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READING BETWEEN THE WASTE: CORRELATION ANALYSIS OF INORGANIC POLLUTION IN LANDFILLS

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Abstract: Landfills represent one of the most prevalent sources of inorganic pollution, with leachates carrying a complex mixture of dissolved ions and trace elements that can migrate into surrounding soils and groundwater. Understanding the relationships among these contaminants is crucial for evaluating environmental risks and designing effective monitoring strategies. Collected leachate samples stem from a landfill in northern Serbia and were analyzed for a range of inorganic parameters. Using the Spearman rank correlation analysis, it was confirmed that there are four strong positive correlations between different parameters (Chemical Oxygen Demand/Total Kjeldahl Nitrogen, Total Kjeldahl Nitrogen/Ammonia Nitrogen, Chemical Oxygen Demand/Chromium and Chromium/Total Kjeldahl Nitrogen). Furthermore, there were two moderate positive correlations (Total Dissolved Solids/Total Kjeldahl Nitrogen and Nickel/ Chemical Oxygen Demand). These correlations provide additional insight into secondary interactions, dilution effects, and environmental transformations happening within the landfill body. This research emphasizes the value of statistical approaches in environmental assessment, where the showcasing and interpretation of links between pollutants can be used to support sustainable waste management and protection of water resources.
Keywords: statistical assessment, leachate quality, inorganic indicators, environmental monitoring

INTRODUCTION

In most developing countries, landfill deposition represents the principal approach to municipal solid waste management. A major drawback of this type of waste management is that the infiltration of rainwater through the landfill produces a highly polluted effluent loaded with organic and inorganic substances [1, 2, 3]. A combination of microbial, chemical, and physical processes within the landfill matrix facilitates the transfer of contaminants from municipal solid waste into percolating or infiltrating water. Most landfill receives a great amount of municipal, commercial, as well as mixed industrial waste all together disposed of in one place. They all contribute to forming significant amounts of leachates as well as the contamination of groundwater [4]. The production of the leachate is an important environmental problem.

The quantity and quality of leachate generated from landfills are influenced by numerous interacting factors, including annual precipitation, runoff, infiltration, evaporation, transpiration, ambient temperature, waste composition and density, initial moisture content, and landfill depth [5, 6, 7, 8, 9]. It is imperative to consider these factors when assessing the potential environmental risks associated with landfills and designing appropriate mitigation measures. The characteristics of the leachate also depend on the pre-treatment of the solid waste, such as separation of recyclable materials (such as plastics, paper, metals, glass, etc.), shredding and/or bailing of the waste. However, it always has a high content of suspended and dissolved matter, which makes it a dangerous pollutant that needs to be treated. Additionally, it has the potential to contaminate aquifers, rivers, and soil, posing risk to natural ecosystems, and public health [5].

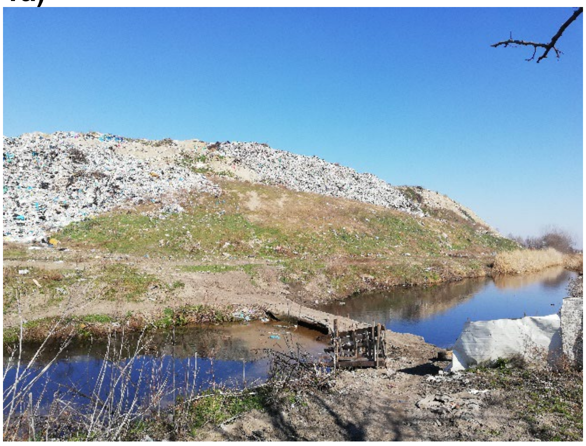
This study aimed to enhance the understanding of the links between the various inorganic parameters in landfill leachate, focusing on exemplary landfills located in Vojvodina region. The findings will provide valuable insights into chemical mechanisms within the landfill body, which ultimately will serve as a guide to future monitoring programs related to unsanitary landfills and their impact on the environment and surrounding population.

MATERIAL AND METHODS

Sampling and analysis

The Novi Sad landfill, a controlled yet non-sanitary landfill, began operations in 1983 and is situated in the northern region of Novi Sad, Serbia. It is located 800 meters away from the nearest residential area and 7 kilometers away from the city center. Waste disposal is divided into three sections on the site. Though the landfill is controlled, it lacks a leachate collection system. The leachate sampling was conducted from a peripheral canal (S1: 45°18'39.33", 19°50'43.25", Figure 1a) and leachate lagoon (S2: 45°18'45.65", 19°50'54.40", Figure 1b). To account for seasonal variation, three sampling campaigns were conducted in 2022, specifically in February, May, and November, resulting in the collection of a total of 6 representative samples.

1a)



1b)

Fig. 1. *Sampling locations in Novi Sad (1a – peripheral canal, 1b – leachate lagoon)*

Determination of physico-chemical indicators

All physicochemical analysis were carried out in the Laboratory for Environmental and Occupational Monitoring, Department of Environmental Engineering and Occupational Safety and Health, Faculty of Technical Sciences, University of Novi Sad**.** For the purposes of this study, the parameters that were examined were: chemical oxygen demand (COD), biological oxygen demand (BOD_5), BOD_5/COD ratio, Total Kjeldahl Nitrogen (TKN) and ammonia nitrogen (AN) and seven heavy metals: hexavalent chromium (Cr^{6+}), iron (Fe), zinc (Zn), nickel (Ni), lead (Pb), manganese (Mn), and copper (Cu). The physico-chemical parameters were determined utilizing standard laboratory EPA and HACH procedures.

Spearman rank correlation

The Spearman correlation is a non-parametric measure of rank correlation that assesses how well the relationship between two variables can be described using a monotonic function. A monotonic relationship is one where the variables tend to change together, but not necessarily at a constant rate. It can be used for relationships that are linear or non-linear [10]. The Spearman correlation coefficient, denoted as ρ, ranges from -1 to 1:

- $\rho = 1$: Perfect positive monotonic relationship.
- $\rho = -1$: Perfect negative monotonic relationship.
- $\rho = 0$: No monotonic relationship.

The IBM SPSS program was employed to determine the strength of the correlation among the examined parameters.

RESULTS AND DISCUSSION

Inorganic parameters

Selected parameters of interest for leachate characterization are shown in Table 1 and 2. In addition, as an important parameter for estimation of leachate biodegradability level, BOD_5/COD ratio was determined. The lead (Pb) concentrations in the examined samples have been determined to be beyond the limit of detection.

Table 1. *Physico-chemical parameters of analyzed leachate*

Landfill	Month	Parameter				
		COD (mg/L)	BOD_5 (mg/L)	BOD_5/COD ratio (/)	TKN (mg/L)	AN (mg/L)
S1	February	280	170	0.61	64.18	41.15
	May	310	142	0.46	60.38	36.49
	November	310	140	0.45	98.09	51.09
S2	February	1488	354	0.24	560.42	424.74
	May	1234	372	0.30	157.92	95.51
	November	670	170	0.25	61.81	33.62

Table 2. *Heavy metal contamination of analyzed leachate*

Landfill	Month	Parameter						
		Cr^{6+} (mg/L)	Fe (mg/L)	Zn (mg/L)	Ni (mg/L)	Pb (mg/L)	Mn (mg/L)	Cu (mg/L)
S1	February	0.03	1.10	0.41	2.42	<1	0.08	0.43
	May	0.12	27.98	0.37	2.49	<1	0.35	0.03
	November	0.08	6.63	0.26	2.56	<1	0.11	0.36
S2	February	0.38	2.78	0.32	2.53	<1	0.30	0.04
	May	0.15	5.98	0.29	2.55	<1	0.61	0.01
	November	0.25	3.74	0.38	2.51	<1	0.28	0.05

The parameter that showcases the biodegradability, BOD_5, is largely dependent on the leachate's maturity, which diminishes over time [9]. These results further confirmed the correlation reported by Bhambore and Kumar [9], as S1 and S2 exhibited very low BOD_5 values, consistent with the landfill's 40-year age. Another parameter highly influenced by the age of landfill is COD, as the susceptibility of waste to biological and chemical degradation processes decreases with time [11]. In terms of COD the average leachate characteristics reported from this research were typical for mature landfills with values <4000 mg/L, which align with the findings reported by Teng et al. [12]. Similar COD values are reported for examined landfills in conducted studies by Wdowczyk and Szymanska-Pulikowska [11]. The transitional phase of a landfill occurs when the ratio of BOD_5/COD is in the range 0.1-0.4 [13]. However, since the BOD_5/COD ratio is above >0.1 for S1 and S2, moderate biodegradability can be considered according to Bhambore and Kumar [9]. As stated in Table 1, maximum concentrations of AN were recorded for S1 (51.09 mg/L) and S2 (424.74) during the November and February camping, respectively. This trend was also observed for TKN values (98.09 and 560 mg/L for S1 and S2, respectively). It is scientifically established that AN does not depend on landfill age and is chemically stable, posing a problem for future landfill water treatment technologies based on microbial decomposition. Due to its high nitrogen content, food waste is the main source of AN amounts that are considered substantial. AN may threaten aquatic life if it exceeds the maximum allowable concentration [14].

The fluctuation in metal contents may be attributed to the waste's high heterogeneity and the increased solubility of metals due to the biological production of organic (fatty) acids resulting from the continuous deposition of fresh waste. Older landfills typically have low metal concentrations due to adsorption and/or precipitation reactions with co-existing sulfide, hydroxide ions, or carbonate. Leaching of heavy metals is affected by complexation, adsorption and desorption processes [15]. In this study, the highest Fe concentrations were observed at 27.98 mg/L (S1). A study by Sanga et al. [16] reported higher Fe concentrations than in our research, with a range from 72.00 - 625.00 mg/L, which were attributed to the disposal of steel objects at landfill sites. Furthermore, high levels of Fe in the leachate may result from the presence of construction materials, paints, dyes, solvents, polishing agents, and electrical equipment in the waste, which are recognized as primary sources of iron in landfill leachate [11]. The range of Cu values of the studied leachates were in accordance with typical copper values in landfill leachate reported by Gupta et al. [17] (0.306 and 0.199 mg/L) and Sanga et al. [15] (<0.01 and 0.80 mg/L). It is suspected that these concentrations may indicate the presence of items such as light bulbs, batteries, used engine oils, varnishes, or pharmaceuticals that were not selectively collected during landfill operation, as found by Wdowczyk and Szymanska-Pulikowska [11]. Nickel (Ni) concentrations at landfill sites were relatively high, with maximum values of 2.56 mg/L (S1) and 2.55 mg/L (S2). High values of nickel found in the present research most likely indicate the disposal of old batteries, which highly contributed to Ni values. Anthropogenic sources of zinc in soils typically include discharges from smelter slags and wastes, mine tailings, coal and fly ash residues, as well as the application of commercial products such as fertilizers and wood preservatives containing zinc [18]. Since leachate permeates the soil, it is expected that these Zn concentrations are also influenced by the soil around the landfill site. Likewise, the Cr values found in the studied leachate are highly likely due to the presence of consumer products like wood treated with copper dichromate, leather tanned with chromic sulfate, and stainless steel cookware. Manganese was found in concentrations below 1 mg/L. Hagelstein [19] listed the nonferrous applications of manganese which included the production of dry-cell batteries, plant fertilizer components, animal feed and colorant for bricks, dry cell batteries and as a black-brown pigment in paint.

Spearman rank correlation

Several statistically significant correlations were detected in the leachate samples. COD was found to be strongly associated with TKN (0.836) and with AN (0.816). This means that as COD values increase, nitrogen compound concentrations tend to rise in parallel. Such relationships are important because COD, TKN, and AN are commonly used indicators of leachate pollution, especially with respect to organic matter. Elevated COD values point to a greater presence of degradable organic substances, while TKN incorporates both inorganic and organic nitrogen fractions. Taken together, these results indicate that the breakdown of organic waste material is a major source of nitrogen release into the leachate. Among all tested parameters, the strongest positive relationship occurred between TKN and AN, with a correlation coefficient of 0.880. COD also exhibited a high correlation with chromium (0.845), suggesting that chromium present in waste items, such as certain industrial products or household materials, can migrate into the leachate. Chromium was further linked to TKN, with a coefficient of 0.837. Moderate correlations were also observed. Nickel also showed a moderate positive correlation with COD (0.643). The presence of Ni is probably related to the disposal of spent batteries, which is more common in non-sanitary landfills. The results provide a clearer understanding of pollutant dynamics across different landfill conditions.

CONCLUSION

This research provides a comprehensive overview of inorganic pollutants present in landfill leachate, which, in the absence of well-established or effective landfill management practices, are released into the surrounding environment. The Spearman rank correlation analysis for the selected Serbian landfill was conducted, yielding four very strong correlations. These results emphasize the complexity of landfill leachate composition and reveal the strong interactions among the examined parameters. Such findings can serve as valuable evidence to guide governmental and regulatory bodies in strengthening waste management policies and implementing more effective pollution control strategies for these toxic sources.

The persistence of these contaminants, coupled with their widespread use in consumer products, underscores the urgency for stricter regulatory measures and the development of innovative strategies aimed at reducing their release into surrounding ecosystems. Furthermore, the study reinforces the necessity of establishing proper leachate collection systems and treatment facilities, as well as the broader benefits of comprehensive waste management programs.

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