



Health Risk Assessment of Aluminum and Chromium(VI) Exposure in Groundwater Near Landfills

Retno Syahriawati Dewi^{1*}, Muhammad Arus Samudro², Astri Rino Okvitasari³, Arisessy Maharani Mulananda⁴, Fadlilatin Nailah⁵

^{1,2,3,4,5}Politeknik Negeri Madura, Indonesia

^{1*}retno.syahriawati@poltera.ac.id, ²arus.samudro@poltera.ac.id, ³astri.rino@poltera.ac.id, ⁴arisessy@poltera.ac.id,

⁵fadlilatin.nailah@poltera.ac.id



*Corresponding Author

Article History:

Submitted: 25-09-2026

Accepted: 08-10-2026

Published: 19-10-2026

Keywords:

Environmental Health Risk
Assessment; Groundwater;
Aluminium; Hexavalent
Chromium; Landfills.

The Journal is licensed under a
Creative Commons Attribution-
NonCommercial 4.0 International
(CC BY-NC 4.0).

ABSTRACT

The degradation of groundwater quality near landfill sites due to potential pollutant exposure requires quantitative evaluation to determine actual health risks to surrounding communities. This study aimed to analyze aluminum and chromium(VI) concentrations and characterize environmental health risk associated with groundwater exposure near the landfill. Water samples were collected from five residential wells using purposive sampling. Health risk assessment was conducted by calculating the Average Daily Dose, Hazard Index (HI) for non-carcinogenic effects, and Total Cancer Risk (TCR) for carcinogenic effects via ingestion and dermal contact. Results showed aluminum concentrations ranged from 0.012 to 0.14 mg/L, complying with the WHO drinking water quality standards, whereas chromium(VI) concentrations remained below the limit of detection (<0.0099 mg/L). Risk characterization revealed all HI values were below 1, ranging from 0.0003 to 0.0094, indicating no potential non-carcinogenic risk. Conversely, the estimated TCR, calculated by substituting the detection limit for chromium(VI), exceeded the acceptable risk range (4.0×10^{-4} for adults and 9.5×10^{-4} for children). However, these results represent a highly conservative theoretical worst-case scenario. Children were identified as a vulnerable group with the highest risk due to their higher water intake per unit of body weight. In conclusion, current exposure to well water does not indicate potential non-carcinogenic risk, and the presence of these metals may be attributed to natural processes or activities around the landfill. These findings highlight the importance of periodic groundwater quality monitoring and further hydrogeological studies to strengthen pollutant source identification.

INTRODUCTION

Municipal landfills frequently operate without engineered liners or leachate collection systems, potentially allowing contaminated leachate to seep into shallow aquifer systems. Exposure to this landfill leachate can cause significant hydrochemical alterations in groundwater through mixing, ion exchange, oxidation-reduction (redox) reactions, and mineral dissolution processes (Pathan et al., 2026). Leachate contamination represents a significant environmental health threat because it transports various organic and inorganic compounds, including toxic, non-biodegradable, and carcinogenic heavy metals. In general, leachate is characterized by high chemical oxygen demand (COD), total dissolved solids (TDS), and heavy metal concentrations (Acarer Arat, 2024). Direct exposure to leachate-contaminated groundwater can cause chronic diseases, reproductive disorders, and developmental toxicity in humans. The vertical and lateral migration of leachate plumes from open landfills into subsurface layers has been shown to extend over considerable distances. Based on geoelectrical profiles, leachate intrusion can penetrate sand and clay formations to depths ranging from 2 meters to more than 24 meters below the ground surface. Environmental conditions characterized by high rainfall and a shallow groundwater table of less than 10 meters create highly conducive conditions for the continuous downward infiltration of leachate contaminants (Abiye et al., 2025).

The Gunung Maddah Landfill operated as an open dumping site from 2004 before transitioning to a sanitary landfill system in 2019. However, residual leachate may continue to migrate vertically and laterally along hydrological flow paths, potentially causing direct exposure among the surrounding community. Leachate toxicity in landfill areas can persist underground even after landfill operations have ceased or been modified (Afolabi et al., 2022). Therefore, the transition from an open dumping system to a sanitary landfill should be accompanied by policies requiring impermeable liners and leachate collection systems.

A previous study analyzed the movement of leachate contaminants in groundwater surrounding the Gunung Maddah Landfill using the Domenico analytical model. This model simulates contaminant transport by considering advection, dispersion, retardation, and degradation. The modeling results indicated that, at landfill operational ages of 10, 25, and 50 years without adequate leachate management, aluminum and chromium(VI) concentrations would





exceed the threshold limits of the Class II Water Quality Criteria under Government Regulation Number 22 of 2021. The dispersion model projected that the metal contaminant plume could migrate longitudinally approximately ± 230 meters from the point source toward residential wells. This spatial distribution mapping provides empirical evidence of an environmental exposure pathway between the primary hazard source and the receptors. Based on groundwater quality data, the aluminum concentration reached 0.14 mg/L, whereas the chromium(VI) concentration remained below the limit of detection. However, long-term hydrological predictions or comparisons of concentration levels with environmental quality standards cannot fully represent the current actual threat. Although the pollutant dispersion rate has been mapped, the quantitative relationship between these concentrations and the toxicological dose entering the human body, or internal dose, has not yet been evaluated.

Estimating the unknown exposure dose is crucial because environmental concentrations that exceed quality standards do not automatically indicate the occurrence of adverse health effects or risks. The impact of metal pollution on human health can be severe even at low concentrations. Metal contamination in groundwater can cause serious health impacts, such as neurological disorders, kidney disease, and cancer (Dąbrowska & Witkowski, 2022). Migrating heavy metals have highly detrimental toxic characteristics: they are persistent and non-biodegradable, and they can substantially bioaccumulate in human body tissues. Specifically, continuous exposure to aluminum can trigger long-term systemic toxicity that impairs cognitive and central nervous system functions, whereas chromium(VI) exhibits mutagenic properties and is classified as a potent carcinogen (Kapoor et al., 2024; Ke et al., 2026). Therefore, environmental health risk assessment serves as a crucial instrument for translating static environmental contamination data into quantitative risk metrics. Health risk assessment measures human exposure levels from groundwater through two primary pathways: oral ingestion and dermal contact. Quantification of non-carcinogenic health threats relies on the calculation of the Hazard Quotient (HQ), whereas carcinogenic potential is assessed by determining the increased likelihood of cancer development in an individual resulting from chronic lifetime exposure to pollutants (Ke et al., 2026).

To address the limitations of previous studies, this research focuses on characterizing the actual probability of public health risks. By using variables such as daily water ingestion rate, body weight, and the frequency and duration of well water use, this study determines hazard levels based on specific exposure doses. This study aims to analyze and characterize the environmental health risks, both non-carcinogenic and carcinogenic, to the community resulting from exposure to aluminum and chromium(VI) contaminants originating from groundwater use near the landfill. The results of this analysis are expected to identify the exposure parameters that contribute most significantly to risk magnitude and provide a scientific foundation for environmental health interventions.

LITERATURE REVIEW

Landfill leachate is a liquid generated from solid waste through physical, chemical, and biological interactions within a landfill system. The composition of this wastewater fluctuates according to climatic conditions, pH levels, the degree of waste stabilization, operational age, and the specific category and composition of the discarded materials. Furthermore, leachate constitutes a heterogeneous aqueous matrix characterized by elevated contaminant levels, encompassing organic constituents, inorganic ions, xenobiotics, metals, emerging pollutants, and microorganisms resulting from the microbiological and physicochemical transformations of diverse waste matrices (Aquino et al., 2025). Heavy metals contained in landfilled solid waste undergo leaching during precipitation. Regional spatial variations in rainfall patterns and intensity significantly contribute to the heterogeneity of these heavy metal concentrations. Alongside climatic factors, the physicochemical parameters of leachate such as pH, total suspended solids (TSS), chemical oxygen demand (COD), and chloride levels influence the behavioral dynamics of heavy metals in the environment. Variations in leachate pH can shift the chemical speciation of heavy metals, directly impacting their concentration fluctuations. For instance, pH conditions control chromium(VI) speciation by shifting the thermodynamic equilibrium between chromate (CrO_4^{2-}) and dichromate ($\text{Cr}_2\text{O}_7^{2-}$) ions. Furthermore, TSS levels are directly proportional to heavy metal concentrations in the leachate; studies indicate that approximately 50% to 99% of the heavy metal fraction in landfill leachate is bound to suspended solids via adsorption mechanisms (Wang et al., 2027). Heavy metals represent a critical hazard within leachate compositions due to their non-biodegradable nature, high toxicity, environmental persistence, bioaccumulative capacity, endocrine-disrupting properties, and carcinogenicity (Afolabi et al., 2022). Metals present in leachate can be toxic to humans and persistent in the environment. Unlike organic pollutants, this persistence enables heavy metals to accumulate and endure within soil and groundwater systems over extended periods. The accumulation of potentially toxic heavy metals through contaminated water can trigger bioaccumulation in organisms, posing risks of carcinogenicity, acute toxicity, and genotoxicity (Gunaratne et al., 2024; Wang et al., 2027).

Environmental Health Risk Assessment serves as a quantitative framework to evaluate health hazards arising from chemical or physical agent exposure among susceptible populations by integrating specific risk parameters (Izza et al., 2025). Methodologically, this framework relies on computing the hazard quotient (HQ) and hazard index (HI) across multiple demographic cohorts and primary exposure routes namely ingestion, dermal absorption, and inhalation thereby differentiating systemic non-carcinogenic toxicity from carcinogenic probabilities. Ingestion (oral consumption) of contaminated groundwater is the primary contaminant transfer pathway contributing to health risks, far exceeding the





effects of dermal absorption or inhalation. For all age groups, the ingestion route yields the highest risk value (HI), whereas the dermal pathway is secondary, and the inhalation pathway is considered negligible (Kamara et al., 2026). Children and adults are the target populations in measuring potential non-cancer health effects associated with water exposure via ingestion and dermal contact (Saha et al., 2023).

Extended consumption of metallic elements including arsenic, cadmium, lead, and nickel can provoke substantial carcinogenic and non-carcinogenic health hazards. To quantify potential adverse health effects driven by chronic heavy metal ingestion via drinking water, human health risk models incorporating the Average Daily Dose (ADD), Hazard Index (HI), and Hazard Quotient (HQ) have been extensively implemented, with a particular focus on susceptible cohorts such as children (Ranjan et al., 2026). Children aged 0 to 6 years represent the most vulnerable population to heavy metal exposure in drinking water due to their immature metabolic systems and detoxification capacities, combined with a high water consumption ratio relative to body weight. Hazard Index (HI) and Carcinogenic Risk (CR) values consistently show the highest levels in the 0–6 age group, decreasing gradually with age to the lowest threshold in individuals aged >50 years (Kissar & Khemmoudj, 2025).

METHOD

The methodological workflow employed in this study is comprehensively illustrated in Figure 1, guided by the Environmental Health Risk Assessment (EHRA) framework. This approach commenced with primary data collection, encompassing environmental sampling and respondent data acquisition. Following the completion of data collection, the EHRA was executed through four sequential steps: hazard identification, dose-response assessment, exposure assessment, and risk characterization.

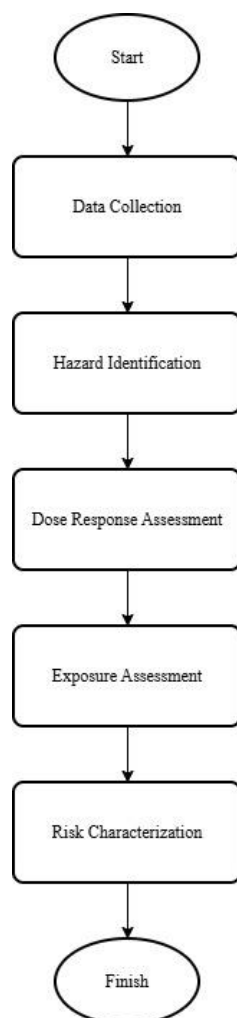


Figure 1. Flowchart

Data Collection

The data required for this study are as follows:

1. Water Samples

Groundwater sampling points were determined using a purposive sampling method based on the hydraulic flow direction (hydraulic gradient) from the landfill. Water samples were obtained from residential boreholes located





within the hydrologically impacted radius surrounding the Gunung Maddah Landfill.

Table 1. Sampling Points

Locations	Coordinates		Elevation
	Lon	Lat	M
SAT1	113°15'39"E	7°11'56"S	41
SAT2	113°15'38"E	7°12'00"S	38
SAT3	113°15'33"E	7°11'58"S	36
SAT4	113°15'31"E	7°12'01"S	32
SAT5	113°15'29"E	7°12'01"S	30

Table 1 details the geographical coordinates and elevations of the five groundwater sampling points (SAT1 to SAT5) established in this study. These locations were purposively selected based on the hydraulic gradient to represent the residential wells situated within the hydrologically impacted zone of the Gunung Maddah Landfill. The topographic elevations of these observation wells exhibit a declining trend, starting from the highest point at SAT1 (41 meters above sea level) down to the lowest point at SAT5 (30 meters above sea level). This variation in elevation is a critical parameter as it indicates the direction of groundwater flow, which generally moves from higher to lower topographical areas, thereby influencing the potential migration pathway of landfill leachate into the surrounding aquifer system.

2. Respondent Data Collection

The target population comprised residents living around the Gunung Maddah Landfill who actively utilized the well water for daily domestic purposes. Questionnaires were administered to obtain data on body weight, ingestion rate, exposure frequency, and exposure duration.

Environmental Health Risk Assessment

1. Hazard Identification

Hazard identification aims to specifically determine the risk agents that potentially cause health disorders upon exposure. This identification was carried out by conducting laboratory tests to analyze groundwater samples for aluminum and chromium(VI) parameters at an accredited laboratory. This stage ensured the empirical presence of the risk agents.

2. Dose-Response Assessment:

This stage established the toxicity parameters of the risk agents to obtain the Reference Dose (RfD) for systemic toxicity and the Cancer Slope Factor (CSF) for carcinogenic agents. The purpose of the dose-response assessment was to determine the exposure pathways of the risk agents, understand the health effects caused by increased concentrations or doses of the risk agents, and identify their respective RfD and CSF values.

Table 2. Toxicity parameters for health risk assessment

Elements	Non-carcinogenic reference dose mg/kg/day	Carcinogenic slope factor mg/kg/day
Al	1,0	-
Cr (VI)	-	0,5

Table 2 presents the established toxicity parameters utilized for the environmental health risk assessment (EHRA) of the identified risk agents, specifically aluminum and chromium(VI). These parameters serve as the fundamental toxicological benchmarks required to quantify the probability of adverse health effects within the dose-response assessment phase. As detailed in the table, aluminum is evaluated exclusively for its systemic toxicity, characterized by a non-carcinogenic Reference Dose (RfD) of 1.0 mg/kg/day. Conversely, chromium(VI) is evaluated for its carcinogenic potential, indicated by a Cancer Slope Factor (CSF) of 0.5 mg/kg/day. The distinction between these parameters is crucial, as the RfD is subsequently applied to compute the Hazard Quotient (HQ) for non-cancer risks, whereas the CSF is utilized to estimate the incremental probability of Carcinogenic Risk (CR) resulting from exposure.

3. Exposure Assessment

The magnitude of the daily intake of risk agents received by individuals was calculated using standard EHRA (Environmental Health Risk Assessment) equations, separating the intake through the ingestion pathway (ingestion intake) and skin absorption (dermal intake).

$$ADD_{ing} = \frac{C \times IR \times EF \times ED}{BW \times AT} \quad (1)$$

$$ADD_{derm} = \frac{C \times K_p \times SA \times ET \times EF \times ED \times CF}{BW \times AT} \quad (2)$$

Where ADD_{ing}= Average daily dose through ingestion of water (mg/kg/day); ADD_{derm} = Average daily dose through dermal absorption (mg/kg/day); C= concentration of risk agent (mg/L); IR= Ingestion Rate (L/day); ET= Exposure Time (hour/day); EF= Exposure Frequency (days/year); ED= Exposure Duration (years); BW= Body Weight (kg); AT= Averaging Time (days); SA=Exposed Skin Area; Kp=Coefficient of dermal permeability.





4. Risk Characterization:

Risk characterization was conducted to establish the risk level by determining the specific dose or concentration of the risk agents that could potentially cause public health disorders

$$HQ = \frac{ADD_{ing}}{RfD} \text{ or } HQ = \frac{ADD_{derm}}{RfD} \quad (3)$$

If the analysis evaluated the accumulation of multi-contaminants and/or multi-pathways, the HQ values were aggregated into a Hazard Index (HI):

$$HI = \sum_{i=1}^n HQ_i \quad (4)$$

Where HQ = Hazard Quotient; RfD = Reference Dose

Based on US EPA guidelines, if the HQ or HI ≤ 1 , it is concluded that the exposure level remains within the physiological tolerance limit (toxicity risk is negligible). Conversely, if the HQ or HI > 1 , there is a probability that the exposure will trigger adverse health effects.

$$CR = ADD \times CSF \quad (5)$$

$$TCR = \sum_{i=1}^n CR_i \quad (6)$$

Where CR=Carcinogenic risk; CSF = Cancer Slope Factor.

The CR value indicates the incremental probability of an individual developing cancer due to exposure. The US EPA establishes the acceptable safety threshold (acceptable risk) within the probability range of 1×10^{-6} to 1×10^{-4} .

RESULT

The concentrations of aluminum and chromium(VI) measured in groundwater across five sampling locations (SAT1 to SAT5) are presented in Table 3. Based on the measurement results, all well points contained dissolved aluminum with concentrations ranging from 0.012 to 0.14 mg/L. Specifically, the highest aluminum concentration was recorded at SAT2 (0.14 mg/L), whereas the lowest concentration was observed at SAT4 (0.012 mg/L). Despite these variations across sampling sites, all recorded aluminum concentrations remained within safe compliance limits for drinking water standards. The spatial variations in aluminum levels among the residential wells reflect local hydrogeochemical influences and varied interactions with subsurface soil matrices within the landfill's hydrological zone.

Table 3. Concentrations of heavy metal in the groundwater

Location	Cr (VI) (mg/L)	Al (mg/L)
SAT1	< 0,0099	0,13
SAT2	< 0,0099	0,14
SAT3	< 0,0099	0,099
SAT4	< 0,0099	0,012
SAT5	< 0,0099	0,016

Meanwhile, the concentration of chromium(VI) in all well water samples remained below the analytical limit of detection (LOD) of the instrument (<0.0099 mg/L). This low concentration of chromium(VI) indicates that specific hexavalent chromium contamination did not occur significantly at the sampling points, which was likely influenced by the natural reduction of chromium(VI) to the less mobile chromium(III) in shallow groundwater environments due to the presence of organic reducing agents.

To estimate the heavy metal intake absorbed by the human body, exposure modeling was performed using predefined anthropometric variables and behavioral patterns (Table 4). Two principal exposure pathways were examined in this study: oral consumption through drinking water and dermal absorption resulting from routine water utilization. The mean daily water ingestion rate was set at 2 L/day for adults and 1 L/day for children.

Table 4. Exposure parameters for health risk assessment

Parameters	Unit	Adult	Children
Concentration of Al	mg/L	0.099-0.14	0.099-0.14
Concentration of Cr (VI)	mg/L	0.007	0.007
Body Weight (BW)	Kg	70	15
Average daily drinking water intake (IR)	L/day	2	1
Exposure frequency through ingestion (EF)	days/year	365	365
Exposure frequency through dermal (EF)	days/year	350	350
Exposure duration (ED)	Year	30	6
Exposure time (ET)	hours/day	0.58	1
Averaging time non cancer (AT)	Days	10,950	2,190
Averaging time cancer (AT)	Days	25,550	25,550
Coefficient of dermal permeability (SA)	cm ²	18,000	6,600



Coefficient of dermal permeability (Kp)	cm/hour		
Cr (VI)		2×10^{-3}	2×10^{-3}
Al		1×10^{-3}	1×10^{-3}
Unit transfer factor (CF)	L/cm ³	0.001	0.001

Given that chromium(VI) concentrations in all samples were below the limit of detection (<0.0099 mg/L), quantitative exposure estimation could not be calculated using a value of zero, as this would underestimate hidden potential risks. In accordance with United States Environmental Protection Agency (USEPA) standard risk assessment guidelines for handling left-censored data below the detection limit, value substitution was performed using the formula $LOD/\sqrt{2}$. Therefore, the substituted chromium(VI) concentration for daily intake dose (ADD) calculations was conservatively established at 0.007 mg/L. This approach enabled exposure quantification despite extremely low actual concentrations.

The Average Daily Dose (ADD) was calculated for ingestion and dermal contact routes based on the exposure parameters outlined in Table 4. For aluminum, the ingestion ADD for children ranged from 0.0008 to 0.0093 mg/kg/day, which was consistently higher than the estimated adult ingestion ADD (0.0003 to 0.0040 mg/kg/day). Long-term chronic exposure to aluminum via ingestion has been associated with an increased risk of neurotoxicity, including cognitive deficits and central nervous system dysfunction. A similar demographic pattern was observed in the chromium(VI) modeling, where the children's ingestion ADD (0.00047 mg/kg/day) exceeded the adult ingestion ADD (0.0002 mg/kg/day).

Table 5. Non-Carcinogenic Health Risk Assessment

Location	ADD ingestion		ADD dermal		HQ ingestion		HQ dermal		HI	
	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children
SAT1	0,003 ₇	0,0087	$1,94 \times 10^{-5}$ ₅	$5,72 \times 10^{-5}$	0,003 ₇	0,0087	$1,94 \times 10^{-5}$ ₅	$5,72 \times 10^{-5}$ ₅	0,003 ₇	0,0087
SAT2	0,004 ₀	0,0093	$2,08 \times 10^{-5}$	$6,16 \times 10^{-5}$	0,004 ₀	0,0093	$2,08 \times 10^{-5}$ ₅	$6,16 \times 10^{-5}$ ₅	0,004 ₀	0,0094
SAT3	0,002 ₈	0,0066	$1,48 \times 10^{-5}$	$4,36 \times 10^{-5}$	0,002 ₈	0,0066	$1,48 \times 10^{-5}$ ₅	$4,36 \times 10^{-5}$ ₅	0,002 ₈	0,0066
SAT4	0,000 ₃	0,0008	$1,79 \times 10^{-6}$	$5,28 \times 10^{-6}$	0,000 ₃	0,0008	$1,79 \times 10^{-6}$ ₆	$5,28 \times 10^{-6}$ ₆	0,000 ₃	0,0008
SAT5	0,000 ₅	0,0011	$2,39 \times 10^{-6}$	$7,04 \times 10^{-6}$	0,000 ₅	0,0011	$2,39 \times 10^{-6}$ ₆	$7,04 \times 10^{-6}$ ₆	0,000 ₅	0,0011

Non-carcinogenic risks for heavy metal exposure were evaluated using the Hazard Quotient (HQ) for each route, which were subsequently accumulated into the Hazard Index (HI). As shown in Table 5, HI values for ingestion and dermal routes across all locations and age groups varied from 0.0003 to 0.0094. These values indicate that heavy metal exposure at the study site yielded an $HI < 1$, implying that the estimated chronic exposure remained below the safe reference dose. Consequently, the population surrounding the landfill currently does not face significant non-carcinogenic health risks.

However, demographic analysis revealed that children consistently received a higher Average Daily Dose (ADD) than adults, resulting in higher HI values (peaking at an HI of 0.0094 for children at location SAT2, compared to adults at the same location). This heightened vulnerability in children is influenced by physiological immaturity, a higher water intake ratio relative to body mass (child body weight of 15 kg versus 70 kg for adults), and underdeveloped biological detoxification capacities compared to the adult population.

Table 6. Carcinogenic Health Risk Assessment

Parameter	ADD ingestion		ADD dermal		CR ingestion		CR dermal		TCR	
	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children
Cr (VI)	0,000 ₂	0,00047	2.1×10^{-6} ₀	6.2×10^{-6}	4×10^{-4} ₄	9.31×10^{-4}	4.2×10^{-6} ₀	1.2×10^{-5}	4×10^{-4} ₄	9.5×10^{-4} ₄

Carcinogenic risk assessment, or Total Cancer Risk (TCR), was conducted specifically for chromium(VI) because this compound is classified as a Group A carcinogen (known to cause cancer in humans) via specific exposure routes. Based on the calculations in Table 6, the estimated TCR due to chromium(VI) exposure was 4.0×10^{-4} for adults and reached 9.5×10^{-4} for children. According to USEPA regulatory thresholds, the acceptable cancer risk range spans from 1×10^{-6} to 1×10^{-4} . The estimated TCR results in this study, for both adults and children, exceeded the upper tolerance threshold ($>1 \times 10^{-4}$). Furthermore, contrary to standard cumulative exposure risk projections, the data showed that the carcinogenic risk for children at the study site was relatively higher (9.5×10^{-4}) than that for adults (4.0×10^{-4}). This indicates that children possess an excessive vulnerability to the accumulation of carcinogenic substance exposure



at critical intake volumes.

Although the TCR calculation results exceeded acceptable risk limits, this interpretation must be weighed against the inherent uncertainties in risk modeling. First, the actual chromium(VI) concentration in the well water was below the instrument's limit of detection (<0.0099 mg/L). The use of a substituted value of 0.007 mg/L generated a highly conservative worst-case exposure calculation scenario. In reality, actual chromium(VI) concentrations could be significantly lower than this substituted value, meaning the true field carcinogenic risk might be negligible or fall within a safe range.

DISCUSSION

Leachate characteristics are strongly influenced by decomposition stages and the maturity level of a landfill. During the early acidic phase, organic matter decomposition and leaching occur intensively, producing leachate with relatively high concentrations of organic matter and inorganic components. In contrast, during the methanogenic phase, leachate characteristics tend to become more stable, as indicated by decreased concentrations of most pollutant parameters and a low BOD/COD ratio. As landfill age and stabilization increase, the mobility of certain metals may decrease, although their persistence and potential release remain controlled by waste characteristics, pH, redox conditions, and interactions between metals, organic matter, and minerals. Therefore, monitoring potentially toxic metals in leachate and in environmental media surrounding landfills, particularly soil and water, is essential for identifying potential contamination and community exposure pathways. Metal contaminants from landfills may migrate through soil into groundwater and subsequently enter the human body through ingestion, inhalation, or dermal pathways, with risk levels influenced by metal type, concentration, exposure duration, and exposure intensity. Landfills can act as point sources that degrade the quality of surrounding groundwater and well water, particularly when continuous leachate infiltration occurs. The persistence of certain metals prevents these contaminants from being readily eliminated from the environment, leading to potential accumulation in environmental components and organisms. Increased metallic concentrations driven by leachate percolation that breach designated water quality thresholds signify environmental degradation, thereby necessitating subsequent investigations focused on pollution sources, contaminant transport pathways, and potential public health or ecological hazards ((Saha et al., 2023; Meyrita et al., 2023).

The measured aluminum concentrations, ranging from 0.012 to 0.14 mg/L, indicate that the well water quality at the study location still complies with the World Health Organization (WHO) drinking water guideline value of 0.2 mg/L. Despite the ubiquitous detection of Al across all monitored shallow aquifer zones, this presence cannot be definitively assigned exclusively to leachate seepage from the landfill facility. Given that aluminum is an exceptionally prevalent element within the Earth's crust, its baseline occurrence is frequently linked to the natural weathering of aluminosilicate minerals. However, hydrogeochemical interactions, such as pH fluctuations or changes in redox conditions triggered by partial organic leachate seepage, may increase the solubility and mobility of natural Al toward residential wells. Conversely, the analytical non-detection of chromium(VI) indicates that substantial hexavalent chromium contamination did not occur. Analysis of well water around the landfill showed that chromium(VI) concentrations consistently remained below the detection limit (<0.0099 mg/L). This finding is consistent with previous groundwater assessments near industrial sites and waste disposal areas, where chromium has frequently been found below detection limits or measured at very low total concentrations (0.006 – 0.007 mg/L). Groundwater in deeper aquifers generally exhibits very low chromium(VI) concentrations due to natural reduction processes during transport, as evidenced by positive chromium isotope fractionation shifts. Highly mobile chromium(VI) is reduced to chromium(III), which tends to precipitate within the soil matrix. This process strongly depends on the presence of natural reducing agents in groundwater, such as organic matter, hydrogen sulfide (H_2S) gas, or iron oxyhydroxides (Ghezzi et al., 2024). From an environmental toxicology perspective, the presence of chromium(VI) in drinking water sources requires special attention because this metal species is globally recognized as a Group 1 carcinogenic agent capable of inducing DNA mutations in the digestive tract.

All obtained Hazard Index (HI) values were well below 1 ($HI < 1$). Based on USEPA guidelines, an $HQ > 1$ indicates the potential for adverse effects, whereas an $HQ < 1$ indicates that the non-carcinogenic risk from exposure remains within an acceptable level for consumption (Ranjan et al., 2026). Toxicologically, this implies that the estimated chronic exposure to heavy metals through ingestion and dermal routes remains below the corresponding safe reference doses. Consequently, the well water does not currently pose a significant non-carcinogenic health threat to residents. The oral ingestion pathway was the dominant contributor to health risks associated with heavy metals in groundwater, far exceeding exposure through dermal contact. Children exhibited significantly higher non-carcinogenic risk indices (HQ/HI) than adults. This elevated risk among children is driven by physiological immaturity, higher water intake per unit of body mass, and internal detoxification capacities that are not yet fully developed compared with those of adults (Ke et al., 2026).

Based on the USEPA risk management framework, the acceptable carcinogenic risk range spans from 1×10^{-6} to 1×10^{-4} . The TCR values obtained in this study, 4.0×10^{-4} for adults and 9.5×10^{-4} for children, clearly exceeded this upper tolerance threshold. Contrary to the general assumption that cancer risk increases primarily with prolonged adult lifetime exposure, these findings demonstrate that the projected carcinogenic risk in children was higher. This suggests





that intensive exposure per unit of body mass during the early growth phase contributes more substantially to the projected lifetime cancer risk than exposure duration alone in adults. Although the TCR values exceeded the 10^{-4} threshold, this conclusion should be interpreted within the context of modeling uncertainty. These risk estimates were derived from a worst-case scenario because they used a substituted concentration value (0.007 mg/L) for a substance that was not detected by the instrument. In environmental reality, actual chromium(VI) concentrations may be much lower, indicating that actual field risks are likely to fall within the safe range (Ghezzi et al., 2024).

CONCLUSION

Aluminum was detected in all well water samples collected around the landfill, with concentrations ranging from 0.012 to 0.14 mg/L, remaining compliant with the guideline values established by the World Health Organization (WHO) for drinking water quality. The presence of aluminum cannot be automatically attributed to landfill leachate infiltration, as it may also originate from natural mineral weathering processes in the surrounding environment. Meanwhile, chromium(VI) concentrations consistently remained below the instrument detection limit (<0.0099 mg/L). This finding indicates that substantial contamination by hexavalent chromium compounds did not occur in the shallow groundwater at the study site.

Evaluation of health risk characterization revealed that Hazard Index (HI) computations across both dermal absorption and ingestion pathways remained below unity ($HI < 1$), suggesting that projected chronic exposure levels have not generated substantial non-carcinogenic health hazards for local residents. Nevertheless, children consistently received higher Average Daily Dose (ADD) and HI values than adults due to their physiological vulnerability and higher water intake-to-body mass ratio. In contrast, the estimated Total Cancer Risk (TCR) from chromium(VI) exposure exceeded the upper acceptable limit established by the USEPA. However, this carcinogenic risk estimate represents a highly conservative worst-case scenario because it was calculated using a substituted value below the detection limit; therefore, the actual probability of cancer risk in the field is likely much lower and may remain within the safe range.

The main implication of this study is that the current well water quality does not indicate toxicologically adverse health effects; however, continuous environmental quality monitoring remains essential to protect vulnerable populations, particularly children. Methodological constraints within this investigation encompass a restricted sampling network and the implementation of substitute values for risk agents falling below analytical detection limits, factors that could potentially inflate carcinogenic risk estimates. Therefore, further research is recommended using tracer methods or isotope modeling to more precisely differentiate metal sources between natural hydrogeochemical processes and leachate contamination. Relevant authorities and landfill managers are also advised to periodically monitor groundwater quality fluctuations as a preventive measure against potential future leachate migration.

REFERENCES

- Abiye, T., Ayotamuno, A., EZEKWE, I., Raimi, M., & Imiete, G. (2025). Mapping Leachate Migration and Groundwater Risk in Port Harcourt: Geoelectrical Insights from Ten Open Dumpsites. *Open Access Journal of Science*, 8, 187–201. <https://doi.org/10.15406/oajs.2025.08.00263>
- Acarer Arat, S. (2024). Microplastics in landfill leachate: Sources, abundance, characteristics, remediation approaches and future perspective. *Desalination and Water Treatment*, 319, 100445. <https://doi.org/10.1016/j.dwt.2024.100445>
- Afolabi, O. O., Wali, E., Ihunda, E. C., Orji, M. C., Emelu, V. O., Bosco-Abiahu, L. C., Ogbuehi, N. C., Asomaku, S. O., & Wali, O. A. (2022). Potential environmental pollution and human health risk assessment due to leachate contamination of groundwater from anthropogenic impacted site. *Environmental Challenges*, 9, 100627. <https://doi.org/10.1016/j.envc.2022.100627>
- Aquino, L. F., Sales Junior, S. F., Kahwage, S., Bila, D. M., Correia, F. V., Saggioro, E. M., Ritter, E., & Mannarino, C. F. (2025). Groundwater contamination and human health risks from leachate at a decade-closed dumpsite: A case study in Rio de Janeiro, Brazil. *Science of The Total Environment*, 1008, 181034. <https://doi.org/10.1016/j.scitotenv.2025.181034>
- Dąbrowska, D., & Witkowski, A. J. (2022). Groundwater and Human Health Risk Assessment in the Vicinity of a Municipal Waste Landfill in Tychy, Poland. *Applied Sciences*, 12(24), Article 24. <https://doi.org/10.3390/app122412898>
- Ghezzi, L., Arrighi, S., Mugnaioli, E., Perchiazzi, N., Zamponi, E., Pollastri, S., Franceschini, F., & Petrini, R. (2024). Environmental impacts and risk assessment in the re-use of Cr-bearing pyrolyzed tannery wastes: A case study in a residential area. *Applied Geochemistry*, 168, 106029. <https://doi.org/10.1016/j.apgeochem.2024.106029>
- Gunarathne, V., Phillips, A. J., Zanoletti, A., Rajapaksha, A. U., Vithanage, M., Di Maria, F., Pivato, A., Korzeniewska, E., & Bontempi, E. (2024). Environmental pitfalls and associated human health risks and ecological impacts from landfill leachate contaminants: Current evidence, recommended interventions and future directions. *Science of The Total Environment*, 912, 169026. <https://doi.org/10.1016/j.scitotenv.2023.169026>
- Izza, N., Karbito, K., Fikri, A., & Masra, F. (2025). Analisis Risiko Kesehatan Lingkungan (ARKL) Pajanan Mangan





- (Mn) Pada Air Sumur Gali Masyarakat Sebagai Sumber Air Minum. *MIDWIFERY JOURNAL*, 5(2), 41–49.
- Kamara, I. N., Raco, B., Re, V., & Frazer-Williams, R. A. D. (2026). Integrated assessment of contaminants of emerging concern and potentially toxic trace elements in groundwater impacted by uncontrolled dump sites: Human and ecological risks in Freetown, Sierra Leone. *Journal of Hazardous Materials Advances*, 23, 101411. <https://doi.org/10.1016/j.hazadv.2026.101411>
- Kapoor, K., Kumar, S., Vishwakarma, D. K., Obaidullah, A. J., & Yadav, K. K. (2024). Health risk assessment of heavy metals in groundwater sources: Carcinogenic and non-carcinogenic evaluation. *Journal of Water and Health*, 22(10), 1972–1987. <https://doi.org/10.2166/wh.2024.243>
- Ke, X., Xiao, X., Chen, Q., Ren, J., & Pan, Y. (2026). Source analysis and Monte Carlo-based risk assessment of groundwater heavy metal contamination in typical industrial regions of Jiangxi, China. *Ecotoxicology and Environmental Safety*, 309, 119728. <https://doi.org/10.1016/j.ecoenv.2026.119728>
- Kissar, S., & Khemmoudj, K. (2025). Human health risk assessment (carcinogenic and non-carcinogenic) for heavy metals in groundwater: Case study of the Soummam Basin, Algeria. *Journal of Ecological Engineering*, 26(12), 383–399. <https://doi.org/10.12911/22998993/208866>
- Meyrita, M., Sandria, F. S., Najmi, I., Firdus, F., Rizki, A., & Nasir, M. (2023). Kontaminasi Logam Berat pada Air Sumur Warga Akibat Air Lindi dari Tempat Pemrosesan Akhir (TPA). *Jurnal Teknologi Lingkungan Lahan Basah*, 425–433. <https://doi.org/10.26418/jtllb.v11i2.64052>
- Pathan, S., Sreedevi, P. D., & Arora, T. (2026). Hydrogeochemical and statistical analysis of leachate-impacted groundwater in an urban landfill setting. *Journal of Contaminant Hydrology*, 282, 105035. <https://doi.org/10.1016/j.jconhyd.2026.105035>
- Ranjan, R. K., Raj, D., Kumar, A., Suman, S., Kumar, A., Somdutta, Mahato, J. K., Saw, S., & Patel, R. (2026). Integrated hydrogeochemical characterization, water quality index, and human health risk assessment of groundwater in Maharashtra, India. *Journal of Trace Elements and Minerals*, 18, 100333. <https://doi.org/10.1016/j.jtemin.2026.100333>
- Saha, P., Kumar Saikia, K., Kumar, M., & Handique, S. (2023). Assessment of health risk and pollution load for heavy and toxic metal contamination from leachate in soil and groundwater in the vicinity of dumping site in Mid-Brahmaputra Valley, India. *Total Environment Research Themes*, 8, 100076. <https://doi.org/10.1016/j.totert.2023.100076>
- Wang, D.-S., Liu, S.-L., Tan, L., He, W., & He, X.-S. (2027). The effect of regional consumption level on heavy metal pollution in landfill leachate across China should not be underestimated. *Waste Management*, 227, 115898. <https://doi.org/10.1016/j.wasman.2026.115898>