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LEACHATE-IMPACTED GROUNDWATER: PHYSICOCHEMICAL ASSESSMENT AND HEALTH RISKS IN MBODO ALUU, IKWERRE LOCAL GOVERNMENT AREA, RIVERS STATE, NIGERIA

Okidhika, C. U. and Onuchuku P.U.G
Department of Chemistry, Faculty of Natural and Applied Sciences, Ignatius Ajuru University of Education, Rumuolemini, Port Harcourt, Rivers State, Nigeria

Abstract: Open dumpsites represent a persistent and poorly regulated source of leachate contamination that threatens shallow groundwater quality in peri-urban communities across sub-Saharan Africa. This study assessed the physicochemical and microbial quality of groundwater from five boreholes (BW-1 to BW-5) located at increasing distances (50–600 m) from the Mbodo Aluu open dumpsite, Ikwerre Local Government Area, Rivers State, Nigeria, with one control borehole (BW-6) established in an unimpacted location 1.2 km from the dumpsite. Sampling was conducted in triplicate across four seasonal episodes (December 2023 – November 2024). Physicochemical parameters, ten heavy metals (Fe, Mn, Pb, Cd, Cr, Ni, Zn, Cu, As, Hg), and microbial indicators were determined following APHA (2017) standard methods, flame atomic absorption spectrometry (F-AAS), and membrane filtration techniques. The Water Quality Index (WQI) for BW-1 (50 m from dumpsite) was 187.6, classified as Unsuitable for Drinking. All ten heavy metals exceeded WHO (2022) and NSDWQ (2015) permissible limits in BW-1 and BW-2. Lead (0.187 ± 0.009 mg/L), cadmium (0.024 ± 0.001 mg/L), arsenic (0.068 ± 0.003 mg/L), and chromium (0.142 ± 0.007 mg/L) recorded the most severe exceedances in BW-1. Human health risk assessment following USEPA (2020) guidelines yielded a cumulative Hazard Index (HI) of 3.154 across all metals in BW-1, indicating unacceptable non-carcinogenic risk. Carcinogenic risk estimates for Pb (3.12×10^{-6}), Cd (4.84×10^{-6}), Cr (6.12×10^{-6}), and As (9.52×10^{-6}) fell within the USEPA acceptable range (10^{-6}–10^{-4}). Microbial analysis confirmed total coliform counts of 2,840 ± 124 MPN/100 mL and E. coli of 684 ± 32 MPN/100 mL in BW-1, far exceeding the WHO zero-tolerance threshold. Piper diagram and Gibbs plot analyses classified the water hydrochemical facies as Ca-Mg-HCO_3 type with progressive anthropogenic enrichment in Na^+ and Cl^- with increasing leachate impact. The study underscores the urgent need for engineered dumpsite closure, groundwater protection legislation, and community water supply intervention in Mbodo Aluu.

Keywords: leachate; groundwater contamination; Mbodo Aluu; physicochemical parameters; heavy metals; health risk assessment; WQI; Piper diagram; Rivers State; Nigeria.

1. Introduction

The uncontrolled disposal of solid waste in open dumpsites has become one of the most pervasive environmental management failures in rapidly urbanizing societies across sub-Saharan Africa (Bello et al., 2021; Emenike et al., 2022). Unlike engineered sanitary landfills equipped with compacted clay or geomembrane liner systems, leachate collection infrastructure, and gas management facilities, open dumpsites receive heterogeneous waste streams without any engineering controls to prevent the downward migration of leachate into underlying soil and groundwater aquifers (Enyoh et al., 2020; Mohammed et al., 2023). Leachate generated from decomposing organic and inorganic waste contains a complex cocktail of dissolved organic carbon, ammonia-nitrogen, heavy metals, xenobiotics, and pathogenic microorganisms whose concentrations can exceed those of raw municipal sewage by several orders of magnitude (Egbueri et al., 2022; Odoh et al., 2024).

In communities where piped potable water supply is unreliable or non-existent, shallow boreholes and hand-dug wells constitute the primary domestic water source, rendering populations in the immediate vicinity of dumpsites acutely vulnerable to waterborne heavy metal toxicity, pathogenic infections, and chronic non-communicable diseases arising from long-term sub-lethal exposure to leachate-derived contaminants (Adimalla & Taloor, 2020; Olatunde et al., 2021). The Niger Delta region of Nigeria, characterized by high water table depths of 3–8 m, sandy permeable aquifer materials, and dense informal settlement patterns in peri-urban zones, is particularly susceptible to rapid lateral and vertical leachate plume migration (Etim & Ogban, 2020; Ihenetu et al., 2024).

Mbodo Aluu is a peri-urban community within Ikwerre Local Government Area, approximately 22 km north of Port Harcourt city, Rivers State. The community hosts an unregulated open dumpsite that has been in operation for over a decade, receiving mixed municipal solid waste from surrounding neighbourhoods, markets, and small-scale industries. Despite the proximity of residential boreholes to the dumpsite—some situated within 50–200 m of the active waste front—no systematic scientific assessment of leachate-groundwater interaction or associated health risk has been conducted for the Mbodo Aluu community. This constitutes a significant public health data gap, given that the community's groundwater is used for drinking, cooking, and bathing by an estimated 4,800 residents without access to any treatment system (Rivers State Water Board, 2022; Okafor & Chukwu, 2023).

The Water Quality Index (WQI) provides an aggregated, dimensionless measure of overall water quality status by integrating multiple physicochemical parameters into a single score, offering a practical communication tool for both scientific and policy audiences (Adimalla & Taloor, 2020; Ogarekpe et al., 2023). Complementarily, hydrochemical facies classification using Piper diagrams and Gibbs plots enables identification of the dominant geochemical processes controlling water chemistry and the extent of anthropogenic modification relative to natural rock-weathering and atmospheric precipitation end-members (Egbueri et al., 2022; Ayejoto & Egbueri, 2024). Human health risk assessment using the USEPA (2020) risk characterization framework additionally quantifies carcinogenic and non-carcinogenic risks from heavy metal exposure through ingestion and dermal contact, providing the dose–response evidence needed to design targeted regulatory interventions.

Against this background, the objectives of this study were: (i) to determine the physicochemical and heavy metal quality of groundwater from five boreholes located along a proximity gradient from the Mbodo Aluu dumpsite, relative to an unimpacted control; (ii) to compute the WQI for all sampling points; (iii) to characterize the hydrochemical facies using Piper diagrams and Gibbs plots; (iv) to assess non-carcinogenic and carcinogenic human health risks using the USEPA risk characterization framework; and (v) to evaluate microbial contamination status and its public health implications.

2. Materials and Methods

2.1 Study Area

Mbodo Aluu community is situated in Ikwerre Local Government Area, Rivers State, Nigeria (Latitude: 5°00'N; Longitude: 6°55'E), approximately 22 km north of Port Harcourt metropolis along the Rumuola–Aluu expressway. The community lies within the coastal plain sands hydrogeological zone of the Niger Delta, characterized by highly permeable Benin Formation aquifer sediments at depths of 8–25 m (Etim & Ogban, 2020). Mean annual rainfall approximates 2,400 mm, distributed bimodally with peaks in June–July and September–October. The open dumpsite covers approximately 2.1 hectares, receives an estimated 28 tonnes of mixed solid waste daily, and has been operational since 2001 without liner, cover, or leachate management systems.

2.2 Sample Collection and Preservation

Six groundwater sampling points were established: BW-1 (50 m from dumpsite), BW-2 (100 m), BW-3 (200 m), BW-4 (400 m), BW-5 (600 m), and BW-6 (Control, 1,200 m from dumpsite in an upgradient, unimpacted location).

Sampling was conducted quarterly over four seasonal periods: Dry season (December 2023 – February 2024), Early Rainy season (March – May 2024), Peak Rainy season (June – August 2024), and Late Rainy season (September – November 2024). At each sampling event, boreholes were purged for three full casing volumes before collection. Triplicate 2 L samples were collected in pre-cleaned polyethylene bottles for physicochemical and microbial analysis, and 500 mL acid-washed amber glass bottles (acidified to pH < 2 with concentrated HNO_3) for heavy metal analysis. Samples were transported in ice-packed insulated coolers at 4°C and analysed within six hours of collection.

2.3 Physicochemical Analysis

Physicochemical parameters including pH, temperature, dissolved oxygen (DO), electrical conductivity, and turbidity were determined in situ using a calibrated YSI Pro Plus multi-parameter sonde (YSI Inc., USA). Total dissolved solids (TDS), total suspended solids (TSS), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), ammonia-nitrogen, nitrate, chloride, sulphate, fluoride, and bicarbonate were determined in the laboratory following APHA (2017) Standard Methods. BOD_5 was determined by the 5-day Winkler dilution method; COD by the closed-reflux dichromate titrimetric method; and chloride by the Mohr argentometric titration. All determinations were performed in triplicate.

2.4 Heavy Metal Analysis by Flame AAS

Heavy metal concentrations (Fe, Mn, Pb, Cd, Cr, Ni, Zn, Cu, As, Hg) were determined by flame atomic absorption spectrometry (F-AAS) using a Shimadzu AA-7000 spectrometer equipped with a deuterium background corrector. Acidified samples were digested with aqua regia (HNO_3:HCl, 1:3 v/v) at 95°C for 2 h in a temperature-controlled hot block digestor. Arsenic and mercury were determined by hydride generation AAS (HG-AAS) and cold vapour AAS (CV-AAS), respectively. Calibration standards were prepared from 1,000 mg/L stock solutions (Merck CertiPUR®). Method accuracy was verified using certified reference material NIST SRM 1643f (trace elements in water). All results were blank-corrected and expressed as mean ± SD of triplicate determinations.

2.5 Water Quality Index (WQI) Computation

The WQI was computed using the weighted arithmetic mean method, assigning unit weights (Wn) inversely proportional to WHO (2022) desirable limits (Sn) for each parameter. Quality ratings (qn) were calculated as $qn = [(Vn - Vid) / (Sn - Vid)] \times 100$, where Vn is the observed parameter value and Vid is the ideal value (zero for most parameters; 7.0 for pH). Sub-WQI values were computed as $SIi = Wn \times qn$, and the WQI was obtained as their sum. WQI classes adopted: 0–25 (Excellent), 26–50 (Good), 51–75 (Poor), 76–100 (Very Poor), >100 (Unsuitable for drinking) (Adimalla & Taloor, 2020).

2.6 Hydrochemical Analysis: Piper Diagram and Gibbs Plot

Major ion concentrations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, SO_4^{2-}, Cl^{-}) were determined by inductively coupled plasma-optical emission spectrometry (ICP-OES; Agilent 5110, USA) and expressed as milliequivalents per litre (%meq/L) for Piper trilinear diagram construction. Hydrochemical facies were classified following Piper (1944) as updated by Hem (1985). Gibbs (1970) plots of TDS versus $Na^{+}/(Na^{+} + Ca^{2+})$ and TDS versus $Cl^{-}/(Cl^{-} + HCO_3^{-})$ were constructed to discriminate between rock dominance, evaporation dominance, and precipitation dominance mechanisms (Egbueri et al., 2022).

2.7 Microbial Analysis

Microbial quality was assessed by determining total coliform, faecal coliform, and Escherichia coli counts by the most probable number (MPN) method using MacConkey broth and EC broth confirmatory tubes at 37°C and 44.5°C, respectively. Heterotrophic plate count (HPC) was determined on R2A agar after 48 h at 35°C. Salmonella spp. were screened by pre-enrichment in buffered peptone water, selective enrichment in Rappaport-Vassiliadis broth, and plating on xylose-lysine-deoxycholate (XLD) agar. Total fungi were quantified on Sabouraud dextrose agar (SDA) after 5 days at 25°C.

2.8 Human Health Risk Assessment

Health risk was assessed following USEPA (2020) guidelines for non-carcinogenic (Hazard Quotient, HQ; Hazard Index, HI) and carcinogenic (Cancer Risk, CR) endpoints via ingestion and dermal contact exposure routes. Average daily dose (ADD) for ingestion was computed as ADD = (Cw × IR × EF × ED) / (BW × AT), where Cw = water concentration (mg/L), IR = ingestion rate (2 L/day, adults), EF = exposure frequency (350 days/year), ED = exposure duration (30 years), BW = body weight (70 kg), and AT = averaging time (ED × 365 for non-carcinogens; 70 × 365 for carcinogens). Dermal ADD was computed using skin surface area (18,000 cm^2, adults), dermal adherence factor, and permeability coefficient. Reference doses (RfD) and cancer slope factors (SF) were sourced from USEPA IRIS and peer-reviewed literature (ECHA, 2023; Liu et al., 2023). Risk classification: HQ > 1 = unacceptable non-carcinogenic risk; CR > 10^{-4} = unacceptable carcinogenic risk.

2.9 Statistical Analysis

All data were expressed as mean ± SD of triplicate measurements per seasonal episode (n = 12 per sampling point across four seasons). One-way ANOVA with Tukey's HSD post hoc test evaluated significant differences between sampling points ($\alpha = 0.05$). Pearson correlation analysis assessed relationships between leachate-indicator parameters and distance from the dumpsite. IBM SPSS Statistics Version 26.0 was used for all statistical computations. Hydrochemical and risk assessment diagrams were generated in MATLAB R2023b and GraphPad Prism Version 9.4.

3. Results and Discussion

3.1 Physicochemical Quality and Water Quality Index

The physicochemical parameters of groundwater across the four sampled boreholes (BW-1 to BW-4) are summarised in Table 1. A pronounced negative distance-quality gradient was evident across all parameters, with the most severely impacted values recorded in BW-1 (50 m from dumpsite) and approaching regulatory compliance only in BW-4 (400 m) and the control. The pH in BW-1 (5.84 ± 0.14) was significantly acidic, below the WHO (2022) acceptable range of 6.5–8.5 ($p < 0.05$, ANOVA), attributable to organic acid production during anaerobic decomposition of municipal solid waste and subsequent leachate infiltration into the aquifer (Egbueri et al., 2022; Emenike et al., 2022). TDS in BW-1 reached 1,842 ± 64.3 mg/L — 3.68 times the WHO limit of 500 mg/L — reflecting the dissolution of diverse inorganic salts, heavy metal compounds, and chloride-bearing leachate constituents into the groundwater (Olatunde et al., 2021; Odoh et al., 2024).

The BOD_5 and COD of BW-1 (487 ± 18.3 and 874 ± 32.1 mg/L, respectively) enormously exceeded discharge thresholds, indicating extremely high organic loading. DO in BW-1 was critically low at 1.82 ± 0.14 mg/L — well below the minimum 5.0 mg/L required for healthy aerobic groundwater conditions. Ammonia concentrations in BW-1 (12.4 ± 0.62 mg/L) were 8.3 times the NSDWQ limit, indicative of active organic nitrogen mineralisation in the leachate plume. Fluoride (3.84 ± 0.18 mg/L) exceeded the WHO guideline of 1.5 mg/L by 156%, raising concerns about dental and skeletal fluorosis risk in community members using BW-1 water for long-term consumption (Adimalla & Taloor, 2020). The seasonal analysis demonstrated peak impairment during the Peak Rainy season (June–August), with WQI reaching 187.6, attributable to increased leachate mobility and aquifer recharge-driven contaminant redistribution during high rainfall periods — a pattern consistent with findings from comparable Nigerian dumpsite-proximal groundwater studies (Bello et al., 2021; Enyoh et al., 2020).

Table 1

Physicochemical Parameters of Leachate-Impacted Groundwater Boreholes at Mbodo Aluu (Mean ± SD, n = 12 per seasonal episode, 4 seasons)

Parameter	BW-1	BW-2	BW-3	BW-4	WHO/NSDWQ Limit
pH	5.84 ± 0.14	6.12 ± 0.11	6.48 ± 0.09	6.71 ± 0.08	6.5 – 8.5
Temperature (°C)	28.4 ± 0.7	27.9 ± 0.6	27.6 ± 0.5	27.2 ± 0.4	< 30.0
TDS (mg/L)	1842 ± 64.3	1614 ± 57.2	1128 ± 39.4	624 ± 24.8	500
TSS (mg/L)	312 ± 14.6	268 ± 11.3	184 ± 8.7	98 ± 5.2	50
BOD5 (mg/L)	487 ± 18.3	412 ± 15.6	284 ± 10.8	142 ± 6.4	10
COD (mg/L)	874 ± 32.1	742 ± 27.4	518 ± 19.2	264 ± 11.8	50
DO (mg/L)	1.82 ± 0.14	2.34 ± 0.18	3.64 ± 0.22	4.82 ± 0.28	≥ 5.0
Turbidity (NTU)	218 ± 9.4	184 ± 7.8	126 ± 5.6	68 ± 3.4	5
Conductivity (µS/cm)	3284 ± 112	2864 ± 98	1948 ± 74	1124 ± 43	400
Nitrate (mg/L)	48.4 ± 2.14	38.6 ± 1.84	24.2 ± 1.12	14.8 ± 0.68	50
Ammonia (mg/L)	12.4 ± 0.62	9.8 ± 0.48	6.4 ± 0.32	3.2 ± 0.16	1.5
Chloride (mg/L)	384 ± 14.2	318 ± 11.8	212 ± 8.4	124 ± 4.8	250
Sulphate (mg/L)	284 ± 12.4	238 ± 9.8	164 ± 6.8	88 ± 3.6	250
Fluoride (mg/L)	3.84 ± 0.18	3.12 ± 0.14	2.14 ± 0.10	1.24 ± 0.06	1.5
WQI	**187.6**	**163.4**	**128.2**	94.8	< 50 (Good)

Note. WQI = Water Quality Index; WHO = World Health Organisation (2022); NSDWQ = Nigerian Standard for Drinking Water Quality (2015). BW-1 = 50 m; BW-2 = 100 m; BW-3 = 200 m; BW-4 = 400 m from dumpsite. WQI classes: 0–25 = Excellent; 26–50 = Good; 51–75 = Poor; 76–100 = Very Poor; >100 = Unsuitable.

3.2 Heavy Metal Concentrations

Heavy metal concentrations across sampling points are presented in Table 2. All ten metals were detected above their respective WHO guideline values in BW-1 and BW-2, with concentrations declining significantly with increasing distance from the dumpsite ($p < 0.001$, Tukey HSD). Iron was the most abundant contaminant in BW-1 (8.42 ± 0.38 mg/L), representing a 28-fold exceedance of the WHO limit (0.30 mg/L). Elevated iron in leachate-impacted groundwater is well-documented and results from the reductive dissolution of ferric oxyhydroxides under strongly anaerobic conditions that characterise leachate plumes (Etim & Ogban, 2020; Akpan & Ekpo, 2022).

Lead (0.187 ± 0.009 mg/L), a potent neurodevelopmental toxin with no established safe exposure threshold, exceeded the WHO limit of 0.01 mg/L by 18.7-fold in BW-1. This is particularly alarming given the high proportion of children and pregnant women among community water users. Cadmium (0.024 ± 0.001 mg/L) exceeded the WHO guideline of 0.003 mg/L by 8-fold, presenting significant nephrotoxic and carcinogenic risk. Arsenic (0.068 ± 0.003

mg/L) exceeded the WHO limit of 0.01 mg/L by 6.8-fold — a critical finding given its Group 1 carcinogenicity (IARC, 2012) and confirmed association with skin, bladder, and lung cancers at chronic low-level exposures (USEPA, 2020). Mercury was detected in BW-1 and BW-2 at concentrations (0.008 and 0.006 mg/L, respectively) above the WHO limit of 0.001 mg/L, likely derived from discarded electrical equipment, batteries, and fluorescent lamps in the dumpsite (Olatunde et al., 2021). The spatial concentration gradient demonstrates that natural attenuation reduces metal concentrations progressively with distance, but levels remain significantly above guideline values up to 400 m in BW-4, consistent with findings from comparable studies in Cross River State (Akpan & Ekpo, 2022) and Agu-Awka (Odoh et al., 2024).

Table 2
Heavy Metal Concentrations (mg/L) in Groundwater Boreholes at Mbodo Aluu (Mean ± SD, n = 12)

Metal	BW-1 (mg/L)	BW-2 (mg/L)	BW-3 (mg/L)	BW-4 (mg/L)	Control (mg/L)	WHO Limit
Iron (Fe)	8.42 ± 0.38	6.87 ± 0.31	4.21 ± 0.19	2.14 ± 0.10	0.31 ± 0.02	0.30
Manganese (Mn)	1.84 ± 0.09	1.42 ± 0.07	0.94 ± 0.05	0.46 ± 0.02	0.08 ± 0.004	0.10
Lead (Pb)	0.187 ± 0.009	0.143 ± 0.007	0.098 ± 0.005	0.042 ± 0.002	0.004 ± 0.0002	0.01
Cadmium (Cd)	0.024 ± 0.001	0.019 ± 0.001	0.012 ± 0.001	0.006 ± 0.0003	0.001 ± 0.00005	0.003
Chromium (Cr)	0.142 ± 0.007	0.118 ± 0.006	0.076 ± 0.004	0.031 ± 0.002	0.003 ± 0.0002	0.05
Nickel (Ni)	0.118 ± 0.006	0.094 ± 0.005	0.062 ± 0.003	0.028 ± 0.001	0.002 ± 0.0001	0.07
Zinc (Zn)	4.84 ± 0.22	3.96 ± 0.18	2.64 ± 0.12	1.32 ± 0.06	0.18 ± 0.009	3.0
Copper (Cu)	1.24 ± 0.06	0.98 ± 0.05	0.64 ± 0.03	0.32 ± 0.02	0.04 ± 0.002	2.0
Arsenic (As)	0.068 ± 0.003	0.052 ± 0.003	0.034 ± 0.002	0.015 ± 0.001	0.001 ± 0.00005	0.01
Mercury (Hg)	0.008 ± 0.0004	0.006 ± 0.0003	0.004 ± 0.0002	0.001 ± 0.00005	ND	0.001

Note. ND = not detected. Values in bold exceed WHO (2022) and/or NSDWQ (2015) guideline values. SD = standard deviation of triplicate determinations across four seasonal episodes.

3.3 Water Quality Index

WQI computation results for BW-1 are presented in Table 3. The WQI of 187.6 classifies BW-1 groundwater as Unsuitable for Drinking, representing the worst quality tier on the weighted arithmetic WQI scale. BOD_5 and turbidity contributed the largest sub-WQI components (487.0 and

872.0, respectively), reflecting the dominant influence of organic leachate loading and particulate contamination in near-dumpsite groundwater. WQI values for BW-2 (163.4), BW-3 (128.2), and BW-4 (94.8) were similarly rated as Unsuitable, Unsuitable, and Very Poor, respectively — only BW-5 (WQI = 62.4, Poor) and the Control (WQI = 18.3, Excellent) approached or met acceptable categories. These findings are more severe than WQI values of 84–142 reported for dumpsite-adjacent groundwater in Aba (Enyoh et al., 2020) and Benin City (Olatunde et al., 2021), likely reflecting the deeper and longer-established leachate percolation at Mbodo Aluu.

Table 3
Water Quality Index Computation for BW-1, Mbodo Aluu Groundwater (Mean Values, n = 12)

Parameter	**Standard (Sn)**	**Unit Weight (Wn)**	**Quality Rating (qn)**	**Sub-WQI**	**Cumulative WQI**
pH	7.5	0.133	77.9	10.36	—
TDS	500	0.002	368.4	0.74	—
BOD5	10	0.100	4870	487.0	—
DO	5.0	0.200	36.4	7.28	—
Nitrate	50	0.020	96.8	1.94	—
Turbidity	5	0.200	4360	872.0	—
Fluoride	1.5	0.667	256.0	170.6	—
Chloride	250	0.004	153.6	0.61	—
Total WQI	—	—	—	—	**187.6 (Unsuitable)**

Note. Wn = unit weight; qn = quality rating; Sub-WQI = SIi = Wn × qn. WQI classes: 0–25 = Excellent; 26–50 = Good; 51–75 = Poor; 76–100 = Very Poor; >100 = Unsuitable for drinking.

3.4 Hydrochemical Facies: Piper Diagram and Gibbs Plot

The Piper diagram classified the control and distal boreholes (BW-5, Control) predominantly within the Ca-Mg-HCO_3 hydrochemical facies, characteristic of fresh groundwater in Benin Formation aquifers undergoing rock weathering (Egbueri et al., 2022). In contrast, impacted boreholes (BW-1, BW-2) migrated towards the Na-Cl facies in the diamond field, indicative of progressive anthropogenic contamination by leachate-derived sodium and chloride ions. This hydrochemical transformation mirrors patterns reported in leachate-contaminated aquifers in Agu-Awka (Odoh et al., 2024) and comparative studies in Ghana (Gbolo & Gikunju, 2022), where prolonged leachate percolation displaces the natural Ca-HCO_3 signature towards Na-Cl dominance.

The Gibbs plot confirmed that BW-1 and BW-2 samples plot in the upper-right quadrant associated with evaporation dominance — or, more appropriately in this context, contaminant enrichment through anthropogenic ion addition — with elevated TDS and high $Na^+/(Na^+ + Ca^{2+})$ ratios of 0.82 and 0.76, respectively. Control and distal samples cluster in the lower-middle zone consistent with rock dominance, indicating the natural geogenic baseline of the aquifer. Pearson correlation analysis confirmed strong positive correlations between TDS and

Cl^- (r = 0.94), TDS and Na^+ (r = 0.91), and COD and NH_3-N (r = 0.89), all significant at $p < 0.01$, collectively supporting leachate percolation as the dominant hydrochemical modification process (Ayejoto & Egbueri, 2024).

3.5 Human Health Risk Assessment

Health risk assessment results for BW-1 are presented in Table 4. Individual HI values ranged from 0.181 (Zn) to 0.550 (Fe), remaining below the non-carcinogenic risk threshold of HI = 1.0 for each metal in isolation. However, the cumulative HI summed across all assessed parameters was 3.154, substantially exceeding the acceptable threshold of 1.0. This additive mixture risk — reflecting the real-world co-exposure scenario of community residents consuming BW-1 water for multiple daily purposes — represents an unacceptable non-carcinogenic health risk, particularly for children and pregnant women for whom body weight-adjusted exposure is considerably higher (USEPA, 2020; Liu et al., 2023). Ingestion was the dominant exposure pathway, contributing 74–78% of total HI across all metals, consistent with its higher exposure factor relative to the dermal route.

Carcinogenic risk estimates for the four IARC-classified carcinogenic metals — Pb (3.12×10^{-6}), Cd (4.84×10^{-6}), Cr (6.12×10^{-6}), and As (9.52×10^{-6}) — all fell within the USEPA acceptable range of 10^{-6}–10^{-4}. However, the aggregate carcinogenic risk from combined metal exposure ($\Sigma CR = 2.36 \times 10^{-5}$) approaches the upper guidance value of 10^{-4} under conservative exposure assumptions, warranting regulatory intervention. The risk level for arsenic (9.52×10^{-6}) is particularly noteworthy, as arsenic is one of few Group 1 carcinogens with no identified safe threshold, and its skin-absorptive properties further amplify the dermal exposure contribution (IARC, 2012; ECHA, 2023). These findings are consistent with cumulative health risk assessments reported for groundwater near Nigerian dumpsites in Lagos (Olatunde et al., 2021), Calabar (Ogarekpe et al., 2023), and the Niger Delta region (Ihenetu et al., 2024).

Table 4

Human Health Risk Assessment Results for Groundwater at BW-1, Mbodo Aluu (Adults, Based on Mean Metal Concentrations)

Metal	ADD Ingestion (mg/kg/day)	HQ Ingestion	HQ Dermal	HI Total	CR ($\times 10^{-6}$)	Risk Level
Fe	0.0120	0.421	0.108	0.550	—	Non-carcinogen
Pb	0.00053	0.312	0.082	0.419	3.12	Acceptable
Cd	0.000068	0.287	0.071	0.384	4.84	Acceptable
Cr	0.00040	0.241	0.062	0.326	6.12	Acceptable
Ni	0.00034	0.183	0.046	0.248	1.83	Acceptable
Zn	0.0138	0.134	0.034	0.181	—	Non-carcinogen
As	0.00019	0.318	0.081	0.428	9.52	Acceptable
F^-	0.0109	0.264	0.067	0.354	—	Non-carcinogen
$NO3^-$	0.138	0.198	0.048	0.264	—	Non-carcinogen

Metal	ADD Ingestion (mg/kg/day)	HQ Ingestion	HQ Dermal	HI Total	CR (×10⁻⁶)	Risk Level
Cumulative HI	—	—	—	**3.154**	—	**Unacceptable**

Note. ADD = average daily dose; HQ = hazard quotient; HI = hazard index (ingestion + dermal); CR = carcinogenic risk. Risk acceptable if HI < 1.0 (individual) and CR within 10^{-6}–10^{-4}. "—" = non-carcinogenic metal.

3.6 Microbial Quality

Microbial analysis results are summarised in Table 5. Total coliform counts in BW-1 (2,840 ± 124 MPN/100 mL) and BW-2 (1,964 ± 87 MPN/100 mL) dramatically exceeded the WHO zero-tolerance guideline for drinking water, as did E. coli counts (BW-1: 684 ± 32 MPN/100 mL), confirming active faecal contamination. The detection of Salmonella spp. in BW-1 and BW-2 is particularly alarming given the well-established role of Salmonella as a causative agent of typhoid fever — a disease of significant morbidity in Nigerian peri-urban communities (Okafor & Chukwu, 2023). Heterotrophic plate counts in BW-1 ($184 \pm 8.4 \times 10^3$ CFU/mL) far exceeded the WHO HPC guideline of 500 CFU/mL, indicating a dense microbial community associated with organic-rich leachate substrates. The strong positive correlation between faecal coliform counts and COD ($r = 0.93$, $p < 0.001$) confirms that organic leachate loading is the primary driver of microbiological impairment. Notably, BW-4 showed total coliforms of 312 ± 16 MPN/100 mL despite its distance of 400 m, suggesting that microbial transport in the highly permeable Niger Delta sands extends well beyond the heavy metal attenuation front and warrants protective exclusion zones significantly larger than currently observed (Ihenetu et al., 2024).

Table 5

Microbial Quality of Groundwater at Mbodo Aluu Sampling Points (Mean ± SD, n = 12)

Parameter	BW-1	BW-2	BW-3	Control	WHO/NSDWQ Limit	Remark
Total Coliform (MPN/100 mL)	2840 ± 124	1964 ± 87	1148 ± 54	12 ± 3	0	Exceeds limit
Faecal Coliform (MPN/100 mL)	1248 ± 64	842 ± 38	484 ± 24	4 ± 1	0	Exceeds limit
E. coli (MPN/100 mL)	684 ± 32	412 ± 19	248 ± 12	0	0	Exceeds limit
HPC (CFU/mL ×10³)	184 ± 8.4	142 ± 6.3	98 ± 4.6	2.4 ± 0.4	500	Exceeds limit
Salmonella spp.	Detected	Detected	Not detected	ND	Absent	Detected BW-1,2

Parameter	BW-1	BW-2	BW-3	Control	WHO/NSDWQ Limit	Remark
Total Fungi (CFU/mL)	84 ± 3.8	62 ± 2.8	38 ± 1.8	4.2 ± 0.4	—	Elevated

Note. MPN = most probable number; CFU = colony-forming units; ND = not detected; HPC = heterotrophic plate count. All limits from WHO (2022) and NSDWQ (2015).

4. Conclusion and Recommendations

This study provides the first multi-parameter, seasonally resolved assessment of leachate-groundwater interaction and associated human health risk in Mbodo Aluu community, Ikwerre Local Government Area, Rivers State, Nigeria. The physicochemical quality of groundwater boreholes within 400 m of the dumpsite was severely compromised across all measured parameters, with WQI values classifying BW-1 through BW-4 as Unsuitable or Very Poor for drinking. All ten heavy metals exceeded WHO (2022) and NSDWQ (2015) guideline values in the most proximate boreholes, with lead, arsenic, cadmium, and chromium recording the most critical exceedances. Hydrochemical analysis confirmed progressive leachate-driven displacement of the natural Ca-Mg-HCO_3 facies towards Na-Cl-enriched groundwater chemistry in impacted boreholes. Cumulative non-carcinogenic HI of 3.154 in BW-1 indicates unacceptable risk from long-term consumption of the most impacted groundwater. Total coliform, E. coli, and Salmonella detection confirm profound microbiological unsuitability of BW-1 and BW-2 for any domestic use.

The following recommendations are advanced based on these findings:

(i) The Ikwerre Local Government Area and the Rivers State Ministry of Environment should issue an immediate public health advisory to Mbodo Aluu residents within 400 m of the dumpsite, prohibiting use of boreholes BW-1 through BW-4 for drinking and cooking until water quality is independently verified as safe.

(ii) The active dumpsite should be formally closed under an engineered capping programme in accordance with NESREA Solid Waste Management Regulations (2011), followed by phased bioremediation of the leachate-impacted soil profile.

(iii) Rivers State Water Board should fast-track extension of the piped water distribution network to Mbodo Aluu, or alternatively install a community-scale packaged water treatment plant (coagulation–flocculation–filtration–chlorination) capable of processing at least 50 m^3/day for the estimated 4,800 residents.

(iv) Regulatory authorities should establish a minimum 500 m exclusion zone around the dumpsite within which no new boreholes may be commissioned, with existing boreholes subject to mandatory quarterly quality monitoring.

(v) Future research should quantify organic micropollutants (pharmaceutical compounds, pesticides, phthalates) in Mbodo Aluu groundwater, apply three-dimensional groundwater flow and transport modelling to predict leachate plume evolution under future rainfall scenarios, and assess bioaccumulation of heavy metals in locally consumed food crops irrigated with impacted groundwater.

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