, Podlasek et al., 2023).

In order to evaluate the pollution potential of leachate from the Radiowo and Petrůvky landfills, the LPI values were determined. For the Radiowo landfill, the minimum, maximum, and average values of LPI were 10.7, 22.5, and 18.5, respectively. The leachate from the Petrůvky landfill was characterized by the following minimum, maximum, and average values of LPI: 5.0, 18.2, 6.9, respectively. According to Singh et al. (2016), the value of LPI higher than 35 suggests poor environmental quality. In the analysed case of the Radiowo and Petrůvky landfills, this value was not exceeded. It was also found that due to the stabilization of wastes, the LPI values tend to decrease over time (Naveen, 2017). Nevertheless, this trend was not observed in the analysed landfills (Figure 7).

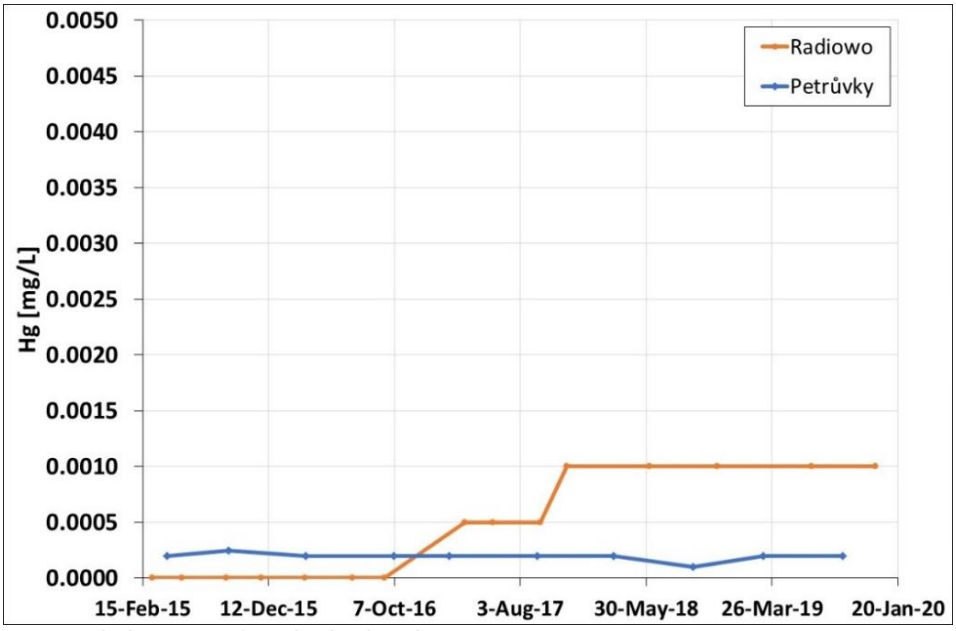


Figure 6. *Temporal changes of Hg in the leachate.*

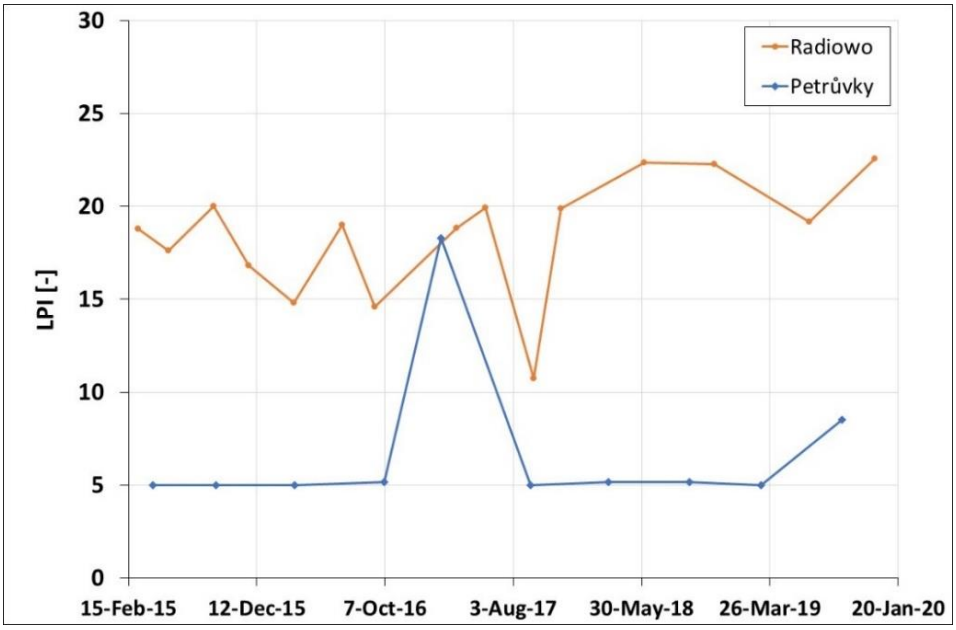


Figure 7. *Temporal changes of LPI.*

According to Kumar and Allapat (2005), the allowable limit for the disposal of treated leachate to the surface water is LPI=7.378. For the Radiowo landfill, the LPI values were higher during the entire monitoring period. For the Petrůvky landfill, this value was exceeded only twice, and the average value of LPI was below the LPI=7.378. These findings may suggest that the leachate from the Radiowo landfill has higher potential to be source of pollution in comparison to the Petrůvky landfill.

An attempt was also made to assess the phase of waste decomposition in the landfill using the ratio of BOD_5/COD. This assessment was performed only for the Radiowo landfill because in the Petrůvky landfill BOD_5 and COD were not monitored. The minimum, maximum, and average ratio of BOD_5/COD measured in the leachate from the Radiowo landfill were: 0.02, 0.34, and 0.16, respectively. These values are characteristic for transitional phase in which the ratio of BOD_5/COD is in the range 0.1–0.4 (Ehrig and Stegmann, 2018). Another ratio taken into consideration during the assessment of leachate from the Radiowo landfill was TOC/COD. In the presented research, it was indicated that the range of this ratio is 5.96-19.13, and the average is 12.43. These values are characteristic for the leachate of an old landfill (TOC/COD>0.5) (Teng et al., 2021). Also, in terms of NH_4^+ concentrations (on average 900 mg/L), the leachate from the Radiowo landfill can be classified as typical for old landfills (400-900 mg/L), according to Gomez et al. (2019). The results indicate that the lack of the above-mentioned parameters in the scope of the monitoring of the Petrůvky landfill reduces the accuracy of the leachate quality recognition and the selection of the appropriate method of their treatment. Especially, when it is known that the ratio of BOD_5/COD is crucial tool to decide whether biological or physicochemical treatment techniques will be more effective (Abunama et al., 2021). When choosing the proper treatment method it should be noted that low vales of BOD_5/COD ratio is a confirmation of the occurrence of non-biodegradable organic compounds which are not prone to biological degradation (Bhalla et al., 2013).

To estimate the degree of association between the parameters of leachate, the correlation analysis was performed. This analysis, according to many studies (Durmusoglu & Yilmaz, 2006; de Medeiros Engelmann, 2017; Naveen et al., 2017; Abunama et al., 2021), is found as a preliminary technique used for this purpose. For the Radiowo landfill, statistically significant correlations between parameters were found (Table 2). Strong positive correlations were measured between EC and TOC, EC and COD, EC and Cl^-, Cu and Zn, Hg and BOD_5. Strong negative correlations occurred between Cd and BOD_5, Cd and SO_4^{2-}. Moderate positive correlations were found between Pb and Zn, Hg and NH_4^+, Hg and Cl^-, TOC and Cl^-, PAH and Cl^-, NH_4^+ and COD, NH_4^+ and BOD_5, NH_4^+ and Cl^-, COD and BOD_5, COD and Cl^-, BOD_5 and SO_4^{2-}. For the Petrůvky landfill, strong positive correlations were calculated only between EC and Cr_{tot}, EC and Ni, Cr_{tot} and Ni (Table 3). For both analysed landfills, negligible or weak correlations were not statistically significant.

Table 2. *Correlation matrix between leachate parameters of the Radiowo landfill.*

r	pH	EC	Pb	Cd	Cu	Zn	Cr^{6+}	Hg	TOC	PAH	NH_4^+	COD	BOD_5	Cl^-	SO_4^{2-}
pH	1.00														
EC	0.40	1.00													
Pb	0.08	0.18	1.00												
Cd	0.12	0.16	0.30	1.00											
Cu	0.28	0.11	0.47	0.43	1.00										
Zn	0.33	0.17	**0.57**	0.42	**0.78**	1.00									
Cr^{6+}	-0.53	-0.47	-0.10	-0.41	-0.14	-0.07	1.00								
Hg	-0.09	0.42	-0.20	**-0.66**	-0.39	-0.39	-0.05	1.00							
TOC	0.23	**0.87**	0.35	0.20	0.18	0.17	-0.33	0.28	1.00						
PAH	0.45	0.48	-0.07	-0.25	-0.28	-0.14	-0.05	0.38	0.30	1.00					
NH_4^+	0.17	0.44	0.10	-0.47	-0.06	-0.12	-0.40	**0.58**	0.38	0.30	1.00				
COD	0.29	**0.70**	0.18	-0.15	0.06	0.22	-0.39	0.45	**0.57**	0.16	**0.61**	1.00			
BOD_5	-0.02	0.24	-0.25	**-0.86**	-0.34	-0.30	0.07	**0.85**	0.12	0.27	**0.69**	**0.59**	1.00		
Cl^-	0.41	**0.77**	0.31	-0.18	0.24	0.09	-0.37	**0.54**	**0.67**	**0.53**	**0.65**	**0.52**	0.39	1.00	
SO_4^{2-}	-0.34	**-0.53**	-0.24	**-0.78**	-0.17	-0.26	0.45	0.27	**-0.52**	-0.28	0.23	0.00	**0.58**	-0.18	1.00

Bolded values of correlation coefficient (r) are significant at the level of $p < 0.05$

Table 3. *Correlation matrix between leachate parameters of the Petrůvky landfill.*

r	pH	EC	CN	Pl	As	Cd	Cr_{tot}	Ni	Pb	Se	Hg
pH	1.00										
EC	-0.02	1.00									
CN	0.21	0.08	1.00								
Pl	0.27	-0.44	0.20	1.00							
As	0.50	-0.36	-0.31	0.47	1.00						
Cd	0.00	0.00	0.00	0.00	0.00	1.00					
Cr_{tot}	0.30	**0.87**	0.04	-0.07	-0.11	0.00	1.00				
Ni	0.34	**0.84**	0.27	-0.38	-0.20	0.00	**0.81**	1.00			
Pb	0.40	0.11	-0.04	-0.26	0.32	0.00	0.14	0.50	1.00		
Se	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	
Hg	0.51	0.34	0.00	0.05	0.36	0.00	0.47	0.45	0.53	0.00	1.00

Bolded values of correlation coefficient (r) are significant at the level of $p < 0.05$

4 CONCLUSIONS

Based on the findings presented in this research, it can be concluded that the major aspect in proper leachate management and treatment should be always connected with prior comprehensive analysis of the leachate characteristics. The recognition of leachate characteristics also clearly indicate the existing risk resulting from the leachate formation. For the purpose of a complete assessment of the leachate quality, LPI index should be considered as a crucial tool in the evaluation of the leachate pollution potential. In case of analysed landfills, based on the LPI, it was indicated that the leachate cannot be discharged without prior treatment. Significant outcome of this study is also the recognition of the leachate parameters, interrelationships between them and variations over time. Taking into account the variability of leachate parameters over time is important for the selection of an appropriate method of leachate treatment at various stages of the landfill operation.

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