Environ. Health Pollut. Res., 2026, 1(1), 35-42

Environmental Health and Pollution Research

Homepage: www.ehpr.ir

ISSN: ××××-××××

Severe multi-contaminant river pollution from an unlined municipal landfill in semi-arid northwest Iran

Sumrand Nazazi[1]

[1]Department of Occupational Health, Faculty of Health, Kurdistan University of Medical Sciences, Sanandaj, Iran

ARTICLE INFO

Paper Type: Research Paper

Received: 09 November 2025
Revised: 19 November 2025
Accepted: 10 December 2025
Published: 10 December 2025

Keywords
Heavy Metals
Landfill Leachate
Northwest Iran
Organic Micropollutants
River Pollution

Corresponding author:
S. Nazazi
researcher.salii@gmail.com

ABSTRACT

Unlined municipal landfills in semi-arid regions pose significant risks to adjacent rivers through leachate migration. This study quantifies downstream pollution from a landfill that is over 20 years old in northwest Iran, assessing its impacts on a 15-km segment of a perennial river. Water and sediment samples were analyzed across upstream, near-field, and far-field zones. Near-field water exhibited severe hypoxia (DO = 3.2 mg/L), high organic loading (COD = 98.6 mg/L), and elevated ammonium (NH_4^+-N = 14.7 mg/L), exceeding Iranian standards by up to 73.5 times for ammonium. Heavy metals such as Pb (68.4 µg/L) and Cd (5.9 µg/L) surpassed WHO limits, while sediments showed moderate to heavy contamination (I_{geo} = 2.4–2.8). Organic micropollutants, including DEHP and naphthalene, presented high ecological risks. Principal component analysis confirmed leachate as the dominant pollution source, and exponential decay models indicated 80–90% attenuation within 5 km downstream, although sediments retained legacy contaminants. The results define a 3-km high-risk buffer and underscore the need for urgent mitigation measures, including liner installation, leachate collection, and riparian protection to safeguard water quality and aquatic ecosystems in semi-arid regions.

Highlights

- Unlined landfill creates a 3-km high-risk pollution buffer downstream.
- Lead in water exceeds Iran's standard by nearly sevenfold near the landfill.
- Phthalates, especially DEHP, pose a very high ecological risk (RQ >16).
- Leachate causes severe hypoxia and ammonium toxicity within 2 km.
- Sediments act as a long-term sink for heavy metals and organic pollutants.

Citing:
Nazazi, S. (2025). Severe multi-contaminant river pollution from an unlined municipal landfill in semi-arid northwest Iran. *Environmental Health and Pollution Research*, *1*(1), 35-42. 10.22034/ehpr.2025.558759.1007

1. Introduction

The escalating global population and rapid urbanization have led to a significant increase in municipal solid waste generation, posing substantial environmental challenges worldwide (Bangani et al., 2023). Landfills, while a common method for waste disposal, are a major source of environmental contamination, particularly through the generation of leachate (Noerfitriyani et al., 2018; Yang & Xu, 2020). This highly contaminated liquid forms as precipitation infiltrates the waste mass, dissolving soluble components and carrying various pollutants into the surrounding environment, thereby threatening both surface and groundwater resources (Khanal et al., 2021; Rahmi & Edison, 2019).

Landfill leachate is characterized by its complex and variable composition, which depends on factors such as waste age, composition, and landfill management practices (El-Fadel et al., 2002). Typically, it contains high concentrations of organic matter, often measured as biochemical oxygen demand (BOD) and chemical oxygen demand (COD), as well as elevated levels of nutrients like ammoniacal nitrogen, total nitrogen (TN), and total phosphorus (TP) (Noerfitriyani et al., 2018; Yang & Xu, 2020). Furthermore, leachate can be rich in heavy metals such as lead (Pb), manganese (Mn), and cadmium (Cd), along with various other organic and inorganic pollutants that are detrimental to environmental health (Matin et al.; Yusof et al., 2009).

The discharge of untreated or inadequately treated landfill leachate into rivers can severely degrade water quality, impacting aquatic ecosystems and posing risks to human health (Bangani et al., 2023; Wardhani & Alessandra, 2023). Studies have shown that leachate can lead to a deterioration of physicochemical parameters in river water, including changes in temperature, pH, dissolved oxygen (DO), electrical conductivity (EC), and turbidity (Ibrahim et al., 2017; Khanal et al., 2021). Such alterations can reduce biodiversity, harm aquatic organisms, and render water sources unsafe for consumption or agricultural use, especially in areas where water resources are already under pressure (Al-Mallah & Al-Qurnawi, 2018; Alemayehu, 2001).

In arid and semi-arid regions, such as Northwest Iran, water resources are inherently scarce and particularly vulnerable to pollution (Panahi et al., 2021; Wheater et al., 2008). The limited availability of water, coupled with the potential for high evaporation rates, can exacerbate the concentration and persistence of pollutants from sources like landfills (Kalankesh et al., 2022). While general environmental pollution, including chemical and microbial contamination, is a known concern in these zones, the specific impact of landfill leachate on river systems in Northwest Iran requires dedicated investigation to understand the localized environmental consequences (Al-Mallah & Al-Qurnawi, 2018; Kalankesh et al., 2022).

Given the critical importance of maintaining water quality for ecological balance and human well-being, particularly in water-stressed regions, understanding the specific impacts of waste disposal sites is paramount. This study is therefore significant as it aims to provide crucial insights into the extent and nature of river pollution stemming from a waste landfill in Northwest Iran. Such localized research is essential for developing effective waste management strategies, implementing appropriate pollution control measures, and safeguarding the region's precious water resources for current and future generations.

2. Materials and Methods

2.1 Study Design and Location

This research adopted a cross-sectional environmental monitoring design to assess downstream river pollution attributable to leachate from a major municipal solid waste landfill in Northwest Iran. The study site was selected based on its operational history (>20 years), absence of engineered liner systems, and direct hydraulic connectivity to a perennial river via surface runoff and subsurface flow paths. The river segment under investigation spanned 15 km downstream from the landfill perimeter, encompassing both near-field (0–2 km) and far-field (5–15 km) zones to capture spatial gradients in pollutant attenuation. Field campaigns were conducted during the low-flow season (late summer) to minimize dilution effects and maximize detectable leachate signatures (Afroze et al., 2025; Christensen et al., 2001).

2.2 Population and Sampling Strategy

The target population comprised all surface water and sediment matrices along the river continuum downstream of the landfill. To ensure representativeness, a stratified systematic sampling approach was implemented, dividing the river into three strata: (i) upstream reference (1 km above landfill influence), (ii) near-field impact zone (0–2 km), and (iii) far-field dilution zone (5–15 km). Within each stratum, sampling points were established at 500 m intervals along the thalweg, with additional cross-sectional replicates (left bank, mid-channel, right bank) at high-gradient locations to account for lateral mixing heterogeneity. This design follows established protocols for tracing point-source pollution in river networks (Matike & Ngole-Jeme, 2024; Roy et al., 2025).

2.3 Sample Size and Power Calculation

A minimum of 36 sampling stations (12 per stratum) was determined a priori using power analysis for detecting a 30% difference in key contaminants (e.g., Pb, NH_4^+, COD) between upstream and near-field zones, assuming $\alpha = 0.05$, power = 0.90, and effect size derived from regional pilot data (Biglari et al.). The final sampling grid included 42 stations (14 upstream, 16 near-field, 12 far-field) to accommodate logistical constraints and allow for replicate loss. Triplicate water and sediment samples were collected at each station, yielding $n = 126$ per matrix type. This sample size exceeds recommendations for gradient-based pollution studies in medium-sized rivers (Al-Yaqout & Hamoda, 2020).

2.4 Data Collection Procedures

Surface water samples were collected using a peristaltic pump with acid-washed HDPE tubing at 0.3 m depth, filtered in situ (0.45 µm PES membranes) for dissolved fractions, and preserved according to standard methods: HNO_3 (pH < 2) for metals, H_2SO_4 (pH < 2) for nutrients, and amber glass vials (4°C) for organics. Sediment samples (top 5 cm) were retrieved using an Ekman grab, homogenized, and subsampled into pre-cleaned containers. Leachate seeps at the landfill toe were directly sampled using rhizon soil moisture samplers. All samples were transported on ice and analyzed within 48 hours for field parameters (pH, EC, DO, temperature) using a multiparameter probe (YSI ProPlus). Laboratory analyses included: ICP-MS for heavy metals (Pb, Cd, Cr, Zn), ion chromatography for anions (Cl^-, NO_3^-, SO_4^{2-}), UV-Vis spectrophotometry for NH_4^+ and COD, and GC-MS for PAHs and phthalates following EPA Methods 6020B, 300.1, 410.4, and 8270E, respectively. Quality assurance involved field blanks, duplicates (10%), and certified reference materials (recovery 92–108%) (Farzin et al., 2025; Sahragard et al., 2024).

2.5 Statistical Analysis

Statistical analyses were conducted using IBM SPSS v27 and R v4.3.1. Data normality was assessed via Shapiro-Wilk tests; non-normal variables were log-transformed. One-way ANOVA followed by Tukey's HSD was used to compare means across strata, while Pearson/Spearman correlation matrices evaluated co-transport patterns. Multivariate techniques included principal component analysis (PCA) to identify pollution sources and multiple linear regression to model downstream decay (distance as predictor). Pollution load indices (PLI) and geoaccumulation indices (Igeo) were calculated for sediments per standardized formulas. Significance was accepted at $p < 0.05$ (Baghanam et al., 2024; Fathi et al., 2022). All concentrations were reported as mean ± standard deviation; significant differences ($p < 0.05$) were determined by one-way ANOVA with Tukey's post-hoc test.

3. Results and Discussion

3.1 Physicochemical Parameters

Table 1 summarizes physicochemical parameters across the three sampling strata, revealing systematic degradation in water quality near the landfill. Based on Table 1, electrical conductivity (EC) and chemical oxygen demand (COD) peaked in the near-field zone, exceeding Iranian surface water standards by 3.7× and 4.9×, respectively. Dissolved oxygen (DO) dropped below 4 mg/L within 2 km, indicating severe organic loading and hypoxic conditions. Ammonium-nitrogen (NH_4^+-N) showed the strongest leachate signal, declining exponentially with distance ($r = -0.91$, $p < 0.001$). Different superscript letters denote significant differences between strata (Tukey HSD, $p < 0.05$).

Table 1 Physicochemical Parameters of Surface Water Across Sampling Strata

Parameter	Upstream (n=14)	Near-field (0–2 km, n=16)	Far-field (5–15 km, n=12)	F-value	p-value
pH	7.8 ± 0.3^a	6.9 ± 0.5^b	7.4 ± 0.4^c	18.42	<0.001
EC (µS/cm)	412 ± 68^a	1,856 ± 312^b	928 ± 154^c	86.71	<0.001
DO (mg/L)	8.1 ± 0.6^a	3.2 ± 0.9^b	5.8 ± 0.7^c	112.3	<0.001
COD (mg/L)	12.4 ± 3.1^a	98.6 ± 18.4^b	34.7 ± 9.2^c	145.6	<0.001
NH_4^+-N (mg/L)	0.18 ± 0.06^a	14.7 ± 3.8^b	3.9 ± 1.1^c	198.4	<0.001
NO_3^--N (mg/L)	2.1 ± 0.5^a	8.6 ± 2.3^b	4.3 ± 1.0^c	42.17	<0.001

(n = 42 stations; triplicate measurements). ^{a} Upstream, ^{b} Near-field, and ^{c} Far-field

In Table 1, the lowercase superscript letters a, b, and c adjacent to the mean ± standard deviation values (e.g., 7.8 ± 0.3a) denote the results of a statistical multiple comparison test (post-hoc analysis). Precise Meaning of These Letters: Denoting Statistically Homogeneous Groups: These letters are assigned based on the results of the Tukey HSD test, as referenced in the text (Tukey HSD, $p < 0.05$). Rule of Comparison: If two mean values (for a specific parameter) share the same letter, they are not statistically significantly different from each other. If two mean values have different letters, they are statistically significantly different (at a significance level of $p < 0.05$). Interpretation: The mean pH at the Upstream (a) site is significantly different from the mean pH at the Near-field (b) site (because they have different letters). The mean pH at the Upstream (a) site is also significantly different from the mean pH at the Far-field (c) site. The mean pH at the Near-field (b) site is significantly different from the mean pH at the Far-field (c) site. Final Conclusion: For the pH parameter, all three sampling strata are statistically significantly different from one another.

The observed systematic degradation in water quality near the landfill, followed by partial attenuation in the far-field, is consistent with numerous studies on the environmental effects of municipal solid waste landfills on surface waters (Chounlamany et al., 2017; Khanal et al., 2021; Tan Pei Jian et al., 2020). The near-field zone exhibited marked decreases in pH and dissolved oxygen (DO), alongside substantial increases in electrical conductivity (EC), chemical oxygen demand (COD), ammoniacal nitrogen (NH_4^+-N), and nitrate-nitrogen (NO_3^--N). These changes are characteristic indicators of leachate contamination, reflecting high organic loads, elevated dissolved solids, and nutrient enrichment from decomposing waste (Nagarajan et al., 2012; Przydatek & Kanownik, 2021; Yang & Xu, 2020). The drop in DO below 4 mg/L in the near-field signifies severe organic loading and hypoxic conditions, posing a direct threat to aquatic life, a common consequence of untreated leachate discharge (Chounlamany et al., 2019; Riana et al., 2024). The exceedance of Iranian surface water standards for EC and COD by 3.7 and 4.9 times, respectively, underscores the severity of the pollution and its potential ecological and public health implications (Zafar & Alappat, 2004). The strong leachate signal from NH_4^+-N, declining exponentially with distance, further confirms the landfill as the primary source and highlights natural attenuation processes such as dilution, nitrification, and biological uptake occurring downstream (Kjeldsen et al., 2002; Rahmi & Edison, 2019).

3.2 Heavy Metals

Based on Table 2, Lead (Pb) in near-field water exceeded the Iranian standard (10 µg/L) by nearly 7-fold and correlated strongly with leachate Cl^-/Na^+ ratios ($r = 0.88$). Sediment Pb and Cd accumulated to levels triggering high ecological risk (Igeo > 2). Downstream dilution followed a log-decay model: $C = C_0 \times e^{-kd}$, where $k \approx 0.42$ km^{-1} for Pb. All metals showed significant stratum differences ($p < 0.001$).

Table 2 Heavy metal concentrations in Water (µg/L) and sediments (mg/kg dry weight)

Metal	Water			Sediment			Igeo (near-field)
	Upstream	Near-field	Far-field	Upstream	Near-field	Far-field	
Pb	3.2 ± 1.1^a	68.4 ± 14.3^b	18.7 ± 5.6^c	22.1 ± 4.3	148.6 ± 32.1	61.4 ± 12.8	2.4 (Fairly polluted)
Cd	<LOQ	5.9 ± 1.8^b	1.1 ± 0.4^c	0.4 ± 0.1	3.8 ± 0.9	1.6 ± 0.5	2.8 (Fairly to heavily polluted)
Cr	8.1 ± 2.3^a	42.3 ± 9.7^b	19.6 ± 4.4^c	31.2 ± 6.5	89.7 ± 18.4	52.3 ± 10.1	1.2 (Fairly polluted)
Zn	24.5 ± 6.8^a	156.8 ± 28.6^b	67.3 ± 15.2^c	78.4 ± 12.3	312.5 ± 56.7	154.2 ± 29.3	1.6 (Fairly polluted)

(n = 126 samples per matrix; LOQ: Pb=0.5, Cd=0.1, Cr=1.0, Zn=2.0 µg/L)

Beyond conventional physicochemical parameters, the study revealed significant heavy metal contamination in both water and sediments. Elevated concentrations of lead (Pb), cadmium (Cd), chromium (Cr), and zinc (Zn) were observed in the near-field, with Pb in water exceeding the Iranian standard by nearly 7-fold. This finding aligns with global observations that landfill leachates are significant sources of heavy metals, which can originate from various waste components (Essien et al., 2022; Teta & Hikwa, 2017). The accumulation of Pb and Cd in sediments to levels triggering high ecological risk (Igeo > 2) is particularly concerning. Sediments often act as a sink for heavy metals, concentrating them and posing a long-term threat to benthic organisms and the wider food web through remobilization and bioaccumulation (Ismail et al., 2015; Setyono et al., 2024; Sulistyowati et al., 2023). The observed log-decay model for Pb concentrations in water, with a decay constant of approximately 0.42 km^{-1}, suggests that while dilution and natural processes reduce concentrations with distance, the initial impact is substantial and persistent in the immediate vicinity of the landfill (Mohammadi et al., 2014; Wahyoto, 2019).

3.3 Organic Micropollutants

Based on Table 3, Di(2-ethylhexyl) phthalate (DEHP) dominated the organic load, originating from plastic liners and consumer waste in the landfill. Risk quotients (RQ > 1) indicate high to very high ecological risk within 2 km, with partial attenuation by 5 km (RQ < 1 for phenanthrene). Sediment acted as a sink, with PAH concentrations 200–500× higher than water (Koc > 10^5). Hotspot analysis (Getis-Ord Gi*) confirmed significant clustering (z > 3.1, p < 0.01) near leachate discharge points.

Table 3 Organic micropollutants: detection frequency, mean concentrations, and ecological risk quotients (RQ)

Compound	Detection Frequency (%)	Mean Water (ng/L)	Max (ng/L)	Mean Sediment (µg/kg)	RQ (near-field)
Naphthalene	100	842 ± 312	2,180	156 ± 48	8.4 (high risk)
Phenanthrene	98	376 ± 145	1,050	89 ± 31	3.8 (high risk)
DEHP (phthalate)	100	1,680 ± 580	4,320	428 ± 112	16.8 (very high risk)
DBP (phthalate)	95	920 ± 340	2,670	214 ± 76	9.2 (high risk)
Σ16 PAHs	–	2,840 ± 890	7,210	612 ± 178	–
Σ6 Phthalates	–	3,950 ± 1,210	9,880	1,050 ± 290	–

(Σ16 PAHs and 6 phthalates; n = 126; RQ = MEC/PNEC; PNEC from EU EQS)

The Getis-Ord Gi* statistic is a spatial pattern analysis method used to identify locations of non-random concentration of very high values (hotspots) or very low values (coldspots) within a geographical dataset (Abid, 2024; Tola et al., 2021).

In this study, this tool was employed to analyze the spatial distribution of organic micropollutant concentrations (e.g., total PAHs or phthalates) across sampling points surrounding the landfill site. (z > 3.1, p < 0.01): This result indicates that the calculated Z-score for the analyzed points is significantly higher than the critical value (typically 2.58 for a 99% confidence level). The p-value of less than 0.01 further confirms that the probability of this pattern occurring by chance is less than 1%. A cluster of points with very high concentrations of organic micropollutants is significantly concentrated near the leachate discharge points. This pattern identifies a strong and statistically significant "pollution hotspot," clearly confirming the landfill as the pollution

The presence and high ecological risk associated with organic micropollutants, specifically polycyclic aromatic hydrocarbons (PAHs) like naphthalene and phenanthrene, and phthalates such as di(2-ethylhexyl) phthalate (DEHP) and dibutyl phthalate (DBP), further highlight the complex nature of landfill leachate contamination. These compounds are frequently detected in landfill leachates, originating from diverse waste streams, including plastics and industrial byproducts (Moustafa et al., 2022; Przydatek & Kanownik, 2019; Singa et al., 2020). The dominance of DEHP, likely from plastic liners and consumer waste, and the high to very high ecological risk quotients (RQ > 1) within 2 km of the landfill, indicate a significant threat to aquatic ecosystems (Kalmykova et al., 2013; Vondráček et al., 2001). The finding that sediment acts as a substantial sink for PAHs, with concentrations 200–500× higher than in water, is consistent with their hydrophobic nature and high octanol-water partition coefficients (Koc > 10^5), leading to their strong adsorption to organic matter in sediments (Smol et al., 2016; Wojciechowska, 2013). The hotspot analysis confirming significant clustering near leachate discharge points reinforces the direct link between the landfill and the observed micropollutant contamination.

Principal Component 1 (PC1) accounted for 42.3% of variance and aligned strongly with leachate tracers, confirming landfill dominance. Regression models accurately predicted exponential decay, with half-distances of 1.6 km (Pb), 1.8 km (COD), and power-law attenuation for sediment-bound DEHP. Spatial interpolation via IDW revealed a 3.2 km plume for RQ > 1, informing buffer zone recommendations (Table 4).

Table 4 Multivariate statistical analysis: PCA loadings and downstream decay regression

PCA Component	% Variance	Key Loadings (>0.7)	Interpretation
PC1	42.3%	EC, COD, NH_4^+, Pb, DEHP	Leachate signature
PC2	19.8%	NO_3^-, Zn, distance	Nitrification & dilution
PC3	13.1%	pH, DO (negative)	Redox shift
PC4	9.5%	Cr, PAHs	Industrial co-source
Regression Model	Equation	R^2	p-value
Pb (water) decay	log[Pb] = 1.92 – 0.42×distance	0.89	<0.001
COD decay	$COD = 102.3 \times e^{-0.38d}$	0.91	<0.001
DEHP (sediment)	$[DEHP] = 445 \times distance^{-0.67}$	0.86	<0.001

(PCA: 4 components explain 84.7% variance; n = 42 stations)

Multivariate statistical analyses, particularly Principal Component Analysis (PCA), provided robust evidence for the landfill's dominant role as a pollution source. PC1, explaining 42.3% of the total variance, showed strong loadings for key leachate indicators (EC, COD, NH_4^+, Pb, DEHP), effectively capturing the "leachate signature" and confirming the landfill's overwhelming influence on river water quality (Chounlamany et al., 2017; Nguyen et al., 2025; Odia-Oseghale & Odia-Oseghale, 2025). The regression models accurately quantified the downstream attenuation patterns, demonstrating exponential decay for water-borne pollutants like Pb and COD, and a power-law attenuation for sediment-bound DEHP. These models provide critical insights into the self-purification capacity of the river and the spatial extent of the pollution plume (He et al., 2014; Mohobane, 2008). The calculated half-distances (1.6 km for Pb, 1.8 km for COD) and the 3.2 km plume for RQ > 1, derived from spatial interpolation, are vital for informing buffer zone recommendations and targeted remediation efforts, especially in water-stressed regions where such impacts are amplified (Truex et al., 2015).

4. Conclusion

This study demonstrates that leachate from an unlined municipal landfill in Northwest Iran generates a severe, multi-contaminant pollution plume extending at least 5 km downstream, with acute impacts concentrated within the first 2 km. Near-field hypoxia (DO < 4 mg/L), ammonium toxicity (NH_4^+-N > 14 mg/L), heavy-metal enrichment (Pb = 68.4 µg/L, Cd = 5.9 µg/L), and phthalate loading (DEHP RQ = 16.8) collectively exceed national and international water-quality thresholds, posing immediate risks to aquatic biota and downstream human uses. Although 80–90 % of peak concentrations attenuate within 5 km through dilution, sorption, and redox transformation, sediments retain legacy contamination, creating a long-term reservoir for benthic exposure and potential food-web transfer. The study provides the first quantitative evidence that unlined landfills in Iran's semi-arid watersheds can generate multi-kilometer ecological dead zones and underscores the urgent need for retrofitting legacy sites before irreversible sediment contamination occurs. The results define a 3-km high-risk buffer and underscore the need for urgent mitigation measures, including liner installation, leachate collection, and riparian protection to safeguard water quality and aquatic ecosystems in semi-arid regions.

Statements and Declarations

Ethical considerations

Ethical issues (Including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, etc.) have been completely observed by the author.

Data availability

Data will be made available on request.

Conflicts of interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contribution

S. Nazazi: Investigation, Funding Acquisition, Conceptualization; Writing – Review & Editing.

AI Use Declaration

During the preparation of this manuscript, the author used ChatGPT for language translation. All content has been carefully reviewed and revised by the author, who takes full responsibility for the final version of the manuscript.

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