Sahel Journal of Life Sciences FUDMA (SAJOLS)
June 2026 Vol. 4(2): 206-220
ISSN: 3027-0456 (Print)
ISSN: 1595-5915 (Online)
DOI: *https://doi.org/10.33003/sajols-2026-0402-22*

Research Article

Health Risk Assessment of Heavy Metal Pollution and Microbial Contamination of Borehole Water Sources in close proximity to Dumpsite in Kaduna, Nigeria

Olawale Gabriel Olowomofe[1] and *Temitayo Omotunde Olowomofe[2]

[1]Department of Physics, Federal University, Oye-Ekiti, Nigeria
[2]Department of Microbiology, Ekiti State University, Ado-Ekiti, Nigeria
****Corresponding Author's email***: *omotunde.olowomofe@eksu.edu.ng*; **Phone: +2348063132002**

ABSTRACT

Borehole water is widely used for drinking because it is generally considered a safe groundwater source; however, its quality may be compromised when boreholes are located near poorly managed waste disposal sites. This study assessed heavy metal contamination, bacteriological quality, bacterial diversity, antibiotic resistance, and associated health risks of borehole water collected near a military-operated dumpsite within the Nigerian Defence Academy (NDA), Kaduna, Nigeria. Fifty borehole water samples were analyzed for Cu, Zn, Co, Cr, Pb, Mn, Cd, and Ni using Flame Atomic Absorption Spectrophotometry. Microbiological quality was determined by Total bacterial and Coliform counts, while antibiotic susceptibility was evaluated using the Kirby–Bauer disk diffusion method following Clinical and Laboratory Standards Institute guidelines. Heavy metal concentrations were generally below guideline limits, although selected toxicants showed narrow safety margins. Maximum concentrations were Cu (0.1056 mg/L), Mn (0.0144 mg/L), Pb (0.0117 mg/L), and Cd (0.0030 mg/L), with cadmium reaching the World Health Organization and Nigerian drinking water limits. Noncarcinogenic risk assessment indicated a hazard index below 1, while chromium presented a low but non-zero lifetime cancer risk. Total bacterial counts ranged from 3.02 ± 0.08 to 4.89 ± 0.14 $\log_{10}$ CFU/mL, and coliform counts from 1.02 ± 0.11 to 2.79 ± 0.09 $\log_{10}$ CFU/mL. Predominant isolates included *Staphylococcus aureus* (80%), *Escherichia coli* (70%), *Pseudomonas aeruginosa* (60%), and *Klebsiella pneumoniae* (50%). Multidrug resistance was common, particularly among *P. aeruginosa* and *E. coli*. These findings highlight significant groundwater contamination and the need for improved waste management, routine monitoring, and water treatment before consumption.

Keywords: Antibiotic resistance; Borehole water; Groundwater quality; Health risk assessment; Heavy metals; Military dumpsite; Total and Fecal Coliform

Citation: Olowomofe, O.G., & Olowomofe, T.O. (2026). Health Risk Assessment of Heavy Metal Pollution and Microbial Contamination of Borehole Water Sources in close proximity to Dumpsite in Kaduna, Nigeria. *Sahel Journal of Life Sciences FUDMA*, 4(2): 206-220. DOI: https://doi.org/10.33003/sajols-2026-0402-22

INTRODUCTION

Groundwater remains the quiet backbone of domestic water supply across much of Nigeria, particularly where municipal networks are intermittent, undersized, or absent. Within institutional campuses, boreholes often function as the default potable water source, not because they are inherently safer, but because they are available, affordable, and socially trusted. Recent evidence shows that when boreholes are sited near waste dumps and informal industrial nodes, measurable deterioration in groundwater chemistry and human health risk indicators can occur across seasons, with hazard quotients and cancer risk metrics exceeding guideline ranges in some settings (Nlemolisa *et al.,* 2025). These observations are consistent with a broader pattern that is now well established in high impact environmental literature: groundwater quality near waste repositories is governed less by a single contaminant and more by coupled processes of leachate generation, metal mobilization, subsurface transport, and sustained exposure through daily consumption.

Heavy metals are central to this concern because they persist, bioaccumulate, and do not undergo microbial degradation in the way many organic contaminants do. Their toxicology is also heterogeneous: elements such as lead, cadmium, and chromium are associated with neurological impairment, renal injury, haematological effects, and carcinogenic potential under chronic exposure, while copper, manganese, zinc, and nickel can shift from nutritional relevance to toxicity when concentrations or exposure duration rise beyond physiological buffering. The World Health Organization continues to update guidance values and chemical fact sheets for drinking water, including metals such as chromium, manganese, and nickel, reflecting ongoing evidence that low dose, long term exposure and mixture effects matter for public health protection (WHO, 2022). In the Nigerian regulatory context, the Nigerian Standard for Drinking Water Quality provides an important national benchmark for permissible limits and compliance framing, but real-world exposure is shaped by local siting decisions, hydrogeology, and the absence of routine surveillance at many point sources.

Dumpsites represent a particularly efficient interface between surface activities and groundwater systems because they generate leachate with complex and variable composition, especially where waste is unsegregated, and the base is unlined. Recent work in Chemosphere has shown that potentially toxic elements in active landfill leachates can be sufficiently elevated to influence adjacent groundwater within short stand-off distances, with patterns that support leachate migration and site-specific geochemical control on metal mobility (Jolaosho, 2024). Complementary high impact evident from studies similarly emphasizes that the contamination potential of landfill leachate is not a theoretical possibility but a measurable outcome that depends on containment integrity, soil properties, hydrologic connectivity, and time (Adeniran *et al.,* 2023). These insights are directly relevant to institutional dumpsites where engineered liners, leachate collection, and monitoring wells are frequently absent.

Studies in developing regions, particularly in Nigeria and other parts of Sub-Saharan Africa, have consistently shown that borehole water sources near dumpsites are highly vulnerable to contamination by heavy metals and pathogenic microorganisms. This is mainly due to leachate migration from unmanaged solid waste disposal sites into surrounding soil and groundwater systems (WHO, 2022; Ogbuene *et al.,* 2025).

Military environments add a further layer of complexity that is often missing from civilian dumpsite studies. Military installations generate conventional municipal waste, but also produce operationally specific waste streams that may include metal-rich residues, spent ammunition fragments, firing range debris, coatings, solvents, lubricants, batteries, and maintenance byproducts. Reviews of contamination at firing ranges and military impacted soils document that ammunition weathering can enrich soils with lead and associated metals, and that contaminant mobility, bioaccessibility, and eventual transfer to water pathways depend on mineral transformations and environmental conditions (Sanderson *et al.*, 2018; Zhu *et al.,* 2024). A growing ecotoxicological literature also highlights a critical nuance that is especially relevant for military settings: combined exposures are more realistic than single-contaminant scenarios, yet remain underrepresented in field assessments, even though mixtures can alter toxicity, transport, and biological responses (Rodríguez Seijo *et al.,* 2024). In parallel, recent synthesis work on military-related metal pollution underscores that legacy contamination can persist for decades, and that risk management requires both environmental characterization and exposure-focused decision-making (Shukla *et al.,* 2023).

In Kaduna and other parts of northern Nigeria, the hydrogeologic setting further shapes vulnerability. Fractured basement aquifers and shallow weathered zones can provide rapid preferential pathways that shorten the travel time between surface waste zones and borehole screens, particularly during the rainy season when infiltration increases, and the leachate flux intensifies. Recent geophysical and hydrochemical investigations within Kaduna metropolis demonstrate that dumpsite-associated groundwater impairment can be detected using integrated approaches, supporting the plausibility of contaminant migration under local subsurface conditions (Adeniran *et al.,* 2023). This matters for the Nigerian Defence Academy, where cadets and staff may rely on boreholes that are proximal to waste handling zones. In such contexts, risk is not abstract; it accumulates through ordinary routines such as drinking, cooking, and bathing, and becomes more consequential when exposure spans years.

Another emerging direction in contemporary water quality research is the move from concentration only reporting to decision-oriented health risk interpretation. Studies increasingly combine metal quantification with non-carcinogenic indices such as hazard quotient and hazard index, alongside carcinogenic risk estimators such as excess lifetime cancer risk, to translate measured concentrations into exposure relevant meaning for adults and children (Nlemolisa *et al.,* 2025; Ogbuene *et al.,* 2025). Notably, recent Nigerian work has also begun to quantify how risk decays with distance from dumpsites and to propose predictive models that can inform safer borehole siting, illustrating a practical bridge between hydrochemistry and water safety governance (Ogbuene *et al.,* 2025). For institutional settings, this modelling perspective is valuable because it reframes risk management as a spatial planning problem as much as an analytical one.

In addition to chemical pollutants, microbial contamination of groundwater poses equally severe health risks. Although groundwater is generally regarded as microbiologically safe due to natural filtration, boreholes located near dumpsites are highly susceptible to infiltration by fecal matter and environmental microorganisms (Edokpayi *et al.,* 2018). Fecal indicators such as *Escherichia coli* and total coliforms are widely used to assess water safety, with their presence strongly correlated with the risk of waterborne pathogens (Ashbolt, 2015). Opportunistic organisms including *Pseudomonas aeruginosa, Klebsiella pneumoniae,* and *Staphylococcus aureus* may also infiltrate groundwater sources, posing additional threats, particularly to immunocompromised individuals (Igbinosa *et al.,* 2017). Beyond their pathogenic potential, these bacteria are frequently associated with antibiotic resistance, a phenomenon increasingly reported in environmental waters (Martínez, 2009). The presence of resistant organisms in groundwater not only complicates treatment of waterborne infections but also facilitates the dissemination of resistance genes across microbial communities (Manaia, 2017). Indeed, the World Health Organization has identified antimicrobial resistance as one of the most serious global health challenges of the 21st century (WHO, 2014).

The present study investigates heavy metal contamination in borehole water in the vicinity of a long-standing military-operated dumpsite within the Nigerian Defence Academy, Kaduna. The work is positioned to contribute in three ways. First, to extend groundwater contamination evidence in a military institutional setting where waste streams and access constraints have limited systematic evaluation. Second, to couple multi-element quantification with health risk indices to provide an exposure-oriented interpretation rather than a purely descriptive dataset. Third, to generate data that can support actionable controls, including borehole relocation and standoff planning, improved waste segregation, and periodic environmental audits that are defensible within both national standards and global drinking water guidance.

MATERIALS AND METHODS

Study Area

The study was conducted within the Nigerian Defence Academy, Kaduna State, Northwestern Nigeria, a major military training institution located in the Afaka, Igabi axis of Kaduna metropolis. The Academy lies within the Northern Guinea Savanna agroecological belt, a landscape characterized by seasonally controlled vegetation dynamics and strong rainfall seasonality that governs groundwater recharge and shallow subsurface transport processes. (Olufemi *et al.,* 2020)

Boreholes assessed in this study are located approximately 30 to 40 m from dumpsites. Geographic Coordinates for sampling points were obtained using a Garmin 78s handheld Global Positioning System receiver. The Mogadishu borehole was recorded at latitude 10°37′040″ N and longitude 7°22′11″ E, while the Burma borehole was recorded at latitude 10°37′085″ N and longitude 7°22′027″ E. The spatial arrangement of the dumpsite relative to these boreholes is presented in Figure 1, which maps the Mogadishu and Burma battalion lines and the corresponding sampling locations.

Sampling design, collection, preservation and transport

Fifty borehole water samples were collected from functional boreholes serving the Mogadishu and Burma battalion lines within the Nigerian Defence Academy, Kaduna, adjacent to the military operated dumpsite described in Section 2. Sampling was conducted throughout June, selected because peak rainfall conditions increase groundwater recharge and plausibly intensify leachate generation and downward solute transport in unlined waste settings. Samples were collected in 2 L high density polyethylene bottles that had been pre cleaned by detergent washing, thorough rinsing with deionized water, and acid conditioning. At each sampling point, bottles were rinsed three times with the borehole water before final collection. Immediately after collection, samples were acidified in the field using ultrapure nitric acid to pH below 2 to stabilize dissolved metals, suppress adsorption to container walls, and minimize microbially mediated transformations. Preserved samples were transported in insulated containers and stored at 4 °C prior to digestion and instrumental determination.

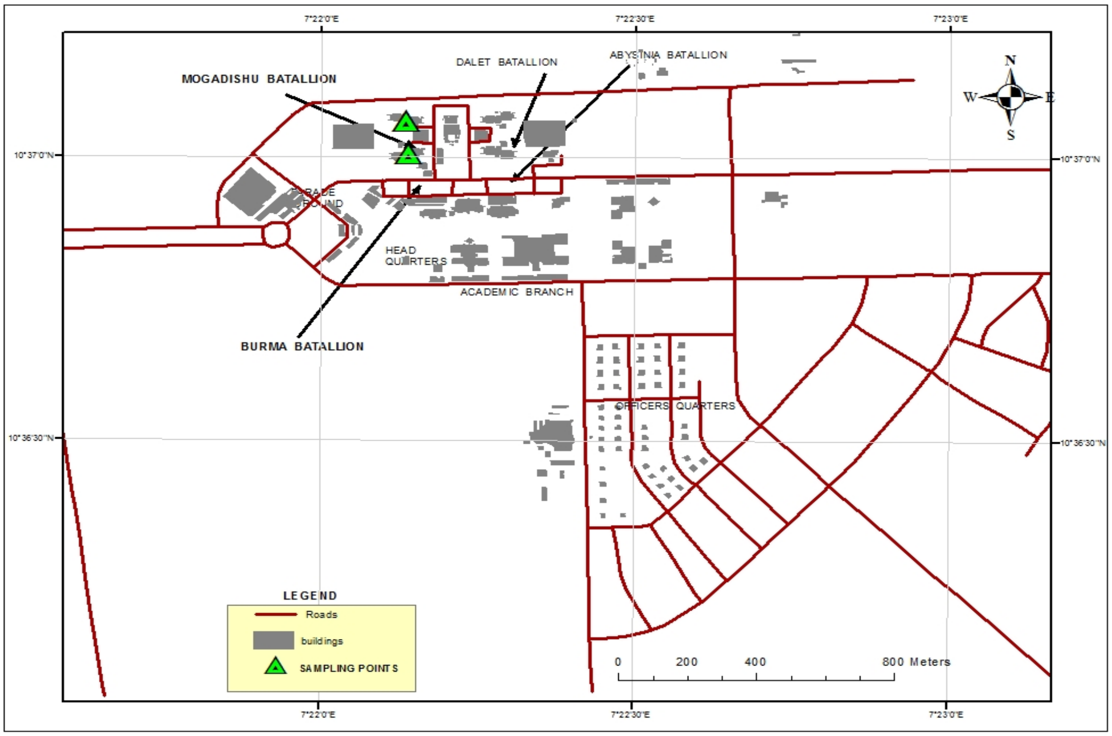

Figure 1: Map of Study Area showing sampling points.

Acid digestion for total recoverable metals

To quantify total recoverable concentrations of Cu, Zn, Co, Cr, Pb, Mn, Cd, and Ni, an oxidative acid digestion protocol was applied to each preserved sample, consistent with widely used wet digestion approaches for water matrices and aligned with the intent of Standard Methods digestion for metals prior to atomic absorption determination.

For each sample, an aliquot was concentrated under controlled heating and digested sequentially with nitric acid, hydrogen peroxide, and hydrochloric acid to achieve complete oxidation of residual organics and stabilization of target metals in solution. Briefly, the sample was heated at approximately 95 °C with concentrated nitric acid, with repeated additions until the digest became clear and the volume reduced without boiling. After cooling, deionized water and 30 percent hydrogen peroxide were added gradually to complete oxidation, followed by addition of concentrated hydrochloric acid and reheating to solubilize metals and minimize loss through precipitation. The final digest was cooled, filtered through Whatman No. 42 filter paper, and made up to a defined volume with deionized water. All reagents were of analytical grade or higher, and deionized water was used throughout to prevent secondary contamination.

Instrumental analysis by flame atomic absorption spectrometry

Metal concentrations were determined using flame atomic absorption spectrometry (FAAS) with a Varian Spectra AA 240FS instrument operated under manufacturer recommended conditions. Metal specific hollow cathode lamps were used at element appropriate wavelengths and slit settings. The flame system employed an air acetylene flame, and background correction was applied where required to minimize non-specific absorption. Calibration curves were prepared for each analyte using certified standard solutions across concentration ranges that bracketed observed sample levels. Instrument response was verified during runs using continuing calibration checks, and sample digests were analyzed in triplicate, with mean values reported after blank correction. The analytical workflow was aligned with Standard Methods for metals determination by atomic absorption.

Quality assurance and quality control

Quality assurance and quality control were embedded across sampling, digestion, and instrumental determination to ensure trace level reliability. All sample containers and digestion vessels were acid washed and rinsed thoroughly with deionized water prior to use. The following laboratory controls were implemented at a frequency of 10 percent of the batch.

i. Reagent blanks to quantify any contamination introduced during digestion and analysis
ii. Duplicate digestions to assess method precision across the full analytical chain
iii. Matrix spike recoveries to evaluate matrix effects and recovery performance
iv. Continuing calibration verification standards to confirm calibration stability during the run

Instrument detection limits ranged from 0.0002 to 0.001 mg/L. Precision was evaluated using relative standard deviation for replicate readings and was maintained below 5 percent. Any analytical batch failing blank acceptance criteria, calibration verification criteria, or recovery criteria was re processed and re analyzed.

Determination of Total Heterotrophic Bacterial Count (THBC)

The total heterotrophic bacterial count was assessed using the pour plate method. Briefly, 0.1 mL of a 10^2 dilution of each water sample was aseptically inoculated into sterile Petri dishes, followed by the addition of sterilized molten nutrient agar. The plates were gently swirled to mix, allowed to solidify, and incubated in an inverted position at 37°C for 24 h. After incubation, colonies were enumerated, and the mean count was recorded in colony-forming unit (CFU) per milliliter as described by Chikere *et al*., 2008; APHA, 2017).

Determination of Total and Fecal Coliform Counts

The total and fecal coliform counts were determined using the Most Probable Number (MPN) technique. Water samples were inoculated into double and single-strength MacConkey broth tubes containing inverted Durham tubes and incubated at 37°C for 48 h. Tubes showing acid and gas production were considered presumptive positives. For confirmation, a loopful from positive tubes was streaked onto Eosin Methylene Blue (EMB) agar and incubated at 37°C for 24 h. Colonies displaying typical metallic sheen were subjected to further testing (APHA., 2005; Gruber *et al*., 2014).

Faecal coliform confirmation involved transferring a loopful from presumptive positive broths into EC broth and incubating at 44.5°C for 24 h. Confirmed positive cultures were subsequently inoculated into Brilliant Green Lactose Bile (BGLB) broth and incubated at 37°C for total coliforms and 44.5°C for faecal coliforms, with gas production indicating a positive result. For the completed test, colonies from EMB agar were isolated and subjected to Gram staining and IMViC biochemical tests to confirm identification of coliform and faecal coliform organisms (APHA., 2005; Gruber *et al*., 2014).

Antibiotic Susceptibility Testing

Antibiotic susceptibility testing was performed using the Kirby–Bauer disk diffusion method on Mueller–Hinton Agar (MHA) following the guidelines of the Clinical and Laboratory Standards Institute (CLSI, 2023).

Statistical treatment and standards-based classification

Data were compiled and screened for quality control compliance prior to interpretation. Descriptive statistics were computed, including minimum, maximum, mean, and variability metrics. Statistical summaries were produced using Microsoft Excel, while Python scripts were used for reproducible calculations and figure generation. Measured concentrations were evaluated against World Health Organization guideline values and the Nigerian Standard for Drinking Water Quality to classify samples as compliant or exceeding recommended limits, supporting spatially informed interpretation and management recommendations.

Human health risk assessment for ingestion exposure

Human health risk was evaluated for oral ingestion of borehole water using the United States Environmental Protection Agency framework for chemical exposure assessment and risk characterization. Non carcinogenic risk was expressed as hazard quotient for each metal and hazard index as the sum of hazard quotients across metals.

Chronic daily intake for ingestion, CDI (mg kg^{-1} day^{-1}), was computed as:

$$CDI = \frac{C \times IR \times EF \times ED}{BW\ X\ AT}$$

2.0

where C is the measured concentration (mg L^{-1}), IR is ingestion rate (2.0 L day^{-1}), EF is exposure frequency (365 days $year^{-1}$), ED is exposure duration (4 years, representing cadet residence and routine consumption within the Academy), BW is body weight (70 kg), and AT is averaging time. For non-carcinogenic effects, AT equals ED × 365 days. For carcinogenic risk, AT equals 70 years × 365 days.

Hazard Quotient (HQ): The Hazard Quotient (HQ) evaluates the non-carcinogenic health risk associated with exposure to a single contaminant by comparing the estimated CDI to the established Reference Dose

(RfD). The RfD is the threshold dose below which no adverse effects are expected. An HQ value suggests that exposure levels are within acceptable limits, whereas HQ indicates a potential health concern (USEPA, 2000).

$$HQ = \frac{CDI}{RfD} \qquad 3.0$$

Hazard Index (HI): The Hazard Index (HI) assesses the cumulative non-carcinogenic risk arising from simultaneous exposure to multiple contaminants. It is computed as the summation of individual HQs for each pollutant. An HI value exceeding unity implies that the combined exposure may lead to adverse health outcomes (USEPA, 2010).

$$HI = \sum HQi \qquad 4.0$$

Toxicity factors were obtained from EPA aligned sources. The oral reference dose values applied were: Mn 0.14 mg kg^{-1} day^{-1}(EPA IRIS,2014), Zn 0.3 mg kg^{-1} day^{-1}(ATSDR, 2002), Ni 0.02 mg kg^{-1} day^{-1} (US EPA, 2012) Cd in water 0.0005 mg kg^{-1} day^{-1} , Cr(VI) 0.003 mg kg^{-1} day^{-1} (US EPA, 2012), Co 3×10^{-4} mg kg^{-1} day^{-1} (US EPA, 2012), and Cu 0.04 mg kg^{-1} day^{-1} consistent with the value used in EPA screening practice for copper.

Lead was not assigned an oral reference dose within this assessment because EPA lead risk characterization is typically performed using biokinetic modelling frameworks rather than an RfD based hazard quotient approach. (US EPA, 2012) Accordingly, lead was evaluated through concentration benchmarking against drinking water guideline values, while the cumulative non-carcinogenic indices were computed for metals with established oral reference doses.

Carcinogenic risk was estimated only for chromium under a conservative assumption that measured total chromium represents hexavalent chromium, given that FAAS quantifies total elemental chromium and does not resolve oxidation state. Excess lifetime cancer risk was computed as:

ELCR = CDI × CSF

using the EPA adult based oral cancer slope factor for Cr(VI) of 0.16 (mg kg^{-1} day^{-1})$^{-1}$. (US EPA, 2012)

Conceptual basis for contaminant migration

A physically grounded conceptual link between the unlined dumpsite and borehole contamination was articulated using the advection dispersion equation to represent contaminant movement through the vadose zone and within groundwater:

$$\frac{\partial C}{\partial t} = \frac{D\partial^2 C}{\partial x^2} - \frac{v\partial C}{\partial x} + R(C) \qquad 1.0$$

where C is solute concentration, t is time, x is distance, D is the hydrodynamic dispersion coefficient, and v is the average linear pore water velocity. This formulation was used to support process interpretation of observed metal occurrence patterns under recharge conditions. No site calibrated transport simulation was performed.

RESULTS

Heavy Metal Occurrence and Hydrochemical Characteristics

The concentrations of eight heavy metals were determined in 50 borehole water samples collected from the study area. The mean concentrations followed the order Cu > Mn > Ni > Pb > Cr > Zn > Cd > Co, indicating that copper had the highest average concentration (0.0437 ± 0.0273 mg/L), whereas cobalt had the lowest (0.0010 ± 0.0005 mg/L). Copper also showed the widest concentration range, from 0.0000 to 0.1056 mg/L. The coefficients of variation revealed considerable differences in the distribution of metals across samples. Copper exhibited the highest variability (62.5%), followed by Cobalt (52.6%) and Lead (50.7%), while cadmium showed the lowest variability (19.0%), indicating relatively uniform concentrations among samples.

Comparison of the measured concentrations with drinking water standards showed that most metals were below the guideline values established by the World Health Organization (WHO), the Nigerian Standard for Drinking Water Quality (NSDWQ), and the United States Environmental Protection Agency (US EPA). However, the maximum concentration of lead (0.0117 mg/L) was above the WHO and NSDWQ limit of 0.010 mg/L. The highest cadmium concentration (0.0030 mg/L) was equal to the WHO and NSDWQ guideline value. The maximum concentrations of copper, zinc, cobalt, chromium, manganese, and nickel were all below their corresponding permissible limits.

Compliance and Safety Margin Assessment

Safety margin analysis showed that lead and cadmium were the metals closest to their regulatory limits. Lead recorded one sample (2%) with a concentration above both the WHO and NSDWQ guideline values. In addition, three samples (6%) had lead concentrations at or above 80% of these limits. Cadmium did not exceed any guideline value, but six samples (12%) contained concentrations at or above 80% of the WHO and NSDWQ limits. No samples exceeded the guideline values for copper, zinc, cobalt, chromium, manganese, or nickel. Similarly, none of the measured concentrations exceeded the relevant US EPA benchmark values (Table 2).

Table 1. Descriptive statistics and comparison with drinking water benchmarks (mg/L)

Metal	Min	Max	Mean ± SD	Median (Q1, Q3)	CV (%)	WHO value	NSDWQ limit	US/EPA benchmar
Cu	0.0000	0.1056	0.0437±0.0273	0.0430 (0.0242, 0.0601)	62.5	2.0	1.0	1.3 (action level)
Zn	0.0000	0.0036	0.0020±0.0008	0.0021 (0.0015, 0.0026)	41.4	NA (acceptability may change above ~3)	3.0	5.0 (SMCL)
Co	0.0000	0.0022	0.0010±0.0005	0.0010 (0.0005, 0.0013)	52.6	NA	0.01	NA
Cr (total)	0.0009	0.0039	0.0021 ± 0.0006	0.0021 (0.0015, 0.0024)	30.5	0.05	0.05	0.10 (MCL, total Cr)
Pb	0.0000	0.0117	0.0043 ± 0.0022	0.0044 (0.0027, 0.0054)	50.7	0.01 (provisional)	0.01	0.015 (action level)
Mn	0.0000	0.0144	0.0080 ± 0.0032	0.0081 (0.0060, 0.0102)	39.6	0.08 (health-based screening value)	0.2	0.05 (SMCL)
Cd	0.0013	0.0030	0.0020 ± 0.0004	0.0020 (0.0017, 0.0023)	19.0	0.003	0.003	0.005 (MCL)
Ni	0.0018	0.0083	0.0053 ± 0.0015	0.0052 (0.0041, 0.0063)	28.0	0.07	0.02	No federal MCL

WHO guideline values are from chemical background documents and fact sheets (World Health Organization, 2021, 2022). NSDWQ limits are from the Nigerian Standard for Drinking Water Quality (Standards Organization of Nigeria, 2015). US EPA values include action levels (Lead and Copper Rule), primary standards (MCLs), and secondary standards (SMCLs) where applicable (USEPA,2010 2017,2024).

Table 2. Compliance and safety margin diagnostics relative to WHO, NSDWQ, and US EPA benchmarks.

Metal	Max/limit WHO	≥80% WHO	Exceed WHO	Max/limit NSDWQ	≥80% NSDWQ	Exceed NSDWQ	Max/limit EPA	≥80% EPA	Exceed EPA
Cu	0.05	0 (0%)	0 (0%)	0.11	0 (0%)	0 (0%)	0.08	0 (0%)	0 (0%)
Zn	NA	NA	NA	0.00	0 (0%)	0 (0%)	0.00	0 (0%)	0 (0%)
Co	NA	NA	NA	0.22	0 (0%)	0 (0%)	NA	NA	NA
Cr (total)	0.08	0 (0%)	0 (0%)	0.08	0 (0%)	0 (0%)	0.04	0 (0%)	0 (0%)
Pb	1.17	3 (6%)	1 (2%)	1.17	3 (6%)	1 (2%)	0.78	0 (0%)	0 (0%)
Mn	0.18	0 (0%)	0 (0%)	0.07	0 (0%)	0 (0%)	0.29	0 (0%)	0 (0%)
Cd	1.00	6 (12%)	0 (0%)	1.00	6 (12%)	0 (0%)	0.60	0 (0%)	0 (0%)
Ni	0.12	0 (0%)	0 (0%)	0.41	0 (0%)	0 (0%)	NA	NA	NA

Bacteriological Quality of Borehole Water Samples

The bacteriological analysis showed that total bacterial counts ranged from 3.02 ± 0.08 to 4.89 ± 0.14 $\log_{10}$ CFU/mL. The highest total bacterial count was recorded in BH-07, while the lowest count was observed in BH-02. Total coliform counts ranged from 1.02 ± 0.11 to 2.79 ± 0.09 $\log_{10}$ CFU/mL. BH-03 recorded the highest coliform count, whereas BH-04 had the lowest.

Based on the Microbial Contamination Index (MCI), six boreholes (BH-01, BH-03, BH-05, BH-06, BH-07, and BH-09) were assigned an MCI of 3 and classified as highly contaminated. The remaining four boreholes (BH-02, BH-04, BH-08, and BH-10) had an MCI of 2 and were classified as moderately contaminated. The average total bacterial count was 4.89 $\log_{10}$ CFU/mL, while the average coliform count was 2.74 $\log_{10}$ CFU/mL.

Frequency of Occurrence of Bacterial Isolates

Seven bacterial species were isolated from the borehole water samples. *Staphylococcus aureus* was the most frequently isolated organism, occurring in 8 of the 10 boreholes (80%). *Escherichia coli* was detected in 7 samples (70%), while *Pseudomonas aeruginosa* was present in 6 samples (60%). *Klebsiella pneumoniae* and *Enterobacter* spp. were each isolated from 5 samples (50%). *Micrococcus luteus* occurred in 4 samples (40%), and *Proteus mirabilis* was the least frequently detected species, occurring in 3 samples (30%).

Table 3: Total Bacterial and Total Coliform Counts of water from Boreholes

Sample ID	Total Bacterial Count ($\log_{10}$ CFU/mL)	Coliform Count ($\log_{10}$ CFU/mL)	Microbial Contamination Index (MCI)	Contamination Level
BH-01	4.56±0.12	2.65 ± 0.10	3	High Contamination
BH-02	3.02±0.08	1.88 ± 0.07	2	Moderate Contamination
BH-03	4.78±0.10	2.79 ± 0.09	3	High Contamination
BH-04	3.21±0.15	1.02 ± 0.11	2	Moderate Contamination
BH-05	4.33±0.09	2.55 ± 0.08	3	High Contamination
BH-06	4.25±0.11	2.27 ± 0.09	3	High Contamination
BH-07	4.89±0.14	2.10 ± 0.12	3	High Contamination
BH-08	3.12±0.13	1.20 ± 0.11	2	Moderate Contamination
BH-09	4.67±0.07	2.41 ± 0.07	3	High Contamination
BH-10	3.30±0.10	1.21 ± 0.08	2	Moderate Contamination
Average	**4.89 $\log_{10}$ CFU/mL**.	**2.74 $\log_{10}$ CFU/mL**		

Ta**ble 4: Frequency of occurrence of bacterial isolates from borehole water samples**

S/N	Bacterial Species	Frequency of Occurrence	Percentage (%)
1	*Escherichia coli*	7	70
2	*Pseudomonas aeruginosa*	6	60
3	*Klebsiella pneumoniae*	5	50
4	*Staphylococcus aureus*	8	80
5	*Enterobacter spp.*	5	50
6	*Proteus mirabilis*	3	30
7	*Micrococcus luteus*	4	40

Antibiotic Susceptibility Pattern of Bacterial Isolates

Antibiotic susceptibility testing revealed varying levels of resistance among the bacterial isolates. *Pseudomonas aeruginosa* showed the highest resistance, with resistance to five of the six antibiotics tested, corresponding to a resistance rate of 83.3%. *Escherichia coli* and *Proteus mirabilis* were resistant to four of the six antibiotics, giving resistance rates of 66.7% each. *Klebsiella pneumoniae* and *Enterobacter* spp. were resistant to three antibiotics, corresponding to resistance rates of 50.0%. *Staphylococcus aureus* showed resistance to one antibiotic only, resulting in a resistance rate of 16.7%. *Bacillus subtilis* and *Micrococcus luteus* were susceptible to all antibiotics tested and had resistance rates of 0.0%.

Hotspot Samples for Lead and Cadmium

The hotspot analysis identified specific samples with the highest concentrations of lead and cadmium. For lead, Sample S10 had the highest concentration (0.0117 mg/L), representing 117% of the WHO guideline value. Samples S21 and S35 contained lead concentrations equivalent to 86% and 83% of the WHO limit, respectively.

For cadmium, Sample S24 had the highest concentration (0.0030 mg/L), corresponding to 100% of the WHO guideline value. Samples S15, S07, and S27 contained cadmium concentrations equivalent to 90%, 87%, and 87% of the WHO limit, respectively. Samples S12 and S35 each contained 83% of the WHO guideline value.

Distribution of Heavy Metal Concentrations

Figure 2 presents the distribution of heavy metal concentrations using raincloud plots with regulatory overlays. The violin plots illustrate the spread of concentration values for each metal, the embedded boxplots show the median and interquartile range, and the individual points represent the measured concentrations in each of the 50 samples. Horizontal reference lines indicate the WHO, NSDWQ, and US EPA benchmark values. Lead and cadmium displayed upper values that approached or intersected the benchmark lines. In contrast, the distributions of copper, zinc, cobalt, chromium, manganese, and nickel were positioned below their respective guideline values.

Table 5: Antibiotic susceptibility pattern of Bacterial isolates from borehole water samples

Bacterial Isolates	AMX	TET	CRO	CIP	GEN	CHL	Resistotype	Resistance Rate (%)
Escherichia coli	R	R	R	I	S	R	4/6	66.7
Pseudomonas aeruginosa	R	R	R	I	R	R	5/6	83.3
Klebsiella pneumoniae	R	I	R	S	R	I	3/6	50.0
Staphylococcus aureus	S	I	S	S	R	S	1/6	16.7
Enterobacter spp.	R	R	I	S	S	R	3/6	50.0
Proteus mirabilis	I	R	R	R	R	I	4/6	66.7
Bacillus subtilis	S	S	S	S	I	S	0/6	0.0%
Micrococcus luteus	S	I	S	S	I	S	0/6	0.0%

Amoxicillin (AMX), Tetracycline (TET), Ceftriaxone (CRO), Ciprofloxacin (CIP), Gentamicin (GEN), Chloramphenicol (CHL)

Table 6. Hotspot samples defining the tightest safety margins for Pb and Cd (WHO based).

Metal	Sample	Concentration (mg/L)	Percent of WHO value
Pb	S10	0.0117	117%
Pb	S21	0.0086	86%
Pb	S35	0.0083	83%
Cd	S24	0.0030	100%
Cd	S15	0.0027	90%
Cd	S7	0.0026	87%
Cd	S27	0.0026	87%
Cd	S12	0.0025	83%
Cd	S35	0.0025	83%

WHO lead is a provisional guideline value, and cadmium is a health-based guideline value (World Health Organization, 2011a; World Health Organization, 2011b)

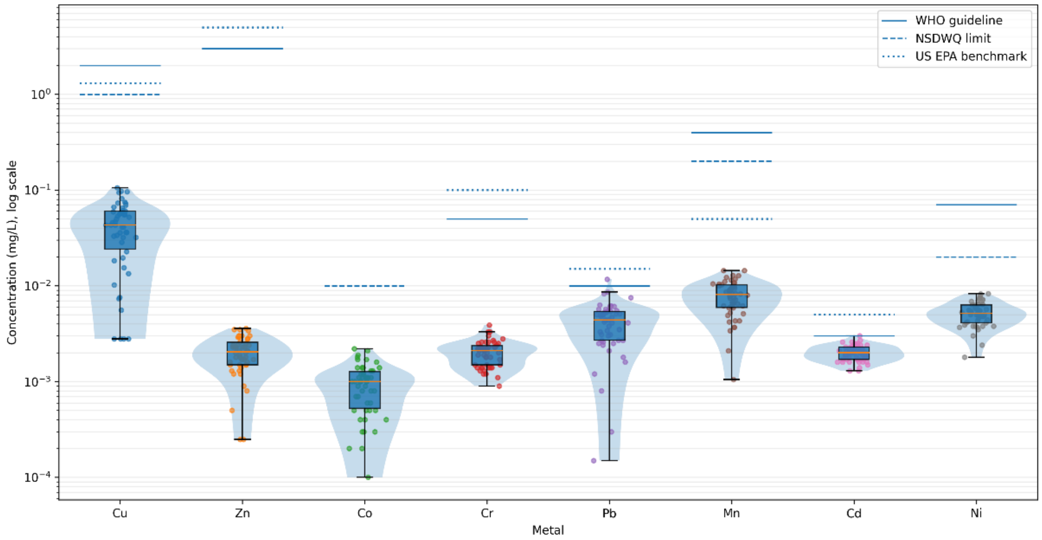

Figure 2. Raincloud distribution of heavy metal concentrations with regulatory overlays (log scale).

Non-Carcinogenic Health Risk Assessment

The non-carcinogenic risk assessment showed that hazard quotient (HQ) values for all evaluated metals were below 1.0. Cadmium had the highest HQ (1.15×10^{-1}), accounting for 65.68% of the total hazard index. Copper had an HQ of 3.12×10^{-2} and contributed 17.81%, while chromium had an HQ of 1.95×10^{-2} and contributed 11.16%. Nickel, manganese, and zinc contributed 4.30%, 0.93%, and 0.11% of the total hazard index, respectively. The cumulative hazard index (HI) for all metals was 0.175.

Toxicity-Weighted Contribution to the Hazard Index

Figure 3 presents a Pareto plot showing the percentage contribution of each metal to the total hazard index. Cadmium contributed the largest proportion, followed by copper and chromium. The cumulative contribution curve showed that these three metals together accounted for more than 90% of the total hazard index. The cumulative hazard index remained below the reference value of 1.0.

Carcinogenic Risk Assessment for Chromium

Carcinogenic risk was estimated for chromium under the conservative assumption that all measured chromium was present as hexavalent chromium [Cr (VI)]. The excess lifetime cancer risk (ELCR) at the mean chromium concentration was 1.68×10^{-6}. At the 95th percentile concentration, the ELCR increased to 2.58×10^{-6}, while the maximum chromium concentration produced an ELCR of 3.18×10^{-6}. The highest estimated carcinogenic risk was therefore associated with the maximum chromium concentration.

Table 7. Noncarcinogenic risk metrics for ingestion exposure (mean based).

Metal	Mean (mg/L)	CDI (mg/kg/day)	RfD (mg/kg/day)	HQ	Contribution to HI (%)	Cumulative HI
Cd	0.0020	5.75×10^{-5}	5.0×10^{-4}	1.15×10^{-1}	65.68	0.11497
Cu	0.0437	1.25×10^{-3}	4.0×10^{-2}	3.12×10^{-2}	17.81	0.14615
Cr (VI, screening)	0.0021	5.86×10^{-5}	3.0×10^{-3}	1.95×10^{-2}	11.16	0.16570
Ni	0.0053	1.50×10^{-4}	2.0×10^{-2}	7.52×10^{-3}	4.30	0.17322
Mn	0.0080	2.28×10^{-4}	1.4×10^{-1}	1.62×10^{-3}	0.93	0.17485
Zn	0.0020	5.81×10^{-5}	3.0×10^{-1}	1.94×10^{-4}	0.11	0.17504
Total HI	*NA*	*NA*	*NA*	*0.175*	*100*	*NA*

The RfD sources are EPA and allied toxicological summaries for drinking water screening: Cd RfD (USEPA, 2012), Mn RfD (USEPA, 2017), Ni RfD (USEPA, 2010c), Zn RfD (ATSDR IRIS, 2005), Cr(VI) RfD (ATSDR IRIS, 2008). Copper RfD is applied as a screening value commonly used in water risk studies and aligned with EPA health-based derivations reported in the risk literature (Mushak, 2022).

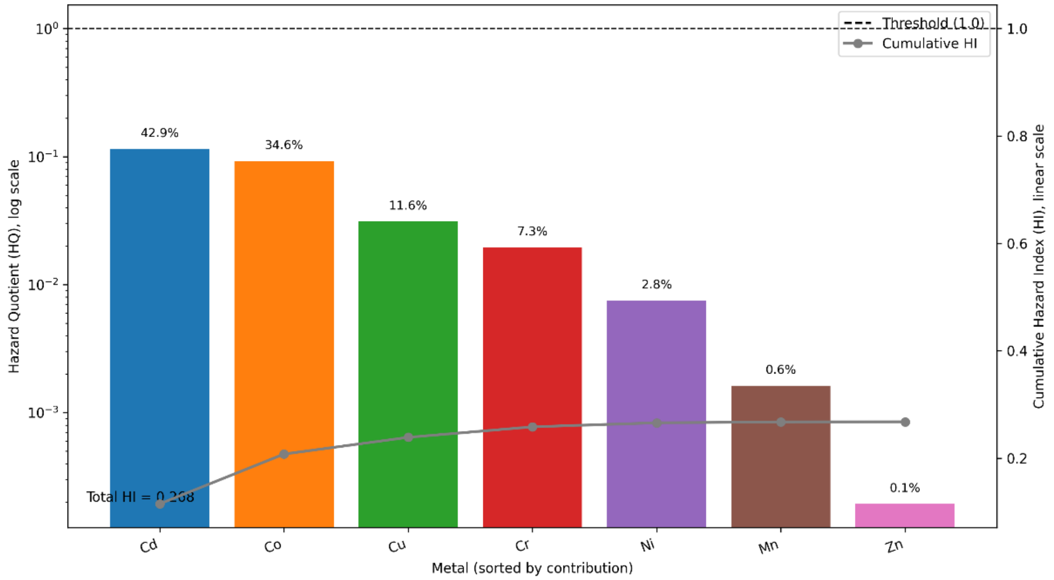

Figure 3. Toxicity weighted risk profile (Pareto plot of HQ contributions)

Table 8. ELCR screening for chromium under a conservative Cr (VI) assumption.

Statistic	Cr (mg/L)	CDI (mg/kg/day)	CSF $(mg/kg/day)^{-1}$	ELCR
Mean	0.002052	3.35×10^{-6}	0.5	1.68×10^{-6}
95th percentile	0.003165	5.17×10^{-6}	0.5	2.58×10^{-6}
Maximum	0.003900	6.37×10^{-6}	0.5	3.18×10^{-6}

DISCUSSION

Borehole water remains the backbone of domestic supply across peri-urban Kaduna, yet the quality of these sources near active dumpsites is rarely examined through both chemical and microbial studies. In this study, groundwater drawn beside a military dumpsite revealed metal levels in the order Cu > Mn > Ni > Pb > Cr > Zn > Cd > Co. Most concentrations fell below WHO and NSDWQ limits, but Pb and Cd consistently operated closest to regulatory thresholds. However, a sample breached the WHO limit for lead, while cadmium in several boreholes approached permissible levels. The spread and upper tails point to localized enrichment driven by heterogeneous leachate infiltration and variable subsurface transport rather than blanket aquifer contamination. Comparable patterns have been documented near unlined dumpsites, where rainfall intensity, waste heterogeneity and hydrogeology dictate contaminant mobility (Alao *et al.*, 2023; Jolaosho, 2024).

These hotspots signal early contamination pressure. Lead warrants scrutiny given its cumulative neurotoxic, renal and cardiovascular effects even at low chronic doses (WHO, 2022), while cadmium presents comparable long-term concerns through nephrotoxicity and bioaccumulation. Because both metals already sit near guideline thresholds, continued waste deposition and seasonal recharge may intensify contamination. The clustering of elevated values implies discrete leachate pathways rather than regional aquifer degradation, with intensity tailing off as distance from the dumpsite increases (Jolaosho, 2024). Rainfall-driven infiltration likely serves as the primary transport vector. Metallic scraps, batteries, paint residues, maintenance debris and ammunition-related waste are probable Pb and Cd donors; weathering of ammunition and metal-containing debris has been shown to elevate lead substantially in military-impacted soils and firing ranges (Zhu *et al.*, 2024).

The sanitary profile of the groundwater is poor. Total bacterial counts spanned 3.02 to 4.89 $\log_{10}$ CFU/mL and total coliforms ranged from 1.02 to 2.79 $\log_{10}$ CFU/mL, both well above WHO (2022) standards demanding zero coliforms per 100 mL and minimal heterotrophic loads. Elevated coliform and heterotrophic counts remain reliable red flags for microbiological deterioration and possible pathogen intrusion (Le Chevallier *et al.*, 2024; Wang *et al.*, 2023). One borehole recorded the highest total bacterial load at 4.89 $\log_{10}$ CFU/mL, yet its coliform count was lower than another site, implying a biofilm-dominated community of heterotrophic non-coliform organisms that colonize casings and distribution lines (Prest *et al*., 2019; Le Chevallier *et al*., 2024). Conversely, the peak coliform count of 2.79 $\log_{10}$ CFU/mL at a different borehole points toward faecal intrusion and a heightened probability of enteric pathogens. The Microbial Contamination Index classified six out of ten boreholes as very contaminated and the remainder as moderately contaminated, confirming sustained microbial pressure. Drinking this water untreated invites waterborne illnesses such as diarrhoea, typhoid and cholera (WHO, 2022), a risk amplified by the tendency of waste-impacted groundwater to harbour pathogenic microbes (Oon *et al*., 2023; Verlicchi and Grillini, 2020).

The diversity of isolates supports multiple contamination vectors. *Staphylococcus aureus*, recovered from 80% of samples, hints at skin contact and poor sanitary protection rather than direct faecal input, though it remains clinically significant for skin infections and food poisoning, particularly in immunocompromised individuals (Tong *et al*., 2015). *Escherichia coli*, found in 70% of samples, is unambiguous evidence of recent faecal contamination and signals the likely co-occurrence of other enteric pathogens. The additional recovery of *Pseudomonas aeruginosa*, *Klebsiella pneumoniae*, *Enterobacter* spp., *Proteus mirabilis* and *Micrococcus luteus* strengthens the argument for human and animal sources, reflecting the established role of opportunistic pathogens in environmental and human microbiomes (Falkinham *et al*., 2015; Vaz-Moreira *et al*., 2017).

Antimicrobial susceptibility testing uncovered widespread resistance concentrated among Gram-negative isolates. *Pseudomonas aeruginosa* led at 83.3% resistance across five of six antibiotics, attributable to intrinsic mechanisms such as low membrane permeability, multidrug efflux pumps and robust biofilm formation (Moradali *et al*., 2017). *Pseudomonas* species are consistently identified as major resistance reservoirs in water systems (Pandey *et al*., 2022; Milligan *et al*., 2023). *Escherichia coli* and *Proteus mirabilis* each resisted four of six antibiotics, while *Klebsiella pneumoniae* and *Enterobacter* spp. registered 50% resistance. These are precisely the organisms WHO (2024) lists as priority pathogens because of escalating resistance to critically important antibiotics. Similar multidrug resistance among these taxa has been reported in Nigerian water systems, underscoring groundwater as both a reservoir and transmission corridor for antimicrobial resistance. In contrast, *Staphylococcus aureus* resistance was modest at 16.7%, and *Bacillus subtilis* and *Micrococcus luteus* remained fully susceptible. This uneven landscape suggests environmental antibiotic pressure from indiscriminate drug use and poor waste management rather than uniform selection.

The simultaneous presence of pathogens and multidrug-resistant organisms in untreated borehole water carries serious public health weight. Direct consumption exposes individuals to resistant strains and creates opportunities for horizontal gene transfer within the human microbiota. Contaminated water bodies are increasingly recognized under the One Health framework as critical environmental reservoirs and dissemination routes for antimicrobial resistance (Murray *et al*., 2022; Pandey *et al*., 2023).

Hazard quotients for every metal remained below unity and the cumulative hazard index stayed under 1, indicating that immediate non-carcinogenic health effects from ingestion are unlikely. Nevertheless, cadmium contributed the largest share of the hazard burden, followed by copper and chromium, while manganese and zinc barely registered. This disproportionate influence reflects toxicological potency and reference dose differences rather than concentration dominance. Cadmium's outsized hazard contribution aligns with previous groundwater studies where its low oral reference dose amplifies risk even at modest concentrations (Nlemolisa *et al*., 2025).

Chromium generated excess lifetime cancer risk estimates within the acceptable 10^{-6} range. Although these values are low, they are non-zero and therefore warrant attention under prolonged exposure. Because flame atomic absorption spectrometry cannot distinguish Cr(III) from Cr(VI), the calculation conservatively assumed the entire chromium pool existed as the more toxic Cr(VI) species. This may overestimate true carcinogenic risk, but it remains a reasonable precautionary approach when speciation data are unavailable.

CONCLUSION

This study highlights the vulnerability of borehole water sources located near a military-operated dumpsite in Kaduna to both heavy metal and microbial contamination. Concentrations of copper, manganese, and zinc in several samples approached or exceeded permissible limits, with hazard quotient and hazard index values indicating potential non-carcinogenic health risks, particularly from Cu and Mn. Although the carcinogenic risks associated with Cr and Pb were low, long-term exposure still poses concern. The high bacterial and coliform counts, coupled with moderate to high Microbial Contamination Index values, confirm significant microbial pollution, with faecal indicators such as *Escherichia coli* and opportunistic pathogens including *Staphylococcus aureus* and *Pseudomonas aeruginosa* frequently detected. The widespread antibiotic resistance among key bacterial isolates further exacerbates the public health risks by limiting effective treatment options for waterborne infections. Collectively, these findings emphasize the urgent need for improved waste management practices, regular monitoring of groundwater quality, and the implementation of effective water treatment interventions to safeguard communities relying on borehole water in the study area.

FUNDING: This research did not receive funding.

COMPETING INTEREST DECLARATION: The authors declare that they have no competing interests.

CONTRIBUTIONS OF AUTHORS:
Olawale Gabriel Olowomofe (OGO) conceptualized and designed the study. Temitayo Omotunde Olowomofe (TOO) and OGO coordinated fieldwork and supervised data collection. OGO and TOO Prepared figures/tables and supported the writing of the results section. TOO conducted the statistical analysis. OGO and TOO drafted and approved the manuscript for publication.

REFERENCES

Adeniran, M. A., Oladunjoye, M. A., & Doro, K. O. (2023). Soil and groundwater contamination by crude oil spillage: A review and implications for remediation projects in Nigeria. *Frontiers in Environmental Science, 11*, 1137496. https://doi.org/10.3389/fenvs.2023.1137496

Agency for Toxic Substances and Disease Registry (ATSDR). (2005). *Toxicological profile for zinc (TP 60).* U.S. Department of Health and Human Services. https://www.atsdr.cdc.gov/toxprofiles/tp60-c8.pdf

Agency for Toxic Substances and Disease Registry (ATSDR). (2008). *Toxicological profile for chromium (TP 7).* U.S. Department of Health and Human Services. https://www.atsdr.cdc.gov/toxprofiles/tp7-c8.pdf

Alao, J. O., Fahad, A., Danladi, E., Danjuma, T. T., Mary, E. T., & Diya'ulhaq, A. (2023). Geophysical and hydrochemical assessment of the risk posed by open dumpsite at Kaduna Central Market, Nigeria. *Sustainable Water Resources Management, 9*(5), 170. https://doi.org/10.1007/s40899-023-00948-6

American Public Health Association, American Water Works Association, & Water Environment Federation. (2005). *Standard methods for the examination of water and wastewater* (21st ed.). APHA

American Public Health Association, American Water Works Association, & Water Environment Federation. (2017). *Standard methods for the examination of water and wastewater* (23rd ed.). American Public Health Association

Ashbolt, N. J. (2015). Microbial contamination of drinking water and human health from community water systems. *Current Environmental Health Reports, 2*(1), 95–106. https://doi.org/10.1007/s40572-014-0037-5

Chikere, C. B., Chikere, B. O., & Omoni, V. T. (2008). Bacterial population dynamics and physicochemical characteristics of a crude oil-polluted soil in Nigeria. *African Journal of Biotechnology, 7*(5), 620–630

Clinical and Laboratory Standards Institute. (2023). *Performance standards for antimicrobial susceptibility testing* (33rd ed., CLSI supplement M100). CLSI

Edokpayi, J. N., Rogawski, E. T., Kahler, D. M., Hill, C. L., Reynolds, C., Nyathi, E., *et al*. (2018). Challenges to sustainable safe drinking water: A case study of water quality and use across seasons in rural communities in Limpopo Province, South Africa. *Water, 10*(2), 159. https://doi.org/10.3390/w10020159

Falkinham, J. O., Hilborn, E. D., Arduino, M. J., Pruden, A., & Edwards, M. A. (2015). Epidemiology and ecology of opportunistic premise plumbing pathogens: Legionella pneumophila, Mycobacterium avium, and Pseudomonas aeruginosa. *Environmental Health Perspectives, 123*(8), 749–758. https://doi.org/10.1289/ehp.1408692

Gruber, J. S., Ercumen, A., & Colford, J. M. Jr. (2014). Coliform bacteria as indicators of diarrheal risk in household drinking water: Systematic review and meta-analysis. *PLoS ONE, 9*(9), e107429. https://doi.org/10.1371/journal.pone.0107429

Igbinosa, I. H., Beshiru, A., Akporehe, L. U., Oviasogie, F. E., & Igbinosa, E. O. (2017). Antimicrobial resistance profile of *Pseudomonas aeruginosa* isolated from aquaculture and abattoir environments in southern Nigeria. *Annals of Clinical Microbiology and Antimicrobials, 16*, 1–8. https://doi.org/10.1186/s12941-017-0184-7

Isah, A., Bassey, E. N., Akinbiyi, O. A., Azeez, R. A., Oji, A. S., & El Badawy, T. (2025). Characterizing groundwater contamination flow paths and heavy metal mobilization near a waste site in Southwestern Nigeria. *Journal of African Earth Sciences, 221*, 105460. https://doi.org/10.1016/j.jafrearsci.2024.105460

Jolaosho, T. L. (2024). Characterization of potentially toxic elements in leachates from active and closed landfills in Nigeria and their effects on groundwater systems using spatial, indexical, chemometric and health risk techniques. *Chemosphere, 369*, 143678. https://doi.org/10.1016/j.chemosphere.2024.143678

LeChevallier, M. W., Prosser, T., & Stevens, M. (2024). Opportunistic pathogens in drinking water distribution systems: A review. *Microorganisms, 12*(5), 916. https://doi.org/10.3390/microorganisms12050916

Manaia, C. M. (2017). Antibiotic resistance in wastewater treatment plants: Tackling the black box. *Environment International, 106*, 37–44. https://doi.org/10.1016/j.envint.2017.05.027

Martínez, J. L. (2009). Environmental pollution by antibiotics and by antibiotic resistance determinants. *Environmental Pollution, 157*(11), 2893–2902. https://doi.org/10.1016/j.envpol.2009.05.051

Milligan, E. G., Calarco, J., Davis, B. C., Keenum, I. M., Liguori, K., Pruden, A., & Harwood, V. J. (2023). A systematic review of culture-based methods for monitoring antibiotic-resistant *Acinetobacter*, *Aeromonas*, and *Pseudomonas* as environmentally relevant pathogens in wastewater and surface water. *Current Environmental Health Reports, 10*(2), 154–171. https://doi.org/10.1007/s40572-023-00393-9

Moradali, M. F., Ghods, S., & Rehm, B. H. A. (2017). *Pseudomonas aeruginosa* lifestyle: A paradigm for adaptation, survival, and persistence. *Frontiers in Cellular and Infection Microbiology, 7*, 39. https://doi.org/10.3389/fcimb.2017.00039

Murray, C. J. L., Ikuta, K. S., Sharara, F., Swetschinski, L., Aguilar, G. R., Gray, A., … Naghavi, M. (2022). Global burden of bacterial antimicrobial resistance in 2019: A systematic analysis. *The Lancet, 399*(10325), 629–655. https://doi.org/10.1016/S0140-6736(21)02724-0

Mushak, P. (2022). Human health reference dose derivation and related issues for copper. *Regulatory Toxicology and Pharmacology, 137*, 105288. https://doi.org/10.1016/j.yrtph.2022.105288

Nigeria Geological Survey Agency (NGSA). (2025). *Nigeria Geological Survey Agency*. https://ngsa.gov.ng

Nlemolisa, O. R., Ogbulie, J. N., Orji, J. C., Nweke, C. O., Kemka, U. N., & Gaius-Mbalisi, V. K. (2025). Groundwater contamination and health risks near waste dumps and mechanic workshops: A seasonal perspective. *Cleaner Water, 4*, 100090. https://doi.org/10.1016/j.clwat.2025.100090

Ogbuene, E. B., Nlemolisa, O. R., & Nwankwoala, H. O. (2025). Groundwater contamination and health risks near waste disposal sites and mechanic workshops in Aba, Abia State, Nigeria. *Discover Environment, 3*(1), 28. https://doi.org/10.1016/j.disenv.2025.100028

Okafor, T. E., Umar, N. D., Igwe, O., Solomon, O. O., Abdullahi, S., & Abdullahi, A. I. (2023). Hydrogeochemical characteristics and quality assessment of surface and groundwater around Adudu-Abuni lead-zinc minefields, Northcentral Nigeria. *Water Science, 37*(1), 439–457. https://doi.org/10.1080/23570008.2023.2287788

Olaniyan, I. O., & Omotoso, A. S. (2025). Evaluation of hydrogeologic conditions of crystalline basement aquifers in Lere Local Government Area, Eastern Kaduna State, Nigeria. *Environmental Technology and Science Journal, 16*(1), 252–261. https://doi.org/10.4314/etsj.v16i1.25

Olufemi, J. A., Temitope Ajibola, A., Julius Adeniyi, O., Aiyedogbon Adoga, I., Olusegun William, B., & Jayeola Oladimeji, E. (2020). Impacts of flood on food crop production and adaptive measures among farmers in Northern Guinea Savanna agroecological zone of Kaduna State, Nigeria. *American Journal of Environmental Science and Engineering, 4*(3), 42. https://doi.org/10.11648/j.ajese.20200403.13

Pandey, R., Mukherjee, R., & Chang, C.-M. (2022). Antimicrobial resistance surveillance system mapping in different countries. *Drug Target Insights, 16*, 36–48

Prest, E. I., Hammes, F., van Loosdrecht, M. C. M., & Vrouwenvelder, J. S. (2019). Biological stability of drinking water: Controlling factors, methods, and challenges. *NPJ Clean Water, 2*, 25

Proctor, D., Jiang, X., Reichert, H., & Thompson, C. (2023). Derivation of oral cancer slope factors for hexavalent chromium informed by pharmacokinetic models and in vivo genotoxicity data. *Regulatory Toxicology and Pharmacology, 145*, 105507. https://doi.org/10.1016/j.yrtph.2023.105507

Rodríguez-Seijo, A., Fernández-Calviño, D., Arias-Estévez, M., & Arenas-Lago, D. (2024). Effects of military training, warfare and civilian ammunition debris on soil organisms: An ecotoxicological review. *Biology and Fertility of Soils, 60*(6), 813–844. https://doi.org/10.1007/s00374-024-01835-8

Sanderson, P., Naidu, R., Bolan, N., Bowman, M., & Mclure, S. (2018). Effect of soil type on distribution and bioaccessibility of metal contaminants in shooting range soils. *Science of the Total Environment, 438*, 452–462. https://doi.org/10.1016/j.scitotenv.2012.08.093

Shukla, A. K., Lafuente, A., & Vázquez Rodríguez, G. (2023). Environment and health hazards due to military metal pollution: A review. *Environmental Nanotechnology, Monitoring and Management, 20*, 100857. https://doi.org/10.1016/j.enmm.2023.100857

Standards Organization of Nigeria. (2015). *Nigerian standard for drinking water quality (NIS 554:2015).* https://africacheck.org/sites/default/files/Nigerian-Standard-for-Drinking-Water-Quality-NIS-554-2015.pdf

Tong, S. Y. C., Davis, J. S., Eichenberger, E., Holland, T. L., & Fowler, V. G. (2015). *Staphylococcus aureus* infections: Epidemiology, pathophysiology, clinical manifestations, and management. *Clinical Microbiology Reviews, 28*(3), 603–661

U.S. Environmental Protection Agency. (2000). *Supplemental guidance for developing soil screening levels for Superfund sites.* Office of Solid Waste and Emergency Response. https://www.epa.gov/risk/superfund-risk-assessment

U.S. Environmental Protection Agency. (2012). *Cadmium compounds: Technical fact sheet*. https://cfpub.epa.gov/ncea/iris/iris_documents/documents/toxreviews/0141tr.pdf

U.S. Environmental Protection Agency. (2017). *Nickel compounds (EPA 635 R 01 103F).* Office of Research and Development. https://www.epa.gov/sites/default/files/2016-09/documents/nickle-compounds.pdf

United States Environmental Protection Agency. (2010c). *Exposure factors handbook: 2011 edition.* https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=236252

United States Environmental Protection Agency. (2024). *National primary drinking water regulations.* https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations

Vaz-Moreira, I., Nunes, O. C., & Manaia, C. M. (2017). Ubiquitous and persistent Proteobacteria and other Gram-negative bacteria in drinking water. *Science of the Total Environment, 586*, 1141–1149. https://doi.org/10.1016/j.scitotenv.2017.02.104

Verlicchi, P., & Grillini, V. (2020). Surface and groundwater quality in South Africa and Mozambique—Analysis of the most critical pollutants for drinking purposes and challenges in water treatment selection. *Water, 12*(1), 305. https://doi.org/10.3390/w12010305

Wali, S. U., Alias, N., & Harun, S. B. (2021). Reevaluating the hydrochemistry of groundwater in basement complex aquifers of Kaduna Basin, NW Nigeria using multivariate statistical analysis. *Environmental Earth Sciences, 80*(5), 09421. https://doi.org/10.1007/s12665-021-09421-z

Wang, H., Edwards, M. A., Falkinham, J. O., & Pruden, A. (2023). Probiotic approach to pathogen control in premise plumbing systems? A review of opportunities and challenges. *Environmental Science & Technology, 57*(3), 1017–1030. https://doi.org/10.1021/acs.est.2c07278

World Health Organization. (2014). *Antimicrobial resistance: Global report on surveillance*. Geneva: WHO

World Health Organization. (2017). *Global priority list of antibiotic-resistant bacteria to guide research, discovery and development of new antibiotics*. Geneva: WHO

World Health Organization. (2022). *Guidelines for drinking-water quality* (4th ed., incorporating first and second addenda). https://www.who.int/publications/i/item/9789240045064

Wu, L., Zhan, L., Lan, J., Chen, Y., Zhang, S., Li, J., *et al*. (2021). Leachate migration investigation at an unlined landfill located in granite region using borehole groundwater TDS profiles. *Engineering Geology, 292*, 106259. https://doi.org/10.1016/j.enggeo.2021.106259

Zhu, Y., Li, X., Wang, J., & Chen, W. (2024). Contamination and remediation of contaminated firing range soils: A review of heavy metals and organic contaminants. *Frontiers in Environmental Science, 12*, 1352603. https://doi.org/10.3389/fenvs.2024.1352603