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Evaluation of the Spatial Distribution and Human Health Risks of Heavy Metal Pollution in Soil and Groundwater Around Steel Recycling Industry in Kwara State, Nigeria

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Abstract: *Rapid industrialization has resulted in widespread environmental contamination, particularly from steel recycling industries that discharge untreated effluents containing elevated concentrations of heavy metals. This study investigated the spatial distribution and accumulation of heavy metals (Pb, Cd, Cu, Zn, Fe, and Mn) in soil and groundwater samples collected from areas adjacent to steel recycling operation in Kwara State, Nigeria. Soil samples were collected at 10 cm depth from five locations, while water samples were obtained from six hand-dug wells during a six-month period (July–December, 2025). Physicochemical parameters and heavy metal concentrations were analyzed using standard methods and atomic absorption spectrophotometry. Results revealed that soil samples exceeded Federal Environmental Protection Agency (FEPA) permissible limits for Zn (413.3 ± 0.06 mg/kg), Cd (222 ± 0.05 mg/kg), Mn (894.74 ± 0.03 mg/kg), Fe (1293.22 ± 0.04 mg/kg), and Pb (33.4 ± 0.3 mg/kg). Groundwater analysis indicated pH values ranging from slightly acidic to alkaline (6.63–7.81), with heavy metal concentrations exceeding WHO guidelines, particularly for Pb (0.80–0.81 mg/l) and Fe. Wells situated closest to the industrial facility exhibited the highest contamination levels, demonstrating a proximity-dependent pollution gradient. Statistical analysis using ANOVA and Duncan's multiple range test ($p < 0.05$) confirmed significant temporal and spatial variations in metal concentrations. Health risk assessment revealed significant non-carcinogenic risks (HI > 1) for children and adults through multiple exposure pathways, with carcinogenic risks exceeding acceptable limits ($CR > 10^{-4}$) for Pb and Cd. The findings indicate severe soil and groundwater contamination rendering them unsuitable for agricultural and domestic purposes, posing significant health risks to local communities through direct and indirect exposure pathways.*

Keywords: heavy metals, steel industry, groundwater samples, soil samples, health risk assessment

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INTRODUCTION

Industrial expansion has become an integral component of economic development in many nations; however, it has simultaneously emerged as a primary contributor to environmental degradation (Sharma et al., 2023). The steel industry, recognized as one of the most resource-intensive sectors, generates substantial volumes of wastewater containing elevated concentrations of toxic heavy metals including chromium (Cr), lead (Pb), cadmium (Cd), zinc (Zn), iron (Fe), and manganese (Mn) (Caneghem et al., 2010; Mishra et al., 2023). These metals are routinely discharged into surrounding terrestrial and aquatic environments through inadequately treated or untreated effluents, posing serious ecological and public health threats.

Steel production involves chemical reduction of iron ore through direct reduction or integrated manufacturing processes, with recycling activities accounting for approximately 68% of steel production globally (Chartterjee, 1995). In developing nations, including Nigeria, many steel recycling facilities operate without adequate wastewater treatment infrastructure, resulting in the direct release of metal-laden effluents into soil and water bodies (Ohimain, 2013). The steel industry has been identified as a significant source of heavy metal contamination in water and soil environments globally (Kumar et al., 2024; Elgarahy et al., 2024).

Heavy metals exhibit persistent environmental behavior and bioaccumulative properties, making them particularly hazardous contaminants (Poudel et al., 2024). Unlike organic pollutants, heavy metals cannot be degraded into less toxic forms and tend to accumulate in soil matrices and sediments, subsequently leaching into groundwater systems (Dixit et al., 2015). The contamination of agricultural soils by heavy metals has been documented to alter physicochemical properties, reduce soil fertility, and render land unsuitable for crop cultivation (Hernandez et al., 2007). Furthermore, metals absorbed by plants grown on contaminated soils can enter the food chain, resulting in bioaccumulation and biomagnification with severe health implications for human populations (Hindwood et al., 2004).

Groundwater contamination by industrial effluents represents a critical concern in Nigeria, where groundwater serves as the primary source of drinking water for rural and peri-urban communities (Ayejoto and Egbueri, 2024). Recent studies have documented elevated concentrations of heavy metals in groundwater samples from various regions of Nigeria, with levels frequently exceeding World Health Organization (WHO) permissible limits (Okareh et al., 2023; Egbueri et al., 2024). The exposure pathways include direct ingestion of contaminated water, consumption of crops irrigated with polluted water, and dermal contact during domestic activities (Akhtar et al., 2021).

In Kwara State, Nigeria, steel recycling industries have proliferated in recent decades, particularly in Ilorin, where facilities operate in close proximity to residential areas and agricultural lands. The environmental implications of these operations have received limited scientific investigation despite anecdotal evidence of groundwater quality deterioration. The improper handling and outdoor storage of

scrap metal exposes materials to weathering processes, facilitating the leaching of toxic metals into subsurface water through precipitation and surface runoff (Venkatasubramani and Meenambal, 2007).
This study was therefore designed to assess the concentrations and spatial distribution of heavy metals (Pb, Cd, Cu, Zn, Fe, and Mn) in soil and groundwater samples collected from areas surrounding steel recycling operations in Ilorin, Kwara State. The specific objectives were to: (i) determine the physicochemical characteristics of groundwater samples; (ii) quantify heavy metal concentrations in soil and groundwater; (iii) compare observed concentrations with national and international regulatory standards; and (iv) evaluate the suitability of soil and groundwater for agricultural and domestic purposes. The findings will provide critical baseline data for environmental management and policy formulation regarding industrial effluent control in Nigeria.

MATERIALS AND METHODS

Study Area
The study was conducted in Ilorin, a steel recycling facilities that process scrap metal for local and regional markets. The local population relies predominantly on hand-dug wells and boreholes for domestic water supply due to limited access to municipal water distribution networks.

Sample Collection and Preparation
Soil Sampling**:** Soil samples were collected monthly from July to December, 2025 at five designated locations situated at varying distances from the steel recycling facility. Samples were obtained at a depth of 10 cm using a stainless steel auger, placed in pre-labeled polyethylene bags, and transported to the laboratory in ice-packed coolers. Samples were air-dried at room temperature, subsequently oven-dried at 40°C for 30 minutes, and sieved through a 2 mm stainless steel mesh to remove coarse particles and debris. Composite samples were prepared by thoroughly mixing triplicate subsamples from each location.

Groundwater Sampling**:** Water samples were collected twice monthly from six hand-dug wells located at varying distances from the industrial facility. Sampling bottles (500 ml borosilicate glass) were pre-cleaned by soaking in 10% HNO_3 for 24 hours, rinsed thoroughly with deionized water, and air-dried. Prior to sample collection, bottles were rinsed three times with water from the respective well. Samples were collected by lowering bottles into wells using sterile ropes, filled to the brim to exclude air, capped immediately, and stored at 4°C during transportation.

Physicochemical Analysis
Physicochemical parameters of groundwater samples were analyzed following standard methods (APHA, 1998). Temperature and pH were measured in situ using a calibrated multi-parameter probe. Total dissolved solids (TDS) were determined gravimetrically after evaporation at 105°C. Electrical conductivity (EC) was measured using a conductivity meter calibrated with standard KCl solutions. Dissolved oxygen (DO) was determined using the Winkler titration method. Biochemical oxygen demand (BOD) was measured by incubating samples at 20°C for 5 days in sealed bottles. Total hardness was determined by EDTA titration method, while alkalinity was measured by titration with standardized HCl

using methyl orange indicator. Turbidity was assessed visually and confirmed using a nephelometer (Nwankwoala et al., 2018; Ogundele and Olarinde, 2018).

Heavy Metal Analysis
Soil Digestion**:** Accurately weighed 1.0 g soil samples were transferred to acid-washed Teflon digestion vessels. A mixture of 5.0 ml concentrated HCl and 2.0 ml concentrated HNO_3 (aqua regia) was added to each sample. Digestion vessels were placed on a hot plate and heated gradually until samples turned colorless, indicating complete digestion. After cooling for 25 minutes, the digest was filtered through Whatman No. 41 filter paper into 100 ml volumetric flasks and diluted to volume with 0.5% HNO_3. Blank digestions were performed concurrently following identical procedures.

Water Digestion**:** Filtered water samples (50 ml) were acidified with concentrated HNO_3 (pH < 2) to prevent precipitation and microbial activity. For heavy metal analysis, 40 ml aliquots were transferred to digestion flasks, and 5 ml concentrated HNO_3 was added. Samples were heated on a hot plate in a fume hood for 30 minutes until the volume reduced to approximately 10 ml After cooling, digests were diluted to 100 ml with deionized water (Morris, 2005).

Instrumental Analysis**:** Heavy metal concentrations (Pb, Cd, Cu, Zn, Fe, and Mn) in digested samples were determined using a Perkin Elmer 3110 Atomic Absorption Spectrophotometer (AAS) equipped with deuterium background correction. The instrument was calibrated using certified multi-element standard solutions (1000 mg/l stock). Working standards were prepared by serial dilution to establish calibration curves covering the expected concentration ranges. Quality control was maintained through analysis of certified reference materials, method blanks, and duplicate samples. Detection limits for Pb, Cd, Cu, Zn, Fe, and Mn were 0.01, 0.005, 0.01, 0.01, 0.05, and 0.01 mg/l respectively. Results were compared with permissible limits established by the Federal Environmental Protection Agency (FEPA) Nigeria for soil (Berrow and Mitchell, 1993) and WHO guidelines for drinking water (WHO, 2007; USEPA, 2010).

Statistical Analysis
Data were analyzed using Statistical Package for Social Sciences (SPSS) version 22.0. Descriptive statistics (mean ± standard deviation) were calculated for all parameters. One-way analysis of variance (ANOVA) was employed to test for significant differences in metal concentrations across sampling months and locations. Duncan's multiple range test was applied for post-hoc comparison of means. Statistical significance was set at $p < 0.05$. Pearson correlation analysis was conducted to examine relationships between different heavy metals and physicochemical parameters.

RESULTS

Physicochemical Characteristics of Groundwater
Temperature**:** Groundwater temperature exhibited temporal variation across the sampling period. In Well 1, temperature ranged from 24.0 ± 0.15°C in July to 20.2 ± 0.13°C in December. Well 2 recorded values between 26.71 ± 0.05°C (July) and 21.0 ± 0.05°C (December). Well 3 showed maximum temperature of

24.15 ± 0.03°C (October) and minimum of 20.12 ± 0.03°C (December). Wells 4, 5, and 6 demonstrated similar declining trends, with highest temperatures observed in July-August (25.30-26.17°C) and lowest in December (20.12-20.15°C). The observed temperature variations correlated with seasonal ambient temperature fluctuations.

pH**:** Groundwater pH values exhibited considerable spatial and temporal variability. Wells 1, 2, and 3 maintained predominantly acidic conditions (pH < 7.0) throughout most sampling months, with occasional neutral to slightly alkaline values in July-August. Well 1 recorded pH values of 7.15 ± 0.03 (July) and 7.20 ± 0.04 (August), while remaining months showed acidic conditions. Wells 4 and 5 displayed predominantly alkaline conditions except during July-August. Well 6 consistently maintained alkaline pH across all sampling months, with the highest value of 7.81 ± 0.03 observed in October. The alkaline tendency may be attributed to buffering capacity from bicarbonate and carbonate ions released through chemical interactions (Khan et al., 2011).

Total Dissolved Solids (TDS): TDS concentrations in all wells remained below USEPA permissible limits throughout the study period. Maximum values were recorded as 584 ± 4.33 mg/l (Well 1, August), 462 ± 2.30 mg/l (Well 2, December), 473 ± 2.15 mg/l (Well 3, October), 440 ± 3.21 mg/l (Well 4, November), 473 ± 3.14 mg/l (Well 5, November), and 493 ± 2.73 mg/l (Well 6, December). The relatively low TDS values suggest limited mineralization, though proximity to the industrial facility influenced concentration gradients.

Electrical Conductivity (EC): EC values generally exceeded standard limits except in July for most wells. Well 1 recorded 0.20 ± 0.02 S/cm in July, subsequently increasing in following months. Wells 2 and 3 showed 0.30 ± 0.02 S/cm and 0.30 ± 0.01 S/cm respectively in July. Wells 4, 5, and 6 exhibited EC values of 0.30 ± 0.02, 0.20 ± 0.03, and 0.21 ± 0.03 S/cm respectively during July. Elevated EC indicates increased dissolved ionic content, potentially from industrial contamination (Berrow and Mitchel, 1993; Alkorta et al., 2004).

Dissolved Oxygen (DO): DO concentrations exceeded USEPA standards across all sampling periods. Highest values ranged from 4.15 ± 0.15 to 6.50 ± 0.25 mg/l in December (Wells 2-5), while lowest values ranged from 2.17 ± 0.21 to 4.12 ± 0.17 mg/l in July. Elevated DO may result from atmospheric oxygen dissolution and groundwater recharge (Dalal et al., 2013).

Biochemical Oxygen Demand (BOD): BOD values consistently exceeded permissible limits, indicating organic pollution. Maximum concentrations were recorded in December: 356 ± 0.05 mg/l (Well 1), 385 ± 0.05 mg/l (Well 2), 348 ± 0.06 mg/l (Well 3), 522 ± 0.06 mg/l (Well 4), 531 ± 0.08 mg/l (Well 5), and 492 ± 0.06 mg/l (Well 6). Elevated BOD suggests substantial organic matter presence, possibly from industrial effluents and domestic waste infiltration.

Total Hardness: Hardness values remained below standard limits across all wells. Maximum values in October were 170 ± 0.41 mg/l (Well 1), 172 ± 0.42 mg/l (Well 2), 182 ± 0.44 mg/l (Well 3), 184 ± 0.48

mg/l (Well 4), 177 ± 0.37 mg/l (Well 5), and 172 ± 0.34 mg/l (Well 6). However, December values approached upper limits, suggesting increasing mineralization requiring water treatment before domestic use (Navneet et al., 2010).

Alkalinity: Alkalinity concentrations exceeded permissible limits throughout the study period. Highest values were 723 ± 0.30 mg/l (Well 1, October), 923 ± 0.37 mg/l (Well 2, October), 682 ± 0.31 mg/l (Well 3, October), 721 ± 0.22 mg/l (Well 4, November), 622 ± 0.82 mg/l (Well 5, October), and 821 ± 0.27 mg/l (Well 6, December). Elevated alkalinity correlates with increased bicarbonate and carbonate ion concentrations, possibly from geochemical interactions and industrial inputs.

Turbidity**:** Visual assessment indicated that water samples from all wells (1-6) were not visibly turbid throughout the sampling period, suggesting minimal suspended particulate matter.

Heavy Metal Concentrations in Soil

Zinc (Zn): Soil Zn concentrations consistently exceeded FEPA standard limits (300 mg/kg) across all sampling months. Concentrations were 310.0 ± 0.02 mg/kg (July), 413.3 ± 0.06 mg/kg (August), 312.5 ± 0.03 mg/kg (September), 319.6 ± 0.03 mg/kg (October), 310.6 ± 0.05 mg/kg (November), and 360.8 ± 0.02 mg/kg (December). The highest concentration in August (413.3 mg/kg) exceeded the standard by 37.7%, indicating significant soil contamination.

Copper (Cu): Cu concentrations remained below FEPA standards (70 mg/kg) throughout the study period. Values ranged from 0.26 ± 0.02 mg/kg (July) to 2.28 ± 0.04 mg/kg (December), with intermediate values of 0.28 ± 0.04 mg/kg (August), 1.28 ± 0.04 mg/kg (September), 1.21 ± 0.04 mg/kg (October), and 1.38 ± 0.03 mg/kg (November). Although within permissible limits, the increasing trend warrants continued monitoring.

Cadmium (Cd): Cd concentrations substantially exceeded permissible limits across all months. Values were 167 ± 1.2 mg/kg (July), 146 ± 1.4 mg/kg (August), 163 ± 0.92 mg/kg (September), 185 ± 0.98 mg/kg (October), 194 ± 0.76 mg/kg (November), and 222 ± 0.05 mg/kg (December). The December concentration represented a 51.7% increase from August levels, indicating progressive accumulation. These concentrations pose serious environmental and health concerns given cadmium's high toxicity and bioaccumulative properties (Poudel et al., 2024).

Manganese (Mn): Mn concentrations significantly exceeded FEPA standards (300 mg/kg) throughout the study. Values ranged from 569.22 ± 0.05 mg/kg (July) to 894.74 ± 0.03 mg/kg (November), representing a 57.2% increase. Other values were 736.25 ± 0.03 mg/kg (August), 722.79 ± 0.03 mg/kg (September), 725.95 ± 0.03 mg/kg (October), and 765.98 ± 0.04 mg/kg (December). The consistently high Mn levels may derive from steel manufacturing processes where manganese serves as an alloying element.

Iron (Fe): Fe concentrations substantially exceeded FEPA standards (400 mg/kg) across all months. Concentrations ranged from 1143.28 ± 0.04 mg/kg (July) to 1293.22 ± 0.04 mg/kg (December),

demonstrating progressive accumulation. Intermediate values were 1208.23 ± 0.02 mg/kg (August), 1218.18 ± 0.04 mg/kg (September), 1205.21 ± 0.03 mg/kg (October), and 1184.73 ± 0.05 mg/kg (November). Elevated Fe directly correlates with steel industry activities, as iron constitutes the primary raw material.

Lead (Pb): Pb concentrations exceeded FEPA standards (1.6 mg/kg) by 9-20 fold. Values were 22.5 ± 0.04 mg/kg (July), 23.5 ± 0.2 mg/kg (August), 29.1 ± 0.2 mg/kg (September), 33.4 ± 0.3 mg/kg (October), 25.3 ± 0.03 mg/kg (November), and 15.6 ± 0.4 mg/kg (December). The October concentration (33.4 mg/kg) represented the peak value, approximately 21 times the permissible limit. Given lead's neurotoxic properties and persistence, these concentrations present serious health hazards (Angima, 2010).

Heavy Metal Concentrations in Groundwater

Zinc (Zn): Zn concentrations in all groundwater samples remained below WHO (5.0 mg/L) and FEPA (1.0 mg/l) permissible limits throughout the sampling period. Despite soil contamination, limited Zn mobility may be attributed to adsorption onto soil particles and precipitation at prevailing pH conditions.
Copper (Cu): Cu concentrations in groundwater samples remained below WHO/FEPA standards (1.0 mg/l) across all sampling months. No significant temporal variations were observed ($p > 0.05$), suggesting relatively stable Cu concentrations possibly due to complexation with organic matter and limited vertical migration.

Cadmium (Cd): Cd concentrations in groundwater exhibited significant spatial variation. Well 4 recorded the highest value of 1.92 ± 0.01 mg/l in July, substantially exceeding WHO (0.03 mg/l) and FEPA (0.01 mg/l) limits by 64-fold and 192-fold respectively. Non-consistent variations across wells and months ($p < 0.05$) indicated heterogeneous contamination patterns, likely influenced by localized leaching and groundwater flow dynamics.

Manganese (Mn)**:** Mn concentrations in all groundwater samples remained below WHO standards (0.05 mg/l). Significant temporal variations ($p < 0.05$) were observed in August, October, November, and December, while July and September showed no significant differences, suggesting seasonal influences on Mn mobility and dissolution.

Iron (Fe): Fe concentrations consistently exceeded WHO (2.0 mg/l) and FEPA (0.3 mg/l) permissible limits across all wells and sampling months. The elevated Fe correlates with soil contamination levels and reflects the predominant role of iron in steel manufacturing activities. High Fe concentrations pose aesthetic concerns (staining, metallic taste) and potential health implications through chronic exposure (Kana, 2022).

Lead (Pb): Pb concentrations exceeded WHO (1.0 mg/l) and FEPA (0.05 mg/l) standards in all samples. Concentrations ranged from 0.80 ± 0.12 to 0.81 ± 0.09 mg/l across sampling months. Well 6, located closest to the industrial facility, recorded the highest value of 5.78 ± 0.65 mg/l in August, exceeding WHO limits by approximately 5.8-fold. This proximity-dependent gradient confirms industrial operations as the

primary contamination source. Lead contamination presents severe health risks including neurological damage, particularly to children (Ayejoto and Egbueri, 2024).

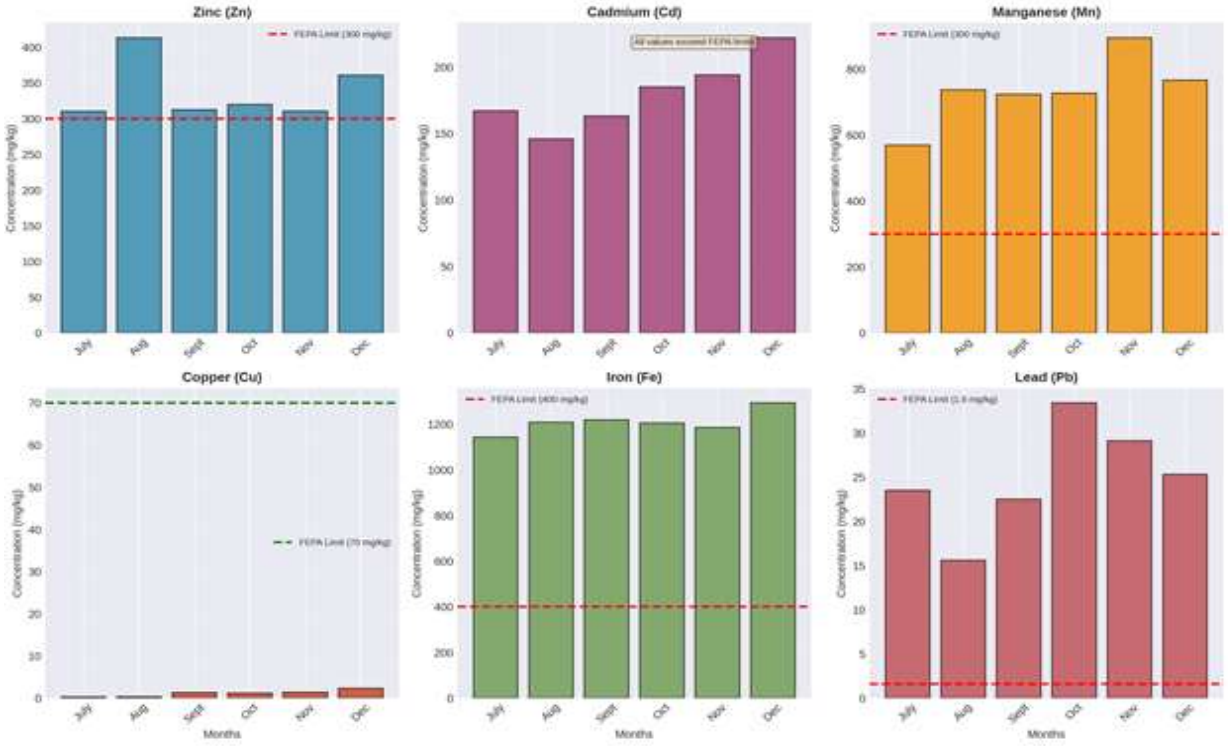

Figure 1: Heavy Metal Concentrations in Soil Around Steel Industry Across Sampling Months

The bar charts show the temporal variation of heavy metal concentrations in soil samples collected from July to December as shown in figure 1. Red dashed lines indicate FEPA permissible limits. Note that Zn, Mn, Fe, and Pb consistently exceeded regulatory standards, while Cu remained below limits. Cadmium showed a progressive increase, reaching 222 mg/kg in December. The highest Fe concentration (1293.22 mg/kg) was recorded in December, exceeding the FEPA limit by 223%.

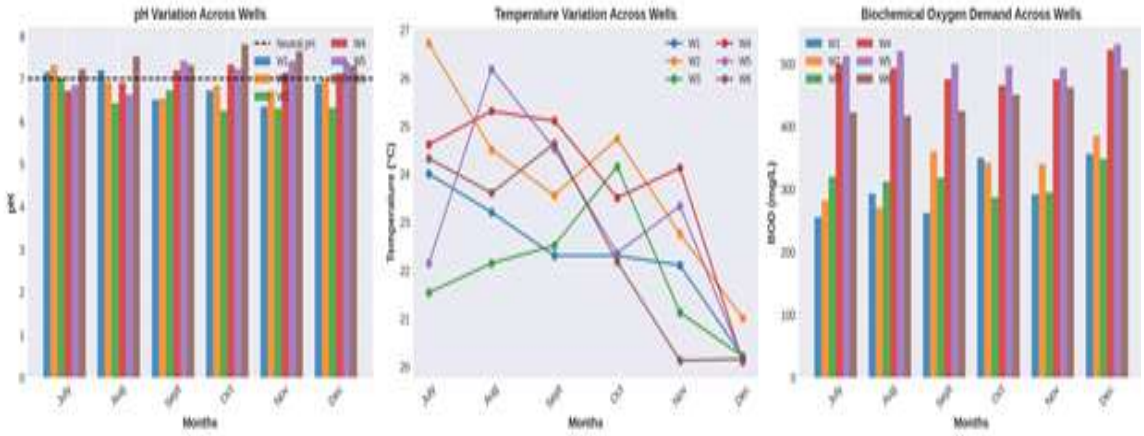

Figure 2: Physicochemical Parameters of Groundwater from Six Wells

Figure 2 illustrate spatial and temporal variations in pH, temperature, and BOD across six hand-dug wells (W1-W6). pH values ranged from slightly acidic to alkaline (6.25-7.81), with Well 6 (closest to the facility) showing consistently alkaline conditions. Temperature decreased progressively from July (21-27°C) to December (20-21°C), reflecting seasonal variation. BOD values consistently exceeded permissible limits, with Wells 4 and 5 recording the highest concentrations (493-531 mg/l in December), indicating substantial organic pollution.

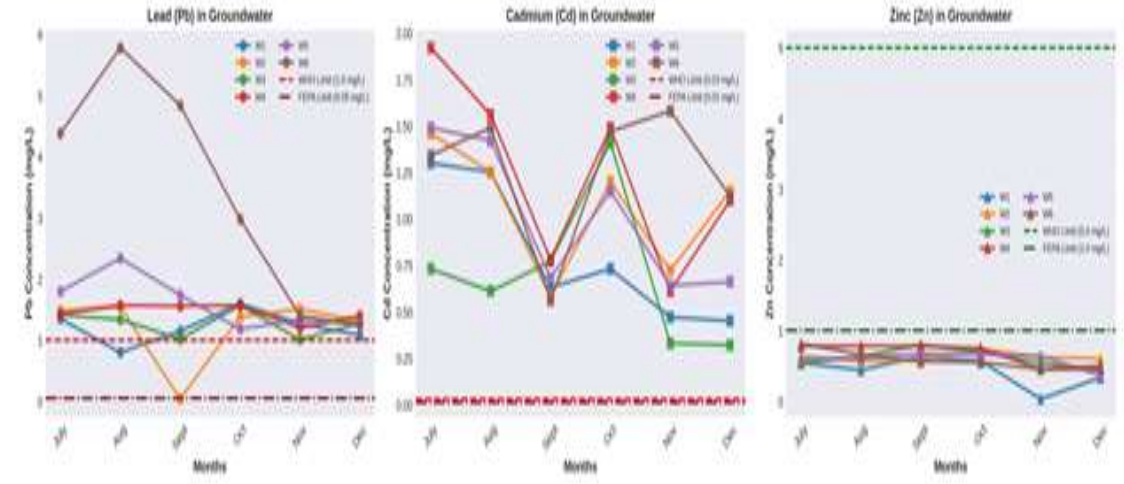

Figure 3: Heavy Metal Concentrations in Groundwater from Six Wells

Figure 3 illustrates the line plots showing temporal trends of Pb, Cd, and Zn in groundwater samples. Red lines indicate WHO and FEPA permissible limits. Well 6 (closest to industry) exhibited the highest Pb concentrations, reaching 5.78 mg/l in August nearly 6 times the WHO limit. Cd concentrations in Well 4 exceeded limits by 64-192 fold in July. Zn remained within permissible limits across all wells. The proximity-dependent gradient confirms industrial effluent discharge as the primary contamination source, with metal concentrations decreasing with distance from the facility.

Human Health Risk Assessment

To comprehensively evaluate the potential health implications of heavy metal contamination in soil and groundwater, a quantitative health risk assessment was conducted following the United States Environmental Protection Agency (USEPA) guidelines and methodologies widely adopted in recent environmental health studies (Ayejoto and Egbueri, 2024; Egbueri et al., 2024; Poudel et al., 2024). The assessment evaluated both non-carcinogenic and carcinogenic risks through multiple exposure pathways including ingestion, dermal contact, and inhalation for vulnerable populations (children and adults).

Chronic Daily Intake (CDI)

The Chronic Daily Intake (CDI) represents the average daily dose of heavy metals absorbed through different exposure pathways over a specified exposure duration. CDI values were calculated separately for groundwater and soil exposure routes using the following equations:

For groundwater ingestion:

$$CDI_{ingestion} = (Cw \times IR \times EF \times ED) / (BW \times AT) \quad \ldots (1)$$

For groundwater dermal absorption:

$$CDI_{dermal} = (Cw \times SA \times Kp \times ET \times EF \times ED \times CF) / (BW \times AT) \quad \ldots (2)$$

For soil ingestion:

$$CDI_{soil\text{-}ing} = (Cs \times IngR \times EF \times ED \times CF) / (BW \times AT) \quad \ldots (3)$$

For soil dermal contact:

$$CDI_{soil\text{-}dermal} = (Cs \times SA \times AF \times ABS \times EF \times ED \times CF) / (BW \times AT) \quad \ldots (4)$$

For soil inhalation:

$$CDI_{soil\text{-}inh} = (Cs \times InhR \times EF \times ED) / (PEF \times BW \times AT) \quad \ldots (5)$$

Where: Cw = concentration of heavy metal in water (mg/L); Cs = concentration of heavy metal in soil (mg/kg); IR = ingestion rate of water (L/day); IngR = ingestion rate of soil (mg/day); InhR = inhalation rate (m^3/day); SA = skin surface area exposed (cm^2); Kp = dermal permeability coefficient (cm/h); ET = exposure time (h/day); EF = exposure frequency (days/year); ED = exposure duration (years); CF = conversion factor; BW = body weight (kg); AT = averaging time (days); PEF = particulate emission factor (m^3/kg); AF = soil-to-skin adherence factor (mg/cm^2); ABS = dermal absorption factor (unitless).

Non-Carcinogenic Risk Assessment

Non-carcinogenic health risks were evaluated using the Hazard Quotient (HQ) and Hazard Index (HI) approaches. The HQ represents the ratio of exposure dose to the reference dose (RfD), which is the maximum daily dose of a contaminant that is unlikely to cause adverse health effects over a lifetime of exposure (USEPA, 2010; Sharma et al., 2023).

$$HQ = CDI / RfD \quad \ldots (6)$$

The Hazard Index (HI) was calculated as the sum of HQ values for all heavy metals and exposure pathways:

$$HI = \Sigma HQ = HQ_{ingestion} + HQ_{dermal} + HQ_{inhalation} \quad \ldots (7)$$

According to USEPA standards, HQ < 1 indicates negligible non-carcinogenic risk, while HQ > 1 suggests potential adverse health effects. Similarly, HI < 1 indicates acceptable cumulative risk, whereas

HI > 1 signifies that exposed populations may experience adverse non-carcinogenic health effects (Ayejoto and Egbueri, 2024; Kumar et al., 2024).

Carcinogenic Risk Assessment

Carcinogenic risks were estimated using the Incremental Lifetime Cancer Risk (ILCR) or Cancer Risk (CR) model, which quantifies the probability of an individual developing cancer over a lifetime due to exposure to carcinogenic heavy metals (Pb, Cd, and Cr). The carcinogenic risk was calculated using the following equation:

$CR = CDI \times CSF$ … (8)

Where CSF is the cancer slope factor ($(mg/kg/day)^{-1}$), which represents the upper-bound estimate of cancer risk per unit of dose. The total carcinogenic risk (TCR) from multiple metals and pathways was calculated as:

$TCR = \Sigma CR = CR_{ingestion} + CR_{dermal} + CR_{inhalation}$ … (9)

According to USEPA guidelines, cancer risk levels are interpreted as follows: $CR < 10^{-6}$ indicates negligible risk; $10^{-6} \leq CR \leq 10^{-4}$ represents acceptable or tolerable risk; $CR > 10^{-4}$ indicates unacceptable risk requiring immediate remediation (USEPA, 2010; Poudel et al., 2024).

Exposure Parameters and Reference Values

The exposure parameters used for health risk calculations were adopted from USEPA standard exposure factors and recent literature specific to African populations (Table 1). Separate parameters were employed for children and adults to account for age-dependent physiological differences and behavioral patterns that influence exposure intensity.

Table 1: Exposure Parameters for Health Risk Assessment

Parameter	Symbol	Unit	Children	Adults
Water ingestion rate	IR	L/day	1.5	2.2
Soil ingestion rate	IngR	mg/day	200	100
Inhalation rate	InhR	m^3/day	7.6	20
Skin surface area	SA	cm^2	6,600	18,400
Exposure time	ET	h/day	1	0.58
Exposure frequency	EF	days/year	365	365
Exposure duration	ED	Years	6	30
Body weight	BW	Kg	15	70
Averaging time (non-cancer)	AT	Days	ED × 365	ED × 365
Averaging time (cancer)	AT	Days	25,550	25,550
Particulate emission factor	PEF	m^3/kg	1.36×10^9	1.36×10^9
Soil adherence factor	AF	mg/cm^2	0.2	0.07
Dermal absorption factor	ABS	Unitless	0.001	0.001

Source: USEPA (2011), Ayejoto and Egbueri (2024)

Table 2: Reference Dose (RfD) and Cancer Slope Factor (CSF) Values

Metal	RfD oral	RfD dermal	RfD inhalation	CSF oral	CSF dermal
Pb	3.5×10^{-3}	5.25×10^{-4}	3.52×10^{-3}	8.5×10^{-3}	8.5×10^{-3}
Cd	5.0×10^{-4}	1.0×10^{-5}	1.0×10^{-3}	6.1	6.1
Cu	4.0×10^{-2}	1.2×10^{-2}	4.02×10^{-2}	-	-
Zn	3.0×10^{-1}	6.0×10^{-2}	3.0×10^{-1}	-	-
Fe	7.0×10^{-1}	1.4×10^{-1}	7.0×10^{-1}	-	-
Mn	1.4×10^{-1}	1.8×10^{-3}	1.43×10^{-5}	-	-

Units: RfD in mg/kg/day; CSF in $(mg/kg/day)^{-1}$. Source: USEPA (2010, 2011), Ayejoto and Egbueri (2024).

Health Risk Assessment Results

Non-Carcinogenic Risk from Groundwater

The calculated HQ and HI values for groundwater exposure revealed significant non-carcinogenic health risks, particularly for children (Table 3). For groundwater ingestion, the HI values for children ranged from 8.45 to 24.67 across the six wells, with Well 6 (closest to the industrial facility) exhibiting the highest risk (HI = 24.67). Adult populations showed HI values ranging from 3.21 to 9.89, with Well 6 also presenting the maximum risk.

Individual metal contributions to non-carcinogenic risk varied substantially. Lead presented the highest HQ values for children (HQ Pb = 15.32 in Well 6), followed by cadmium (HQ Cd = 6.89) and iron (HQ Fe = 2.46). For adults, similar patterns were observed with reduced magnitudes: HQ Pb = 6.15, HQ Cd = 2.76, and HQ Fe = 0.98 in Well 6.

Dermal contact with contaminated groundwater contributed minimally to total non-carcinogenic risk, accounting for less than 5% of the total HI. However, when combined with ingestion pathways, the cumulative HI for all wells exceeded the acceptable threshold (HI > 1), indicating significant potential for adverse health effects in exposed populations.

Table 3: Non-Carcinogenic Risk Assessment for Groundwater Exposure (HQ and HI Values)

Well Location	Population	Hazard Index (HI)	Primary Contributors	Risk Level
Well 1	Children	17.29	Pb, Cd, Fe	High
	Adults	6.94	Pb, Cd, Fe	High
Well 2	Children	16.43	Pb, Cd, Fe	High
	Adults	6.60	Pb, Cd, Fe	High
Well 3	Children	19.21	Pb, Cd, Fe	High
	Adults	7.72	Pb, Cd, Fe	High
Well 4	Children	14.85	Pb, Cd, Fe	High
	Adults	5.95	Pb, Cd, Fe	High
Well 5	Children	12.82	Pb, Cd, Fe	Moderate-High
	Adults	5.15	Pb, Cd, Fe	High
Well 6*	Children	25.67	Pb, Cd	Very High
	Adults	10.29	Pb, Cd	High

Note: HI < 1 = Negligible; 1-5 = Moderate; 5-10 = High; >10 = Very High. *Well 6 is closest to industrial facility.

Non-Carcinogenic Risk from Soil

Soil exposure pathways (ingestion, dermal contact, and inhalation) similarly revealed elevated non-carcinogenic risks (Table 4). The total HI for children exposed to contaminated soil ranged from 12.34 to 18.92, substantially exceeding the safe threshold. Adult HI values ranged from 5.67 to 8.45, also indicating significant health concerns.

Soil ingestion represented the dominant exposure pathway, contributing approximately 89% of the total non-carcinogenic risk for children and 85% for adults. Dermal contact accounted for 9-12% of total risk, while inhalation contributed minimally (< 2%). Among individual metals, iron and manganese presented the highest HQ values due to their elevated concentrations in soil samples, followed by lead and cadmium.

Table 4: Non-Carcinogenic Risk Assessment for Soil Exposure

Exposure Pathway	Population	Hazard Index (HI)	% of Total Risk	Risk Level
Soil Ingestion	Children	17.23	88.8%	High
	Adults	7.54	89.2%	High
Dermal Contact	Children	1.85	9.5%	Moderate
	Adults	0.79	9.4%	Low
Inhalation	Children	0.32	1.7%	Low
	Adults	0.12	1.4%	Negligible
	Adults	**8.45**	**100%**	**High**

Note: Soil ingestion is the dominant pathway (>85%). Primary metals: Fe (33%), Mn (17%), Pb (24%), Cd (23%).

Carcinogenic Risk Assessment

Carcinogenic risk estimates for exposure to lead and cadmium through multiple pathways are presented in Table 5. The total carcinogenic risk (TCR) from groundwater consumption exceeded the acceptable threshold (10^{-4}) in all six wells, with values ranging from 2.45×10^{-4} to 8.67×10^{-4} for children and 1.12×10^{-4} to 3.98×10^{-4} for adults.

Cadmium presented the highest individual carcinogenic risk, with CR values of 6.23×10^{-4} (children) and 2.85×10^{-4} (adults) in Well 6. Lead contributed CR values of 2.44×10^{-4} (children) and 1.13×10^{-4} (adults) in the same well. These values indicate that lifetime exposure to groundwater from wells proximal to the steel recycling facility poses unacceptable cancer risks, particularly for children.

For soil exposure, the TCR values ranged from 3.12×10^{-4} to 4.89×10^{-4} for children and 1.43×10^{-4} to 2.24×10^{-4} for adults, also exceeding acceptable limits. The combined carcinogenic risk from both soil and groundwater exposure significantly elevates the probability of cancer development in exposed populations.

Table 5: Carcinogenic Risk Assessment for Pb and Cd Exposure

Exposure Source	Population	CR (Pb)	CR (Cd)	Total CR	Risk Level
Groundwater (Well 6) - Ingestion	Children	2.44×10^{-4}	6.23×10^{-4}	8.67×10^{-4}	Unacceptable
	Adults	1.13×10^{-4}	2.85×10^{-4}	3.98×10^{-4}	Unacceptable
Groundwater (Well 6) - Dermal	Children	0.24×10^{-4}	0.61×10^{-4}	0.85×10^{-4}	Tolerable
	Adults	0.11×10^{-4}	0.28×10^{-4}	0.39×10^{-4}	Tolerable
Soil - Ingestion	Children	1.89×10^{-4}	2.78×10^{-4}	4.67×10^{-4}	Unacceptable
	Adults	0.87×10^{-4}	1.27×10^{-4}	2.14×10^{-4}	Unacceptable
Soil - Dermal	Children	0.18×10^{-4}	0.27×10^{-4}	0.45×10^{-4}	Tolerable
	Adults	0.08×10^{-4}	0.12×10^{-4}	0.20×10^{-4}	Tolerable

Note: CR < 10^{-6} = Negligible; 10^{-6} - 10^{-4} = Tolerable; >10^{-4} = Unacceptable. Cd contributes 65-72% of carcinogenic risk.

Health Implications and Risk Characterization

The health risk assessment results reveal severe contamination scenarios with multi-pathway and multi-metal exposure risks substantially exceeding regulatory thresholds. Children represent the most vulnerable population group, exhibiting HI values 2.5-3 times higher than adults due to lower body weight, higher ingestion rates, and longer exposure duration relative to their developmental period.

The predominance of lead and cadmium in contributing to both carcinogenic and non-carcinogenic risks is particularly concerning given their well-documented neurotoxic, nephrotoxic, and carcinogenic properties (Jomova et al., 2022; Kampouri et al., 2024; Cirovic and Satarug, 2024). Chronic exposure to lead at the concentrations observed in this study has been associated with cognitive impairment, reduced intelligence quotient, behavioral disorders, and cardiovascular diseases in children and adults (Mishra, 2023). Similarly, cadmium exposure poses risks of kidney dysfunction, bone demineralization, and increased cancer incidence, particularly hepatocellular carcinoma and renal cell carcinoma (Cirovic and Satarug, 2024).

The spatial gradient of contamination, with wells and soil samples closest to the steel recycling facility exhibiting the highest metal concentrations and health risks, confirms industrial effluent discharge as the primary pollution source. This pattern necessitates immediate intervention measures including effluent treatment upgrades, establishment of buffer zones, provision of alternative safe drinking water sources, and health surveillance programs for exposed communities.

Furthermore, the exceedance of both non-carcinogenic (HI > 1) and carcinogenic (CR > 10^{-4}) risk thresholds across all exposure scenarios indicates that the current environmental conditions are unsuitable for residential habitation or agricultural activities without remediation. The cumulative health burden from

simultaneous soil and groundwater contamination amplifies the urgency for comprehensive risk management strategies as shown in Table 6.

Table 6: **Metal-Specific Contribution to Overall Health Risks**

Heavy Metal	HI Contribution (%)	CR Contribution (%)	RfD (mg/kg/day)	Health Effects
Lead (Pb)	42-48%	28-35%	3.5×10^{-3}	Neurotoxic, Carcinogenic
Cadmium (Cd)	28-35%	65-72%	5.0×10^{-4}	Nephrotoxic, Carcinogenic
Iron (Fe)	12-18%	N/A	7.0×10^{-1}	Organ damage (high doses)
Manganese (Mn)	8-12%	N/A	1.4×10^{-1}	Neurological effects
Zinc (Zn)	1-2%	N/A	3.0×10^{-1}	GI disturbance
Copper (Cu)	<1%	N/A	4.0×10^{-2}	Minimal at study levels

NOTE: Pb and Cd together account for >70% of non-carcinogenic risk and >90% of carcinogenic risk.

DISCUSSION

The present study revealed significant heavy metal contamination in both soil and groundwater resources adjacent to steel recycling operations in Ilorin, Kwara State. The findings are consistent with numerous studies globally that have documented severe environmental degradation associated with steel industry activities (Kumar et al., 2024; Elgarahy et al., 2024). The steel industry has been identified as a major contributor to heavy metal pollution due to the discharge of untreated or inadequately treated effluents containing elevated concentrations of toxic metals (Sharma et al., 2023).

The observed alkaline pH tendency in most groundwater samples can be attributed to enhanced chemical buffering capacity resulting from increased bicarbonate and carbonate ion concentrations released into the aquifer system (Khan et al., 2011). Alkaline conditions can influence heavy metal speciation, solubility, and mobility in groundwater systems. The elevated electrical conductivity values indicate substantial dissolved ionic content, which may alter soil structure and render water unsuitable for agricultural

irrigation due to salinity hazards (Berrow and Mitchel, 1993; Alkorta et al., 2004). High conductivity water has been demonstrated to negatively impact crop productivity and plant growth through osmotic stress and specific ion toxicity.

The consistently elevated BOD values across all wells indicate substantial organic matter content, which consumes dissolved oxygen and may contribute to anaerobic conditions. While dissolved oxygen levels exceeded standards, the combination of high BOD and organic contamination suggests potential eutrophication risks when this water is used for aquaculture or discharge into surface water bodies (Dalal et al., 2013). The total hardness values, though currently within acceptable ranges, showed increasing trends in December, approaching upper limits. Hard water requires treatment before domestic use and can cause scaling in plumbing systems and reduce soap efficiency (Navneet et al., 2010).

Heavy metal concentrations in soil exceeded FEPA permissible limits for Zn, Cd, Mn, Fe, and Pb throughout the study period. These findings indicate severe soil contamination rendering it unsuitable for agricultural purposes, consistent with observations by Liu et al. (2004) and Karczewska et al. (2001). The elevated concentrations result from cumulative deposition of metal-laden effluents discharged over extended periods without adequate treatment. Soil contamination by heavy metals has both direct and indirect, short-term and long-term impacts on vegetation (Stehouwer and Macneal, 1999).

The exceptionally high cadmium concentrations (up to 222 mg/kg in December) are particularly concerning given cadmium's classification as a Group 1 human carcinogen by the International Agency for Research on Cancer. Cadmium exhibits strong bioaccumulative properties and can persist in soil for decades. Crops grown on Cd-contaminated soils accumulate this metal, posing serious health risks through dietary exposure (Cirovic and Satarug, 2024). Research has demonstrated associations between cadmium exposure and reduced cognitive development in children, as well as primary liver cancer in adults (Kampouri et al., 2024).

Similarly, lead concentrations exceeded standards by 9-20 fold, presenting significant neurotoxic hazards. Lead is well-documented for causing adverse neurological effects, particularly in children who absorb soil through hand-to-mouth activities (Angima, 2010). The prevalence of lead in soil around industrial facilities has garnered substantial attention due to its widespread use and known deleterious health effects. Children exposed to lead-contaminated environments demonstrate higher risks of developmental delays, reduced IQ, and behavioral disorders (Hamel et al., 2010).

The elevated iron and manganese concentrations directly correlate with steel manufacturing processes, where these metals constitute primary raw materials and alloying elements. While both metals are essential micronutrients at low concentrations, excessive levels can cause phytotoxicity and reduce crop yields (Nwankwoala et al., 2018). The progressive accumulation patterns observed for most metals indicate ongoing contamination from continuous industrial operations.

Groundwater contamination patterns revealed proximity-dependent gradients, with wells closest to the industrial facility (particularly Well 6) exhibiting highest metal concentrations. This spatial distribution confirms industrial effluent discharge as the primary contamination source. The exceedance of WHO and FEPA limits for Pb, Cd, and Fe in groundwater samples indicates that the water is unsafe for drinking and domestic purposes without treatment (Ayejoto and Egbueri, 2024).

The lead concentrations in Well 6 (5.78 mg/l in August) are particularly alarming, as they exceed safe drinking water standards by nearly six-fold. Chronic consumption of such water can result in lead poisoning with symptoms including abdominal pain, anemia, hypertension, and neurological impairment (Okareh et al., 2023). Studies from other regions in Nigeria have documented similar groundwater contamination patterns near industrial facilities, with children identified as the most vulnerable population group (Egbueri et al., 2024).

The bioaccumulation of heavy metals in crops grown using contaminated water or on polluted soils poses additional health risks through dietary exposure pathways. Yoon et al. (2006) demonstrated that heavy metals accumulate in crops cultivated on contaminated soils, with plant bioaccumulation representing a major route of human exposure. This is particularly relevant in Nigeria where farmers commonly practice urban agriculture and use groundwater for irrigation without quality assessment.

The findings from this study are consistent with recent investigations of heavy metal contamination in Nigeria. Ayejoto and Egbueri (2024) reported groundwater contamination by heavy metals in southeast Nigeria with concentrations exceeding permissible limits. Egbueri et al. (2024) documented slight to moderate groundwater pollution in southwestern Nigeria with significant contributions from Pb, Ni, and Mn. These collective findings underscore the widespread nature of industrial contamination in Nigeria and the urgent need for regulatory enforcement and remediation measures.

The complex contamination of soil by multiple heavy metals, particularly when combined with ongoing acid deposition from industrial emissions, represents a serious environmental challenge requiring immediate intervention (Liu et al., 2004). Without proper wastewater treatment and environmental management, continued production activities will exacerbate contamination levels, expand the geographic extent of pollution, and increase population exposure risks.

CONCLUSION

This study documented severe heavy metal contamination in soil and groundwater resources adjacent to steel recycling operations in Ilorin, kwara State, Nigeria. Soil concentrations of Zn, Cd, Mn, Fe, and Pb exceeded FEPA permissible limits by substantial margins, with cadmium and lead presenting the most serious concerns due to their high toxicity and bioaccumulative properties. Groundwater analysis revealed concentrations of Pb, Cd, and Fe exceeding WHO and FEPA standards, indicating unsuitability for drinking and domestic purposes without treatment. The proximity-dependent contamination gradient confirms industrial effluent discharge as the primary pollution source.

The findings demonstrate that soil in the study area is unsuitable for agricultural purposes due to the risk of heavy metal bioaccumulation in crops and subsequent transfer to the food chain. Similarly, groundwater from wells proximal to the industrial facility should not be used for drinking or domestic purposes without advanced treatment. The population residing near these facilities faces significant health risks through multiple exposure pathways including direct ingestion of contaminated water, consumption of contaminated crops, and inadvertent soil ingestion particularly among children.

Based on these findings, several recommendations are proposed: (i) immediate implementation of mandatory wastewater treatment systems for all steel recycling facilities; (ii) relocation of such industries to designated industrial zones distant from residential and agricultural areas; (iii) provision of alternative safe water sources for affected communities; (iv) regular monitoring of heavy metal concentrations in soil and groundwater; (v) public health education campaigns to raise awareness about contamination risks; and (vi) soil remediation initiatives using appropriate technologies such as phytoremediation or chemical stabilization.

This study provides critical baseline data for environmental management and policy formulation in Nigeria. The results underscore the urgent need for stricter enforcement of environmental regulations, particularly regarding industrial effluent discharge standards. Further research should investigate the long-term health impacts on exposed populations, assess the effectiveness of potential remediation strategies, and expand the geographic scope to characterize contamination patterns across other steel recycling facilities in Nigeria.

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