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Appraisal of Heavy Metal Levels and Pollutant Characteristics in the Urban Soils of Tebrebie Community, Ghana

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Abstract

This study investigates potential heavy metal exposure in urban soils of the Tebrebie community in the Tarkwa-Nsuaem Municipality, Western Region of Ghana, by collecting ten composite soil samples, which were analyzed for selected toxic heavy metals (As, Pb, Cd and Hg) using flame atomic absorption spectrometry. The results were compared with Canadian Council of Ministers of the Environment (CCME) Canadian Soil Quality Guidelines (CSQG) for the Protection of Environmental and Human Health, Residential/Parkland and a control sample. As concentrations ranged from <0.001 to 3.694 mg/kg, Cd levels were <0.002 mg/kg and Hg ranged from <0.001 to 0.088 mg/kg, all below the control and Canadian standards. However, Pb levels (2.01 to 6.12 mg/kg) exceeded the control sample. As, Pb and Hg exhibited localized hotspots particularly in the central to northern regions suggesting potential pollution sources in the spatial distribution analysis. Pollution indices suggested contamination ranged from uncontaminated to moderately contaminated. The calculated hazard index for the metals was <1.0, indicating no non-carcinogenic hazard to children and adult residents of the Tebrebie community. Cd and Hg cancer risk remained within acceptable levels. However, the estimated cancer risk for Pb (CRing) and arsenic (CRing, CRinh, and CRderm) exceeded the threshold, indicating a probable carcinogenic effect on local residents. This study reveals that the urban soil quality in the Tebrebie community may be deteriorating, potentially adversely impacting the local ecosystem and human health.

Keywords

Soil, Distribution of Heavy Metals, Tebrebie, Urban Soil, Pollution Indices, Mining, Ecological Risk

1. Introduction

Urban areas are the most common heavy metal contamination, especially when certain soil and water become global and are subsequently distributed to other soils. Soils (anthropogenic soils) from urban areas have been deeply affected by human activities in the course of urbanization processes (Cicchella et al., 2020). Previous research suggested that substantial quantities of heavy metals can be released into soils by human activities (Guo et al., 2008). Hence, human activities such as industrial operations pollute the air and soil with heavy metals either by means of vehicle emission or release through other processes like inappropriate waste disposal at landfill sites; usage of pesticides in agricultural practices etc. ultimately causing gradual buildup (Kumari & Mishra, 2021).

These pollutants not only endanger the health of the soil but also have extensive effects, on the well-being of humans and the surrounding environment. The persistence of heavy metals in the environment, coupled with their ability to bioaccumulate in food chains, has made this issue a growing concern in urban areas worldwide. As society has progressed and the mining industry has experienced rapid growth, there has been a rise in the levels of heavy metals such as mercury, cadmium, chromium, lead, arsenic and manganese (Mohammed et al., 2011).

Extensive mineral extraction activities, particularly in mining regions, generate substantial waste and tailings, releasing harmful substances into the surrounding environment (Demková et al., 2017). While mining provides significant economic benefits, it also has the potential to cause severe environmental pollution, impacting both local communities and the country if not properly managed (Pegg, 2006).

The Tebrebie community's proximity to AngloGold Ashanti Iduapriem Limited (AAIL), which employs traditional techniques like drilling and blasting in open pit mining operations to extract gold bearing ore may lead to the discharge of substances, like heavy metals. These contaminants are dispersed into the atmosphere and eventually settle in the soil through precipitation. Additionally, improper waste disposal, such as the dumping of wastes like used batteries or chemicals, and vehicular emissions from mining trucks, heavy machinery, taxis and other gasoline vehicles can release pollutants like lead and carbon monoxide and add to heavy metal contamination in the urban soil (Gupta, 2020).

Moreover, the application of fertilizers and pesticides in agricultural practices further contributes to the area's heavy metal pollution (Alengebawy et al., 2021).

Many studies are conducted in cities to determine the level of pollution of heavy metals and their impact on the ecosystem and human beings. However, up till now, little is known about the pollution characteristics and ecological status of potential toxic metals in the urban soils of the adjacent communities within the mining catchment.

Due to the variety and complexity of the pollution sources, this present study seeks to provide the concentrations of heavy metals, the extent of the pollution and any potential effects on the Tebrebie community about the ecology and health of residents. Besides assessing metal concentrations and analyze their distribu-

tions, this study further estimate the pollution levels and assess the potential human health implications of heavy metal contamination levels in urban soils within the Tebrebie community.

2. Materials and Methods

2.1. The Study Area

Tebrebie is a smaller community or settlement within the broader Tarkwa Nsuaem locality in the Tarkwa Nsuaem Municipality, Western Region. Tebrebie community is positioned at approximately 5.2990˚N latitude and −1.9870˚W longitude. The community lies within one of Ghana's most significant mining regions. This area is renowned for its rich deposits of gold, which have spurred extensive mining activities over the years and the community is characterized by hilly and rugged terrain.

There are about seven (7) sub-communities within the Tebrebie locality and they are defined by the opportunities and challenges presented by its proximity to large-scale mining operations. While the industry brings economic benefits, it also poses significant environmental, social, and health challenges that continue to shape the lives of Tebrebie's residents. Additionally, the displacement of communities due to mining activities has led to social and economic problems.

Activities in Tebrebie Community

Tebrebie is primarily defined by its gold mining activities with operations conducted by AngloGold Ashanti Iduapriem Limited (AAIL). Drilling, blasting, loading, and hauling are the only techniques used to remove the ore (Ramani, 2012). The operations involve the extraction of gold ore, processing, refining, extensive infrastructure, including processing plants, transportation networks (haul roads) and waste management facilities. Agriculture remains vital, with residents engaging in subsistence and small-scale farming of crops like cassava, yams, and cocoa. Local commerce thrives through markets and small businesses serving both residents and mining personnel.

Vehicular movement in Tebrebie is heavily influenced by the local mining industry. The area has a network of roads connecting it to nearby towns like Tarkwa, with specialised haul roads built for transporting mining materials. Public transport options like taxis and minibuses are common, while private vehicles and mining company trucks contribute significantly to traffic.

Tebrebie is geologically significant due to its location within the Ashanti Gold Belt, one of the most prolific gold-bearing regions globally. The geology of Tebrebie is predominantly influenced by the Birimian Supergroup, which dates back to the Proterozoic Eon, approximately 2.1 to 2.2 billion years ago. This supergroup is renowned for its extensive gold mineralization, which has made Tebrebie and its surroundings key areas for gold exploration and mining (Smith et al., 2016).

Gold deposits in Tebrebie are predominantly found in quartz veins that cut through the Birimian rocks. These veins formed during episodes of deformation,

where hydrothermal fluids introduced gold into fractures and fault zones within the host rocks (Oberthuer et al., 1996). Additionally, gold is disseminated within the altered rocks surrounding these veins, which has further enhanced the region's gold potential.

The area's structural geology, characterised by multiple phases of deformation leading to folds, faults, and shear zones are important for controlling gold deposit distribution (Groves et al., 2003). These structures provided pathways for the hydrothermal fluids that transported and deposited gold, making the intersections of these features prime targets for mining operations.

The study area is tropical with a rich vegetation. It has a warm climate the whole year with daily high temperatures between 25˚C and 30˚C (77 to 86˚F) and cool nights of just around 18˚C to 22˚C (64 to 72˚F). The climate is characterized by the distinct wet and dry seasons: wet season, April through October with peaks in rainfall during June and September; and dry season, November to March but has awfully lower levels of precipitation especially between December to February. High humidity, especially in rainy months (Koranteng & Zawila-Niedzwiecki, 2016).

The area's vegetation reflects its tropical rainforest climate. Tebrebie is enveloped by dense tropical rainforests, showcasing a rich array of tree species, including both hardwoods and softwoods. Some areas may transition to savannah-like landscapes, with scattered trees and open grasslands. The fertile soil supports robust agricultural activities, with crops such as cocoa, oil palm, and a variety of fruits and vegetables flourishing in the area (Leakey, 2004). Additionally, wetlands and water bodies contribute to the local biodiversity, supporting plant species adapted to these moist environments (Junk et al., 2006).

2.2. Sample Collections

Ten (10) composite soil samples were collected from selected urban land-use settings within the study area, including residential areas, roadside corridors, commercial centres, transport terminals, markets, and areas characterized by intense human activities. The sampling locations were selected to provide representative coverage of the major urban land-use types and potential sources of metal contamination within the municipality.

The sampling points were identified using a random sampling approach. Within each land-use category, potential sampling locations were first delineated, after which sampling points were selected randomly using field reconnaissance and accessibility criteria to minimize sampling bias and ensure that each location had an equal chance of being included in the study.

At each sampling point, five subsamples were collected within a radius of approximately 5 - 10 m using a stainless-steel scoop and combined to form one composite sample. Compositing was employed to reduce the influence of local spatial variability and to obtain a representative sample of the area. In total, ten composite samples were collected across the study area.

The selection of ten composite samples was considered adequate because the study area is relatively homogeneous in terms of geology and urban land-use characteristics. Furthermore, the composite sampling strategy increased the representativeness of each sampling location by integrating five subsamples into a single sample. Similar environmental contamination studies have successfully employed between 8 and 15 composite samples for preliminary assessments of urban soil contamination and ecological risk. The number of samples was therefore deemed sufficient to characterize the spatial distribution of potentially toxic elements and to evaluate contamination levels within the study area.

Additionally, a composite soil sample collected from the University of Mines and Technology (UMaT) campus was used as a background/control sample. The UMaT location was selected because it is situated away from active mining operations and major industrial activities and is characterized by relatively low anthropogenic influence compared to the study sites. This background sample provided reference concentrations for the calculation of contamination indices. This approach was adopted to obtain a representative estimate of natural metal concentrations while minimizing spatial variability and analytical costs.

Prior to sampling, surface debris, vegetation, and litter were carefully removed. Soil samples were collected from the A-horizon at a depth of approximately 5 - 15 cm and stored in labelled Ziploc bags. The geographical coordinates of each sampling location were recorded using a phone-based Global Positioning System (GPS), Table 1. To prevent cross-contamination, rubber gloves were worn during sample collection, and the scoop was thoroughly cleaned with tissue paper between sampling events as part of the quality control and quality assurance (QC/QA) procedures.

Table 1. Soil sample names and GIS coordinates.

Sample ID	GIS Coordinates
B1	30N 607307 582744
B2	30N 607315 582676
BD1	30N 607175 582546
BD2	30N 607204 582603
A1	30N 607155 582797
A2	30N 607015 582735
A3	30N 607117 582737
M1	30N 607430 582772
M2	30N 607532 582691
M3	30N 607408 582593

The sampling points were plotted on the study area using ArcGIS 10.8, as illustrated in Figure 1 below. The GPS coordinates used to create this map are shown in Table 2.

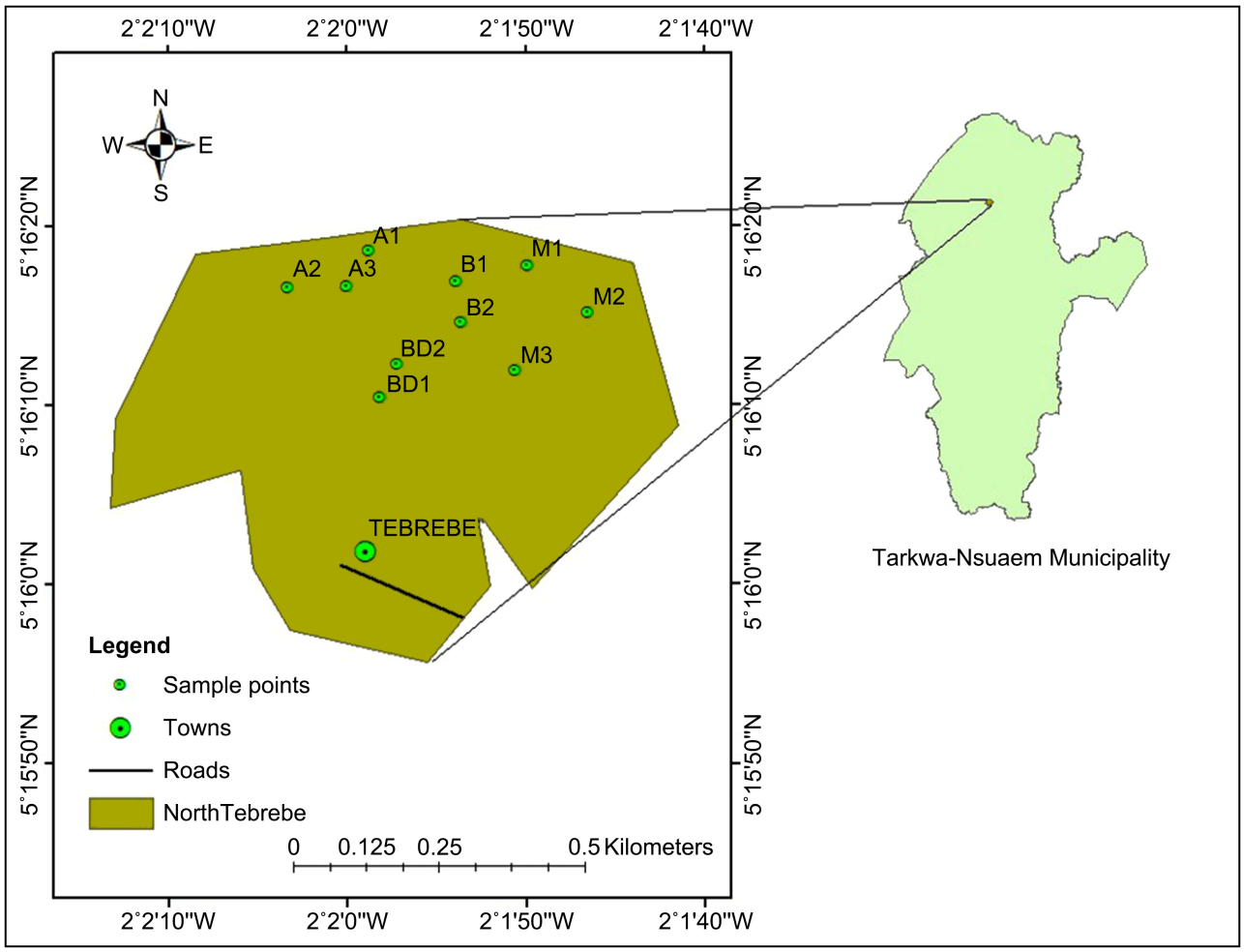

Figure 1. Map of the study area with the sample points.

2.3. Sample Analysis

In this sample analysis, the parameters pH and electrical conductivity (EC) were analyzed. Additionally, the presence of toxic heavy metals, including lead (Pb), arsenic (As), mercury (Hg), and cadmium (Cd), was analyzed.

2.3.1. pH and Electrical Conductivity

In the Environmental Monitoring Laboratory at UMaT, each soil sample weighing 30 grams was measured using ADAM PW 214 electronic balance. Approximately, 150 ml of distilled deionized water was then combined with each weighed soil sample to achieve a soil-water suspension ratio of 1:5 (Wilken & Hintelmann, 1991). The resulting mixture was vigorously shaken for 30 minutes using Stuart SSL1 Orbital Shaker and left to allow suspended soil particles to settle. Afterward, the conductivity metre and pH metre were calibrated using a 1413 µS/cm electrical

conductivity standard solution and standard of pH 4, pH 7, and pH 10 solutions respectively. Measurements of pH and electrical conductivity (EC) were taken using "Hydro Check HC1000" and "Eutech cond 6+" respectively.

2.3.2. Acid Digestion of Soil Samples

For the Aqua Regia digestion, 5 grams of the sieved sample were weighed for each sample using the ADAM PW 214 electronic balance, 5 ml of nitric acid and 15 ml of hydrochloric acid (in a 1:3 ratio), heated to 90 degrees Celsius using a hot plate (Osei et al., 2022). After digestion, the soil samples (now in solution form) were filtered using the Vacuubrand 4 filtration system and diluted with 100 ml of deionized water for analysis using Atomic Absorption Spectrometry (AAS).

2.3.3. Atomic Absorption Spectrometer Analysis

The concentrations of As, Hg, Pb, and Cd in the digested soil samples were determined using an Atomic Absorption Spectrometer (AAS). Metal concentrations were quantified against externally prepared calibration standards and reported as milligrams per kilogram (mg/kg) on a dry-weight basis.

Lead (Pb) and cadmium (Cd) were determined using flame atomic absorption spectrometry (FAAS) with an air-acetylene flame. The instrument was operated under the manufacturer's recommended conditions using element-specific hollow cathode lamps. Arsenic (As) was analysed using hydride generation atomic absorption spectrometry (HG-AAS) because of its improved sensitivity for arsenic determination. Sodium borohydride was used as the reducing agent to generate arsine gas prior to measurement. Mercury (Hg) was analysed using the cold vapour atomic absorption spectrometry (CV-AAS) technique, in which mercury ions were reduced to elemental mercury vapour using stannous chloride ($SnCl_2$) (or sodium borohydride, if applicable), followed by measurement in a dedicated mercury absorption cell.

2.3.4. Spatial Mapping and Distribution

The spatial distribution of soil pH, EC, and the concentrations of Pb, Hg, As, and Cd were mapped using the Inverse Distance Weighting (IDW) interpolation technique in ArcMap 10.8.2. IDW estimates values at unsampled locations based on the assumption that nearby sampled points have a greater influence on predicted values than more distant points. The interpolation was performed using a power parameter (p) of 2, the default setting in ArcMap, with a variable search radius including the 12 nearest neighbouring points and the default output cell size determined from the extent of the study area. The interpolation procedure followed Equation (2.1.);

$$Z_o = \frac{\sum_{i=1}^{N} Z_i \cdot D_i^{-n}}{\sum_{i=1}^{N} D_i^{-n}} \tag{2.1}$$

where Z_o = predicted value of variable z at point i;

Z_i = sample value at point i;

D_i = the distance between the sample point and the predicted point, and

N = the coefficient that assigns weight according to distance.

2.3.5. Quality Assurance and Quality Control (QA/QC)

Quality assurance and quality control procedures were implemented throughout sample preparation and instrumental analysis to ensure the reliability and accuracy of the analytical results.

The pH meter and electrical conductivity meter were calibrated daily using certified buffer solutions (pH 4.00, 7.00, and 10.00) and a 1413 μS/cm conductivity standard, respectively. All reagents used were of analytical grade, and deionised water was used throughout the analysis.

For heavy metal determination, calibration curves were prepared using certified multi-element standard solutions covering the expected concentration ranges of the analytes. Instrument calibration produced correlation coefficients (R^2) greater than 0.995 (or actual value) for all metals.

Method blanks were analysed alongside every analytical batch to assess possible contamination during digestion and analysis. Metal concentrations in the blanks were below the method detection limits, indicating negligible laboratory contamination. Duplicate (replicate) analyses were performed on 10% of the samples to assess analytical precision. The relative percent difference (RPD) between duplicate analyses was less than <20%, demonstrating acceptable analytical precision.

To verify analytical accuracy, a certified reference material (CRM) (or laboratory control sample) was analysed together with the samples. The percentage recoveries obtained fell within the acceptable recovery range of 80% - 120%. The method detection limits (MDLs) for Pb, Cd, As, and Hg were 0.01, 0.002, 0.001, and 0.001 mg/kg, respectively. Any concentrations below the MDLs were reported as below detection limit (BDL).

2.4. Assessment of Pollution Levels

The extent of soils contamination was assessed using the contamination factor, pollution load index and geo-accumulation index (I_{geo}) (Woitke et al., 2003).

2.4.1. Contamination Factor (CF)

In environmental studies, the Contamination Factor (CF) is a commonly make use of metric to assess the degree of pollution by analysing the levels of contaminants in the sample to a background level (Hakanson, 1980).

For each sample, the CF values for Pb, Cd, Hg, and As were determined individually based on the concentration of metals present and also the average CF values for these metals were then calculated by taking the mean of the individual CF values from all samples.

The CF is calculated using Equation (2.2).

$$\mathrm{CF} = \frac{C_i}{C_b} \tag{2.2}$$

where:

C_i = the concentration of the contaminant in the sample.

C_b = the background concentration of the same contaminant.

The CF is classified into different categories to assess the level of contamination:

CF < 1: Minimal contamination.

1 ≤ CF < 3: Moderate level of contamination.

3 ≤ CF < 6: Significant contamination.

CF ≥ 6: Extremely high contamination.

2.4.2. Calculation of Pollution Load Index (PLI)

The Pollution Load Index (PLI) is a tool used to assess the overall level of pollution in a particular environment, PLI is employed to provide an integrated assessment of pollution levels, with values greater than 1 indicating significant contamination.

PLI values were calculated individually for each sample, based on the pollution load of multiple metals present in that sample whereas the mean PLI value was also calculated providing an overall assessment of contamination.

The PLI is calculated using the geometric mean of the CFs of the contaminants studied using Equation (2.3):

$$\mathrm{PLI} = \left(\mathrm{CF}_1 \times \mathrm{CF}_2 \times \cdots \times \mathrm{CF}_n\right)^{\frac{1}{n}} \tag{2.3}$$

where;

$\mathrm{CF}_1, \mathrm{CF}_2, \cdots, \mathrm{CF}_n$ = the Contamination Factors for the different contaminants.

n = the number of contaminants considered.

2.4.3. Geo-Accumulation Index

To gain a thorough understanding, the levels of heavy metal contamination in soils are assessed using the geo-accumulation index (I_{geo}), first introduced by Muller (1969).

The Geo-Accumulation Index (I_{geo}) values for Pb, Cd, Hg, and As were calculated for each sample, a mean value was also calculated for each metal to assess the overall contamination trend across all samples. Equation (2.4) is employed to compute I_{geo};

$$I_{\text{geo}} = \log_2\left(\frac{C_i}{1.5 \times B_i}\right) \tag{2.4}$$

where;

C_i = assessed level of the analyzed metal.

B_i = geochemical baseline value of the metal

1.5 = control values for lithogenic variation in the soil.

2.5. Ecological Risk Assessment (E_r^i)

To evaluate the possible environmental impacts posed by a metal in the lithosphere, researchers often rely on the prospective ecological risk index. The (E_r^i) and R_i values for Pb, Cd, Hg and As were calculated separately for each sample and also the mean values were calculated. This index is derived from ecological risk assessment (E_r^i) and potential ecological risk index (R_i), as per Equations

(2.5) and (2.6) formulated by Hakanson (1980);

$$R_i = \sum E_r^i \tag{2.5}$$

$$E_r^i = T_r \frac{C_n}{C_o} \tag{2.6}$$

where;

R_i = sum of potential ecological risk factors;

T_r = toxic response factor;

C_n = the presence of metals in the soil;

C_o = background value or reference value of metals;

E_r^i = potential ecological risk factors or possible harm associated with each metal.

2.6. Human Health Risk

The assessment of metal exposure in soil for its impact on human health utilised a model developed by the United States Environmental Protection Agency (USEPA). This study considered three potential pathways of exposure: ingestion (ing), inhalation (inh), and dermal contact (derm) using Equations (2.7), (2.8) and (2.9). Table 2 and Table 3 show a list of exposure assumptions and toxicological constants used for adults and children (IngR, InhR, SA, BW, EF, ED, RfD, CSF) with their sources.

$$\mathrm{ADD}_{\mathrm{ing}} = \frac{\mathrm{C} \times \mathrm{IngR} \times \mathrm{EF} \times \mathrm{ED} \times \mathrm{CF}}{\mathrm{BW} \times \mathrm{AT}} \tag{2.7}$$

$$\mathrm{ADD}_{\mathrm{inh}} = \frac{\mathrm{C} \times \mathrm{InhR} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{PEF} \times \mathrm{BW} \times \mathrm{AT}} \tag{2.8}$$

$$\mathrm{ADD}_{\mathrm{derm}} = \frac{\mathrm{C} \times \mathrm{SL} \times \mathrm{SA} \times \mathrm{ABS} \times \mathrm{EF} \times \mathrm{ED} \times \mathrm{CF}}{\mathrm{BW} \times \mathrm{AT}} \tag{2.9}$$

where;

ADD = The average daily dose; the subscript "ing", "inh", and "derm" represent ingestion, inhalation and dermal respectively;

C = Metal concentration in the soil;

IngR = Consumption rate;

AT = Typical exposure time for carcinogens;

InhR = Breathing rate;

CF = Factor for conversion;

SA= Skin surface area;

EF = Exposure frequency;

SL = Skin adherence factor;

ED = Exposure duration;

PEF = Particulate emission factor;

BW = Body weight;

ABS = Dermal absorption factor.

Table 2. Exposure assumptions and toxicological constants used in the human health risk assessment.

Parameter	Adult	Child	Unit
IngR	100	200	$mg \cdot day^{-1}$
InhR	20	7.6	$m^3 \cdot day^{-1}$
SA	5700	2800	cm^2
BW	70	15	kg
EF	350	350	$days \cdot year^{-1}$
ED	24	6	years
AT (non-cancer)	ED × 365	ED × 365	days
AT (cancer)	70 × 365	70 × 365	days
PEF	1.36×10^9	1.36×10^9	$m^3 \cdot kg^{-1}$
SL	0.07	0.20	$mg \cdot cm^{-2} \cdot day^{-1}$
ABS	0.001	0.001	unitless
CF	10^{-6}	10^{-6}	$kg \cdot mg^{-1}$

Sources: (EPA, 1989, EPA, 2001, EPA, 2011).

Table 3. Reference doses (RfD) and cancer slope factors (CSF) used for the analysed metals.

Metal	RfD_{ing}	RfD_{inh}	RfD_{derm}	CSF_{ing}
Pb	3.5×10^{-3}	3.52×10^{-3}	5.25×10^{-4}	—
Hg	3.0×10^{-4}	8.57×10^{-5}	2.1×10^{-5}	—
As	3.0×10^{-4}	1.5×10^{-5}	1.23×10^{-4}	1.5
Cd	1.0×10^{-3}	1.0×10^{-5}	1.0×10^{-5}	6.1

Source: EPA, 2026.

Risk Characterization

1) For non-Carcinogenic assessment

The hazard quotient (HQ) was employed to determine the non-carcinogenic impact of metals present in soil, calculated using the Equations 2.10, 2.11 and 2.12 provided by (EPA, 2001);

$$HQ_{ing} = \frac{ADD_{ing}}{RfD_{ing}} \tag{2.10}$$

$$HQ_{inh} = \frac{ADD_{inh}}{RfD_{inh}} \tag{2.11}$$

$$HQ_{derm} = \frac{ADD_{derm}}{RfD_{derm}} \quad (2.12)$$

The cumulative effect of the hazardous quantities (HQs), referred to as the Hazard Index (HI) according to EPA (2012), represents the non-carcinogenic impact on the population exposed to "*n*" metals through various exposure routes. Calculation of the HI followed Equation (2.13);

$$HI = \sum_n^i HQ \quad (2.13)$$

where;

$HQ_{ing}, HQ_{inh}, HQ_{derm}$ = Hazard quotient for ingestion, inhalation and dermal respectively.

$ADD_{ing}, ADD_{inh}, ADD_{derm}$ = Average daily dose for ingestion, inhalation and dermal respectively.

$RfD_{ing}, RfD_{inh}, RfD_{derm}$ = Reference dose for ingestion, inhalation and dermal respectively.

HI = Hazard index.

2) For Carcinogenic assessment

The carcinogenic risk was also assessed using the Equations (2.14), (2.15) and (2.16) formulated by EPA (2001);

$$CR_{ing} = ADD_{ing} \times CSF_{ing} \quad (2.14)$$

$$CR_{inh} = ADD_{inh} \times CSF_{inh} \quad (2.15)$$

$$CR_{derm} = ADD_{derm} \times CSF_{derm} \quad (2.16)$$

where;

CSF is the cancer slope factor of heavy metals; the subscript "ing", "inh", and "derm" represent ingestion, inhalation and dermal respectively.

CR is the carcinogenic risk of heavy metals; the subscript "ing", "inh", and "derm" represent ingestion, inhalation and dermal respectively.

3) Total Cancer Risk (TCR)

It is a cumulative measure that considers the potential health impact of various heavy metals that have been identified as carcinogenic using Equation (2.17);

$$TCR = \sum_i^n (CR_i) \quad (2.17)$$

where;

n = the quantity of heavy metals being analysed;

CR_i = the cancer risk for the ith heavy metal.

3. Results and Discussions

3.1. Physicochemical Parameters (pH and EC)

3.1.1. Soil pH

The pH Values of the soil varied from 6.78 to 7.86 with a mean value of 7.44. Four sample points B2, BD1, BD2 and M3 recorded pH values ranging from 6.78 to 7.26 were below the reference (control sample) value of 7.30 but falls within the

Canadian Council of Ministers of the Environment (CCME) Canadian Soil Quality Guidelines (CSQG) for the Protection of Environmental and Human Health, Residential/Parkland of 5.5 to 7.5 (CCME, 2007). The remaining six sample points of pH values ranging from 7.46 to 7.86 were all above the reference (control sample) value of 7.30 and the Canadian Soil Quality Guideline of (5.5 to 7.5) with the exception of sample point B1 of pH value of 7.46 which falls within the Canadian Soil Quality Guidelines of (5.5 to 7.5).

The maximum pH (7.86) occurred at sample point M1 and the minimum pH (6.78) occurred at sample point BD2. Figure 2 shows the pH values of all the sample points. The deviation from the reference (control sample) value and the Canadian Soil Quality Guidelines suggests that the soil pH has been influenced by factors such as fertilizer use, decomposition of organic matter and leaching. The slightly alkaline nature of some samples could indicate a source of alkaline material or lower biological activity, whereas samples with pH closer to neutral might be influenced by natural soil processes.

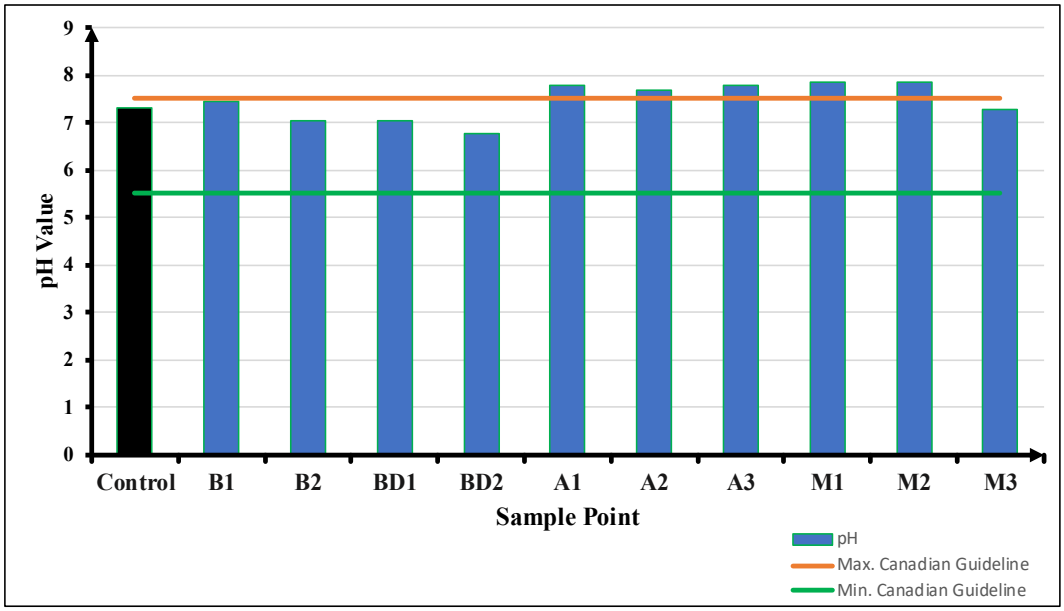

Figure 2. The pH values of all the sample points.

3.1.2. Soil EC

The soil's EC values ranged from 32.2 µS/cm to 193.90 µS/cm, with an average of 100.94 µS/cm. Nine samples were below the control value of 160 µS/cm, and all samples were below the Canadian Soil Quality Guidelines, Residential/Parkland of 1000 µS/cm (CCME, 2007). The lower EC values in most of the sample points compared to the reference sample are likely due to differences in soil texture, variations in soil texture such as the proportion of sand, silt, and clay, can affect EC. Soils with more sand, for instance, tend to have lower EC because they retain less moisture and salts (So & Aylmore,1993). Figure 3 represents a graph showing the EC of all the sample points.

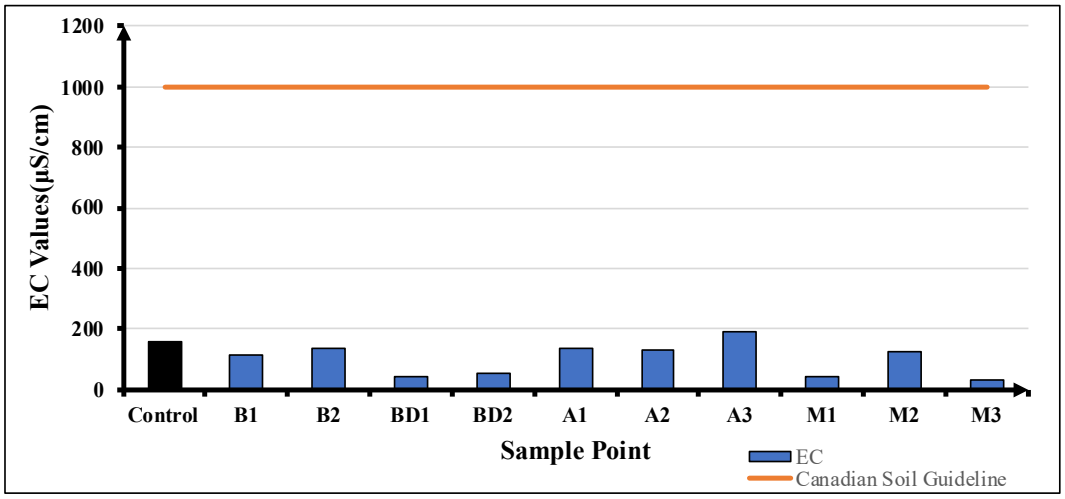

Figure 3. The EC for all the sample points.

3.2. Heavy Metal Concentrations

3.2.1. Lead

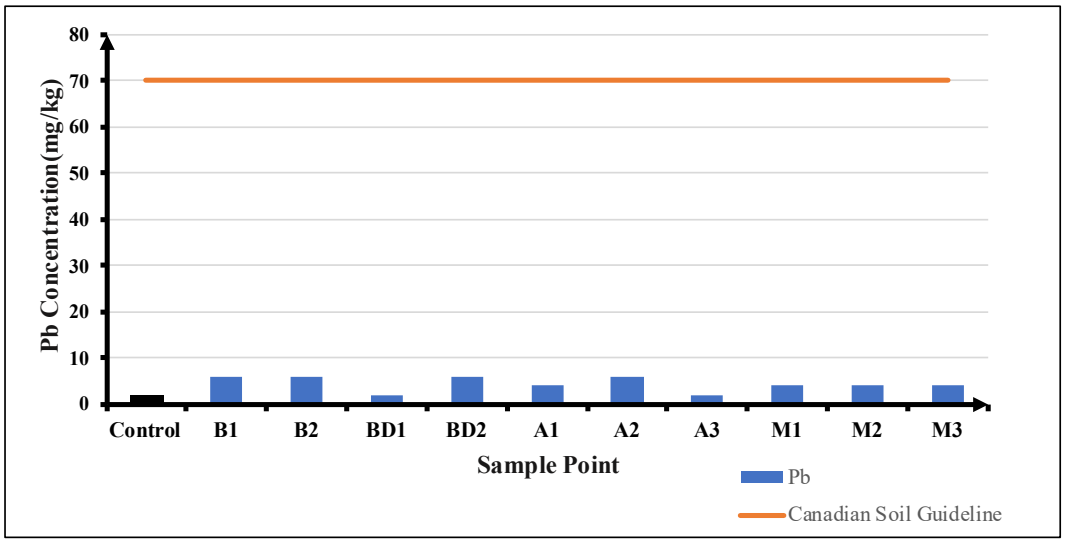

Figure 4. The Pb concentrations for all the sample points.

Lead (Pb) levels ranged from 2.01 mg/kg to 6.12 mg/kg with a mean value of 4.44 mg/kg. The Pb concentrations were all below the Canadian Soil Quality Guidelines, Residential/Parkland value of 70 mg/kg indicating no significant effect on the community (CCME, 2007). However, all the samples exceeded the reference value of 2.00 mg/kg, which could indicate some level of contamination even though it is not above the Canadian Soil Quality Guidelines. This indicates that there may be additional lead sources in the environment, likely from industrial or human activities. Specifically, the improper disposal of electronics, particularly batteries and radios, can result in lead contamination, as the Tebrebie community has no designated waste dump, leading residents to dispose of waste hap-

hazardly. These items may contain lead, which can leach into the soil when they break down.

The maximum Pb concentration 6.12 mg/kg occurred at sample point B2 due to the proximity of B2 to the waste dump of AAIL and also improper dumping of e-waste may contain lead particularly in the screens, solder and wiring of the electrons at that region, and the minimum Pb concentration 2.01 mg/kg occurred at sample point A3 because of distance between waste dump and the sample point. Figure 4 represents a graph showing the concentration of Pb of all the sample points.

3.2.2. Mercury (Hg)

Mercury (Hg) concentrations ranged from below the analytical detection limit (<0.001 mg/kg) at sample point A3 to 0.088 mg/kg at sample point B1. For statistical analyses, concentrations below the detection limit were assigned a value of 0.0005 mg/kg (half the detection limit). The Hg concentrations were all below the Canadian Soil Quality Guidelines, Residential/Parkland value of 0.1 mg/kg suggesting that these areas are generally safe from mercury-related risks (CCME, 2007). The Hg concentrations of all samples were less than the reference (control sample) value of 0.240 mg/kg. The highest mercury concentration (0.088 mg/kg) was detected at sample point B1, close to the guideline limit, likely due to improper disposal of mercury-containing waste such as electronics or batteries. Although the level is below the limit, it is higher than at other locations suggesting possible localized contamination that may need further monitoring. The lowest concentration (<0.001 mg/kg) was found at sample point A3, indicating minimal risk in that area.

On average, the soil in the studied area does not pose a significant mercury contamination risk. Figure 5 represents a graph showing the concentration of Hg of all the sample points.

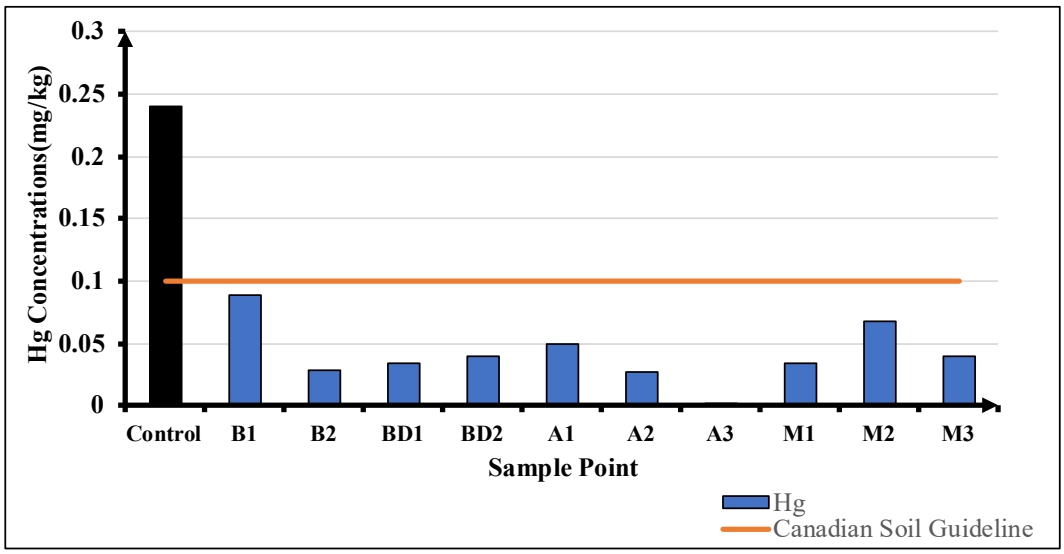

Figure 5. The Hg concentrations for all the sample points.

3.2.3. Arsenic (As)

Arsenic concentrations ranged from below the analytical detection limit (<0.001 mg/kg) to 3.694 mg/kg. Values below the detection limit were substituted with 0.0005 mg/kg for statistical analyses. The As concentrations were all below both the reference (control sample) value of 5.8 mg/kg and the Canadian Soil Quality Guidelines, Residential/Parkland value of 12 mg/kg indicating no significant effect on the residents (CCME, 2007).

The maximum As concentration 3.694 mg/kg occurred at sample point, although this value is the highest among the sampled locations, it is still significantly lower than both the reference value and the Canadian Soil Quality Guidelines, Residential/Parkland, suggesting that while B1 may have relatively higher arsenic levels, it is not at a level that would be considered harmful.

The minimum As concentration (<0.001) occurred at sample point A2 suggests that this location has negligible arsenic contamination. This could be indicative of natural variability in arsenic distribution, possibly due to differences in soil composition or distance from potential contamination sources. Figure 6 represents a graph showing the concentration of As of all the sample points.

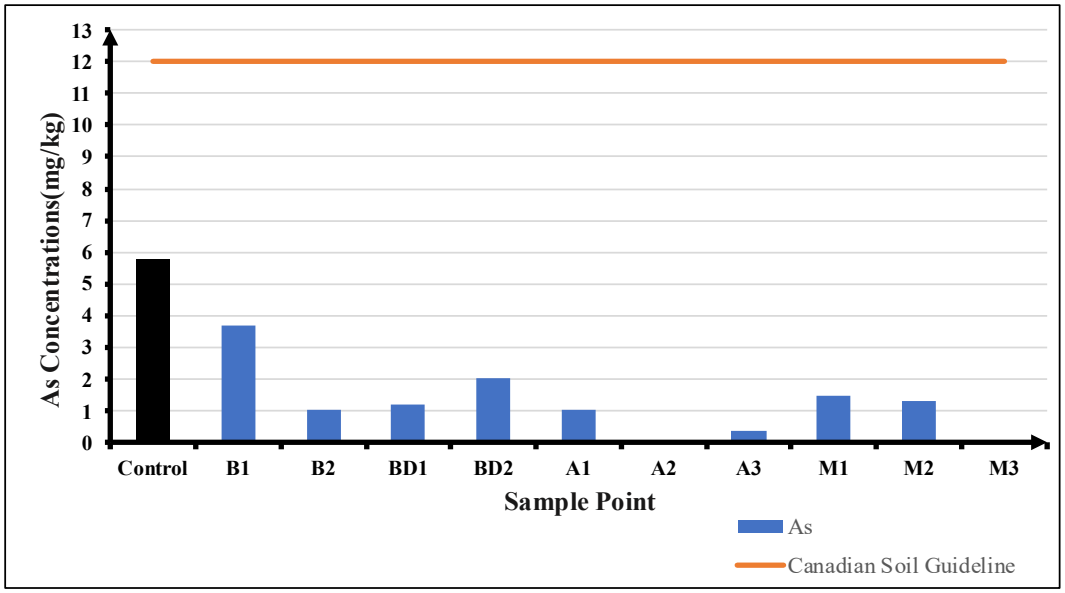

Figure 6. The As concentrations for all the sample points.

3.2.4. Cadmium (Cd)

Cadmium concentrations in all samples were below the analytical detection limit (<0.002 mg/kg). For statistical and risk assessment purposes, a value of 0.001 mg/kg (half the detection limit) was assigned to each sample (Figure 7). That means all the sample points were below both the reference of 0.39 mg/kg and the Canadian Soil Quality Guidelines, Residential/Parkland' of 1.4 mg/kg indicating no significant effects (CCME, 2007). The uniformity of the cadmium concentrations across all sample points suggests a homogenous distribution of cadmium in the area, possibly reflecting natural background levels with minimal anthropo-

genic influence, meaning that soil in these areas is safe for agricultural use, residential development, and other activities that involve direct contact with the soil.

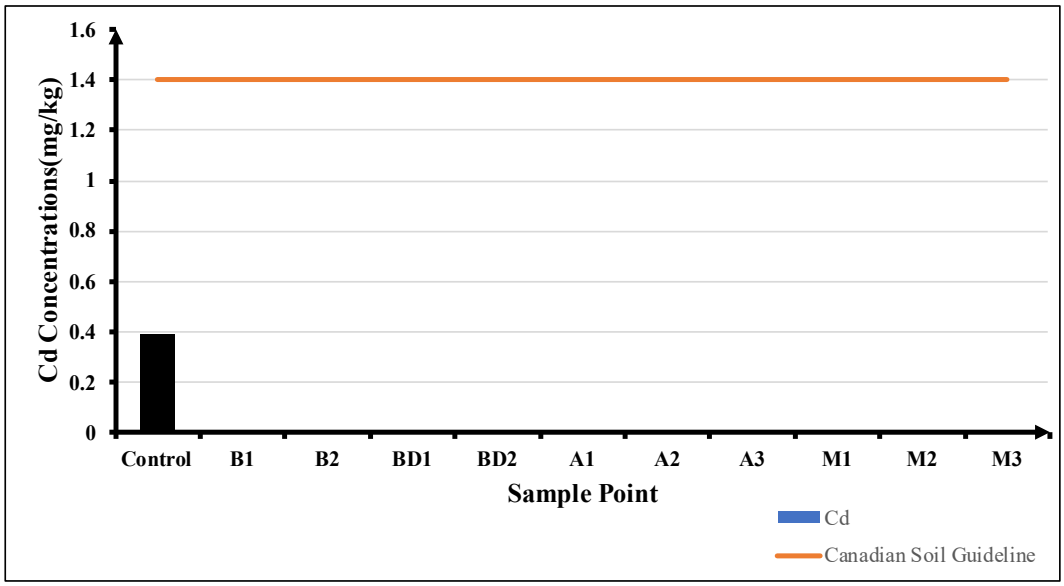

Figure 7. The Cd concentrations for all the sample points.

1) Mean Levels of Heavy Metals

The concentration levels of the heavy metals in the study area are in the order Pb>As >Hg > Cd based on their mean values as shown in Figure 8. Pb's higher concentration could be mainly due to local household waste, while arsenic's prominence could be linked to the mine waste dump. The presence of mercury though lower suggests that both sources contribute to the contamination.

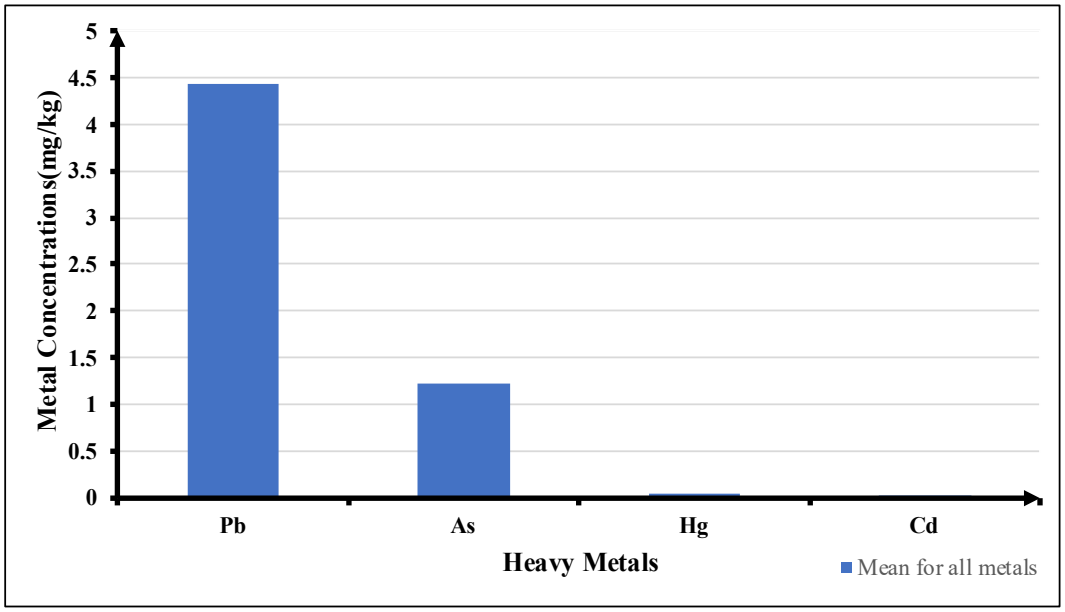

Figure 8. Mean values of the heavy metals (Pb, As, Hg, Cd) in the study area.

3.3. Spatial Distribution

3.3.1. pH Distribution

In the northern part of Tebrebie, the pH levels are neutral to slightly alkaline ranging from 7.1 to 7.4 indicated by a mix of yellow and green colors, this suggests relatively balanced soil conditions. Moving towards the southern section, pH levels become slightly more acidic with values dropping to around 6.78 - 6.88, this more acidic condition represented by the green color suggests a different soil chemistry likely affected by environmental or anthropogenic factors. The western area of the community exhibits higher pH values of 7.6 - 7.8 as shown by the orange to red shading, indicating more alkaline conditions. Conversely, the eastern side shows moderate pH values between 7.2 and 7.6, with a balance between yellow and light green zones (Figure 9).

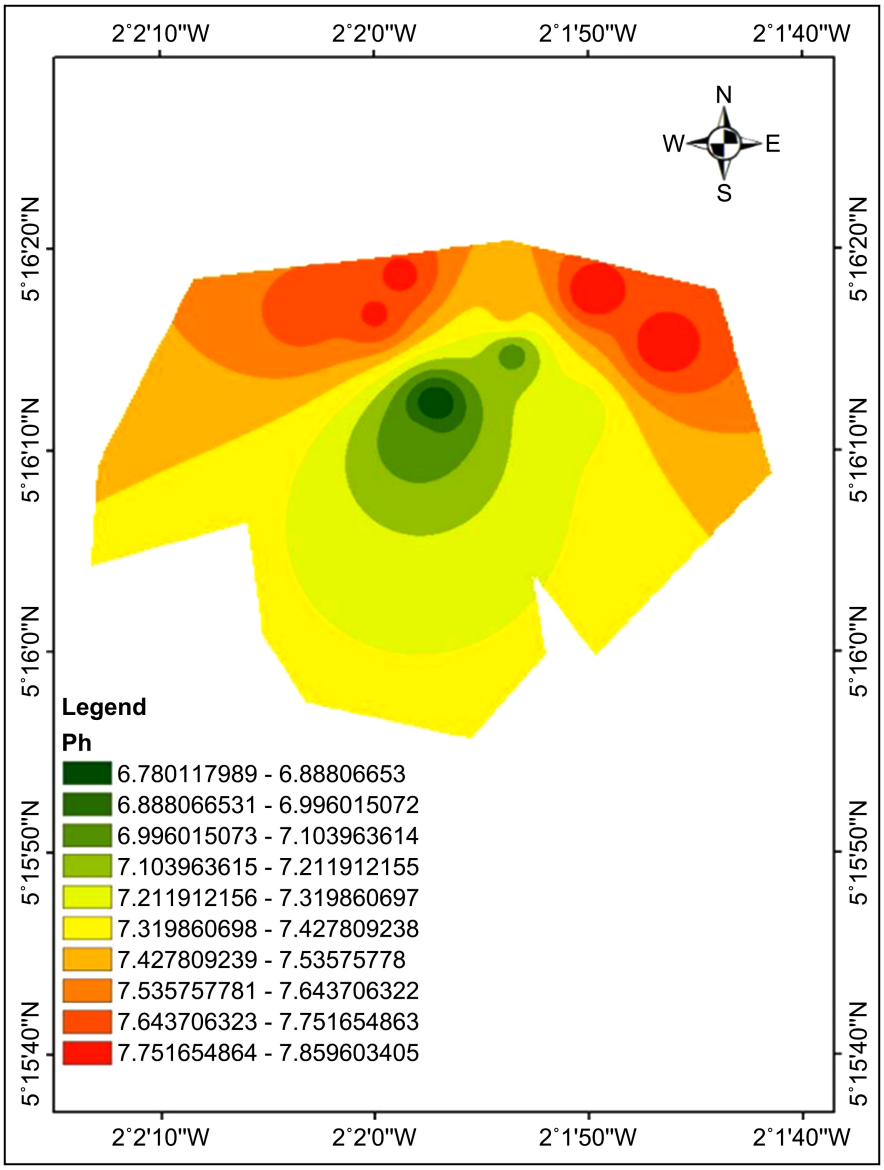

Figure 9. Spatial distribution map for pH.

3.3.2. Conductivity Distribution

The northern part of Tebrebie shows moderate conductivity levels ranging from 64.55 to 96.88 µS/cm, which indicates a moderate amount of dissolved minerals or salts in the soil. In contrast, the southern region particularly in the middle exhibits a significant increase in conductivity, with the highest values reaching up to 193.86 µS/cm. The red areas in the south suggest a greater accumulation of minerals, likely due to industrial or mining activities impacting the soil's salinity. The western side of the community has lower conductivity, with values between 64.55 and 96.88 µS/cm as represented by the green to yellow areas. On the eastern side, conductivity increases significantly with values reaching up to 177.7 µS/cm, showing higher salinity or mineral content, which could be indicative of environmental contamination (Figure 10).

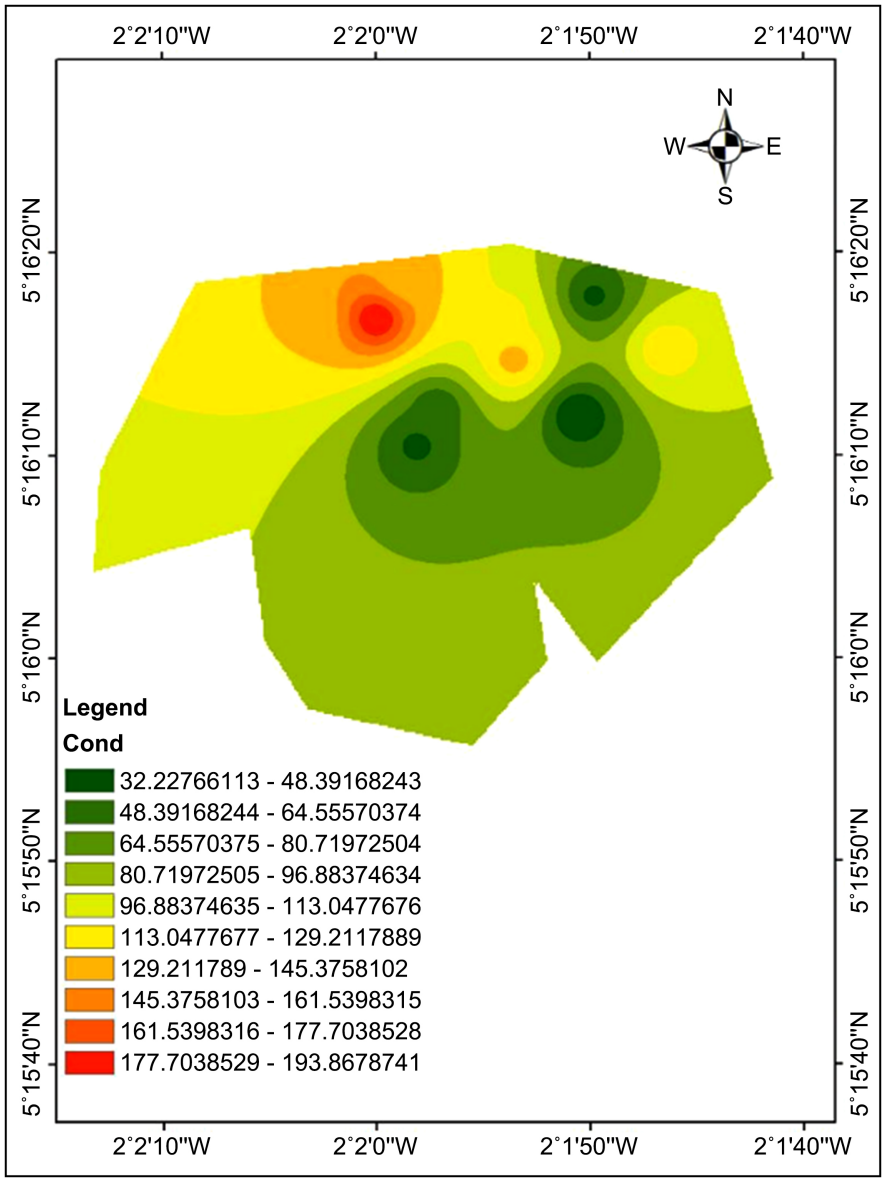

Figure 10. Spatial distribution map for EC.

3.3.3. Lead Distribution

Lead concentrations in the northern part of Tebrebie remain relatively low, with estimated values ranging from 2.01 to 2.42 mg/kg, as shown by the green areas on the IDW interpolation map (Figure 11). Moving southwards, there is a slight increase in the estimated lead concentrations, particularly in the middle-southern section, where values range from 3.65 to 5.29 mg/kg. The orange and red areas represent relatively higher estimated lead concentrations compared to other parts of the study area. The western part of the community also exhibits comparatively higher estimated lead concentrations, ranging from 4.88 to 5.29 mg/kg. In contrast, the eastern part of Tebrebie shows slightly lower estimated concentrations, ranging from 2.83 to 4.06 mg/kg.

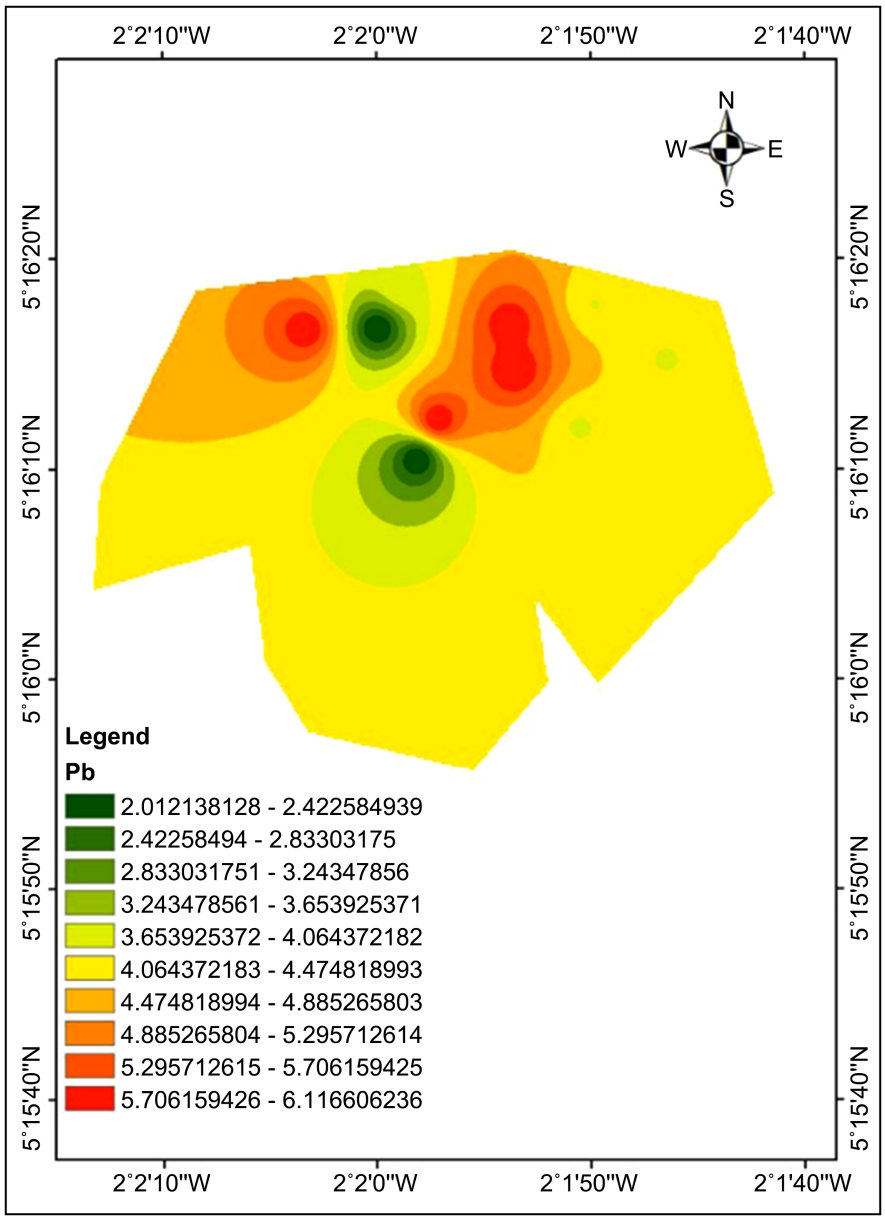

Figure 11. Spatial distribution map for lead.

3.3.4. Mercury Distribution

In the northern part of the study area, estimated mercury (Hg) concentrations are generally low to moderate, with the green areas on the IDW interpolation map representing relatively lower concentrations. Moving southwards, mercury concentrations increase slightly, as indicated by the yellow colour gradient, although no extremely high concentrations are observed. The highest estimated mercury concentrations occur slightly east of the centre of the study area, where the red area represents relatively elevated mercury levels compared to surrounding locations (Figure 12). The western part of the community is characterized by comparatively lower estimated mercury concentrations, as shown by the light green shades.

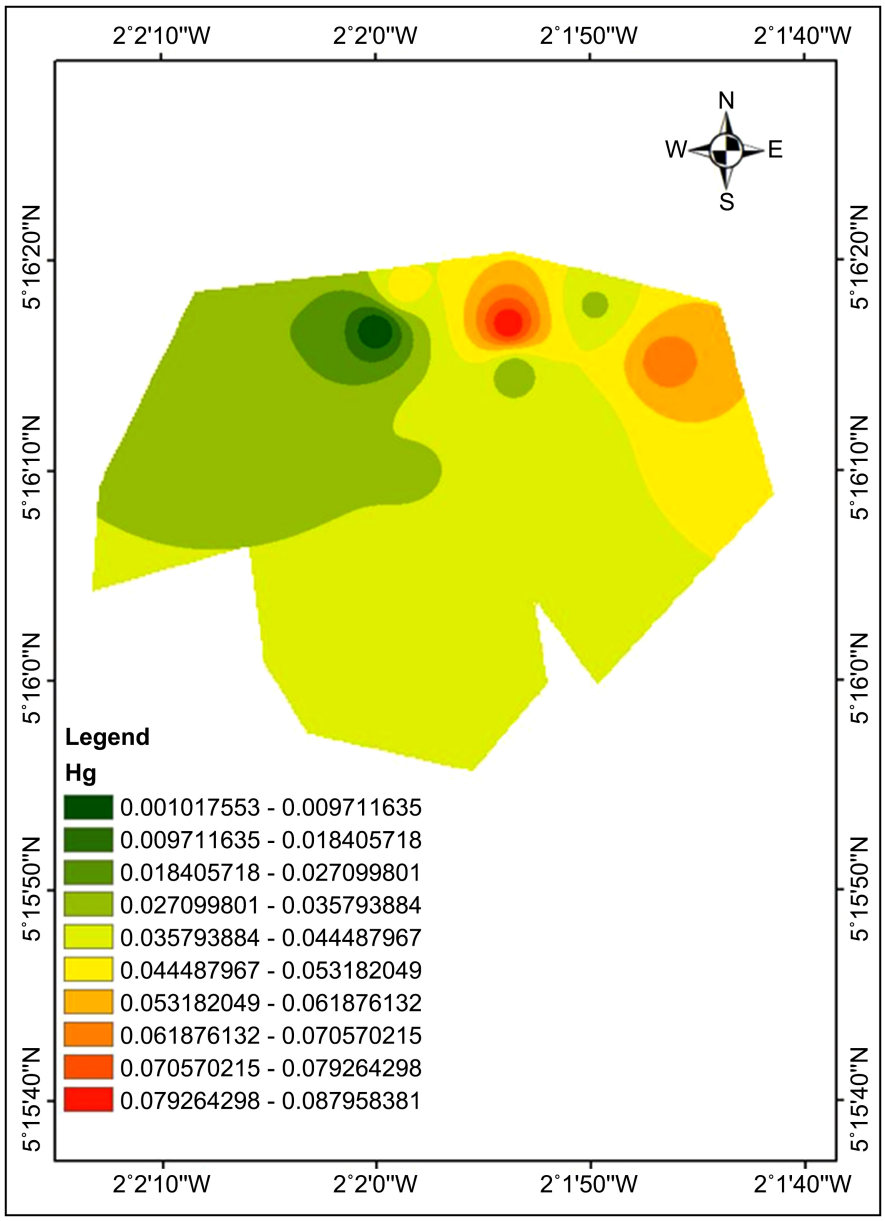

Figure 12. Spatial distribution map for mercury.

3.3.5. Arsenic Distribution

In the northern part of the study area, estimated arsenic (As) concentrations are generally low, as shown by the dark green areas on the IDW interpolation map. Moving southwards, the estimated concentrations increase to moderate levels, particularly in the central and southern sections, where yellow and light green zones are observed. The eastern part of the study area exhibits the highest estimated arsenic concentrations, represented by the red zone, while the western part is characterized by comparatively lower estimated concentrations, as indicated by the green shading (Figure 13).

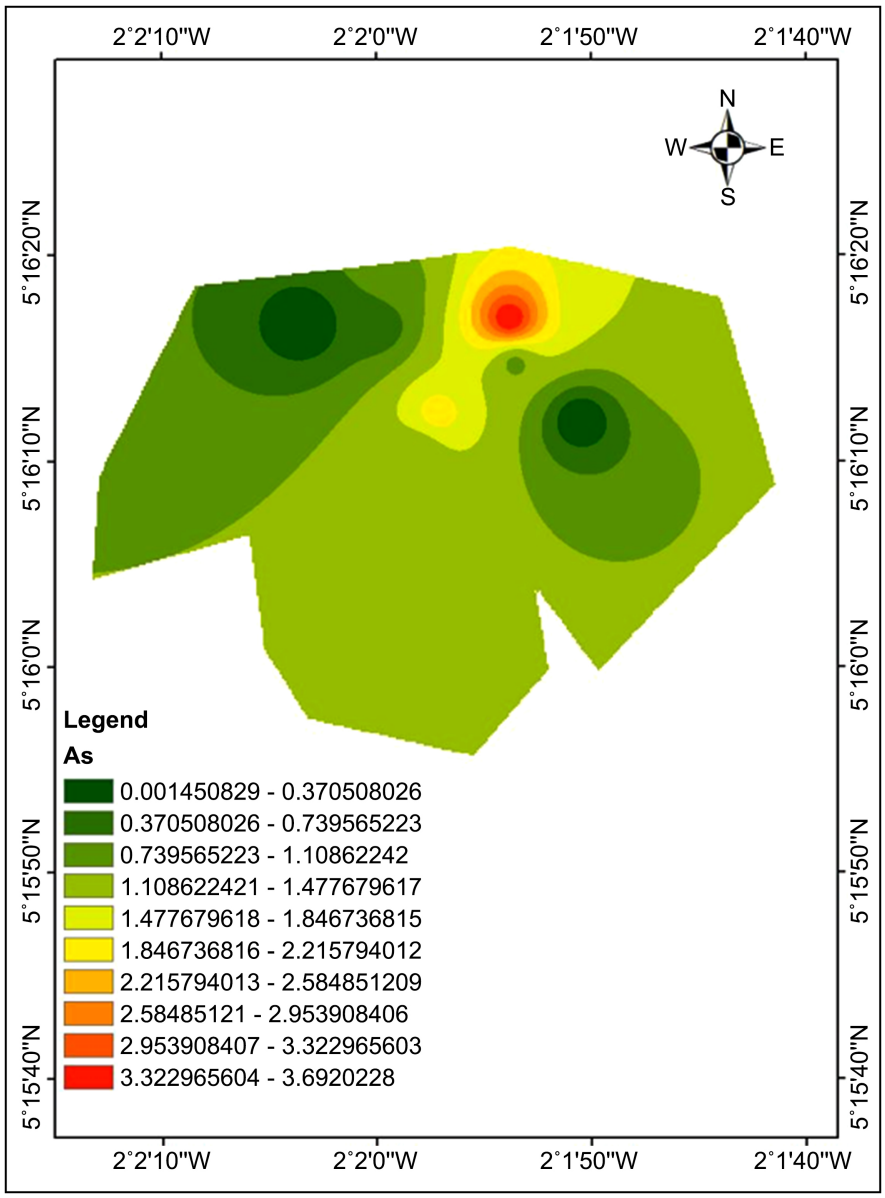

Figure 13. Spatial distribution map for arsenic.

3.3.6. Cadmium Distribution

In contrast to the other analysed metals, the distribution of cadmium (Cd) con-

centrations appears relatively uniform across the study area, with consistently low estimated concentrations throughout the community (Figure 14). The IDW interpolation map indicates little spatial variation in Cd concentrations, suggesting no distinct areas of relatively elevated concentrations within the sampled locations.

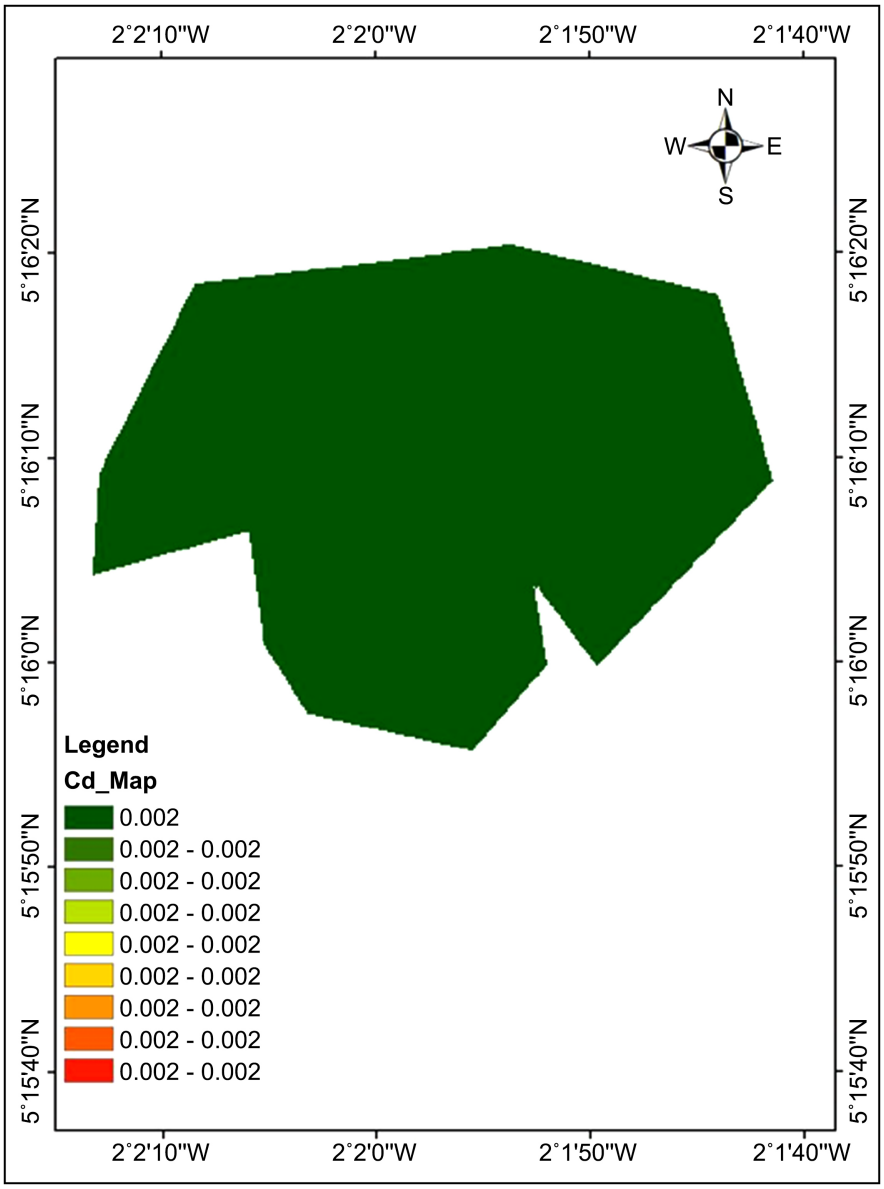

Figure 14. Spatial distribution map for cadmium.

3.3.7. Summary of Spatial Distribution

The IDW interpolation maps of As, Cd, Pb, Hg, pH, and EC provide an exploratory representation of the spatial variation of these parameters across the Tebrebie community (Figures 2-14). The interpolated surfaces suggest relatively higher estimated concentrations of some metals and higher EC values in parts of the central to northern sections of the study area, while the western and eastern sections gen-

erally exhibit comparatively lower estimated concentrations and conductivity values. However, because the interpolation is based on only ten composite soil samples, the maps should be interpreted as indicative of potential spatial patterns and areas of relatively higher or lower concentrations, rather than definitive evidence of contamination hotspots or pollution sources. Additional sampling and detailed source-apportionment investigations would be required to confirm these spatial trends.

3.4. Contamination Factor and Pollution Load Index

3.4.1. Contamination Factor

Pb with a mean CF of 2.2197 falls within the range of $1 \leq CF < 3$, indicating moderate contamination. This means lead levels are elevated and need attention to prevent further increases. Hg with a mean CF of 0.1880 is classified as low contamination ($CF < 1$), suggesting minimal risk at present. As with a mean CF of 0.2343 also falls under low contamination ($CF < 1$), indicating low concern but highlighting the need for regular monitoring. For Cd, the mean value of 0.0026 implies that cadmium levels were too low to be of concern in this analysis. Figure 15 shows a graph of the mean values for CF.

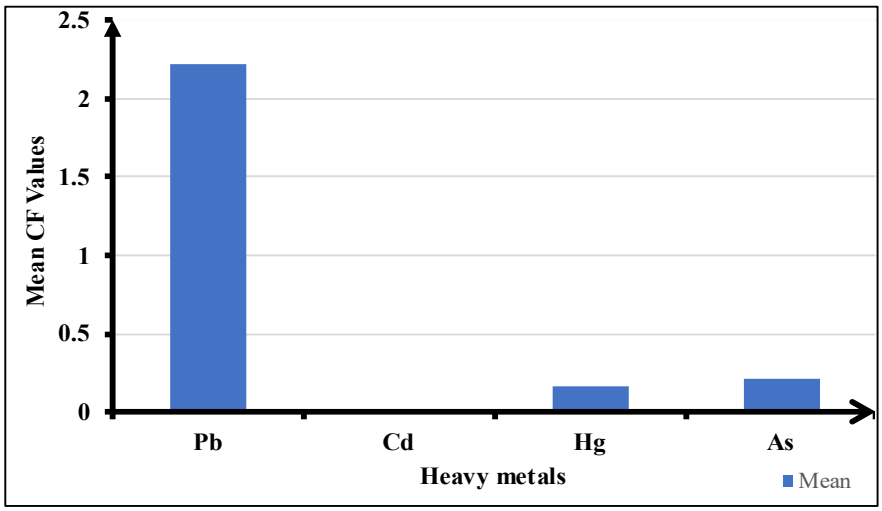

Figure 15. Mean CF Values for all analysed metals.

3.4.2. Pollution Load Index

All the PLI values in the dataset are below 1, this suggests that all the sampled areas are uncontaminated according to the classification. Even though there is variability in the PLI values, none of the samples indicate a level of pollution that would suggest deterioration of the area's quality. Even the highest PLI value (0.29 in Sample B1) is still significantly below the baseline contamination level of 1, meaning that while some areas may have higher relative pollution levels compared to others, they all remain within the uncontaminated range. Figure 16 shows a graph of the PLI levels for all sample points.

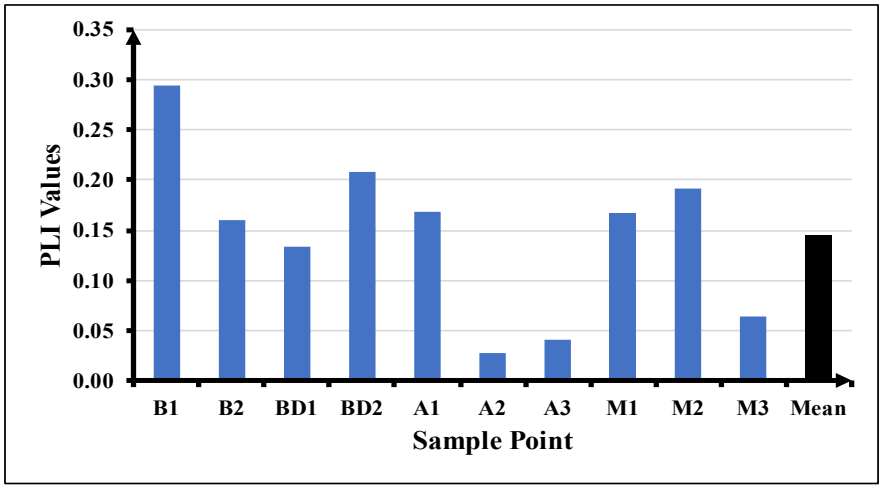

Figure 16. PLI values for all sample points.

3.4.3. Geo-Accumulation Index (I_{geo})

The mean values for Cd, Hg, and As fall below background levels since they are negative, suggesting they are below the threshold of contamination. Pb's mean value of 0.4619 suggests it is in the range of uncontaminated to moderately contaminated. This indicates that while there is some presence of Pb, it is not at concerning level. Figure 17 shows a graph of I_{geo} levels for analysed metals.

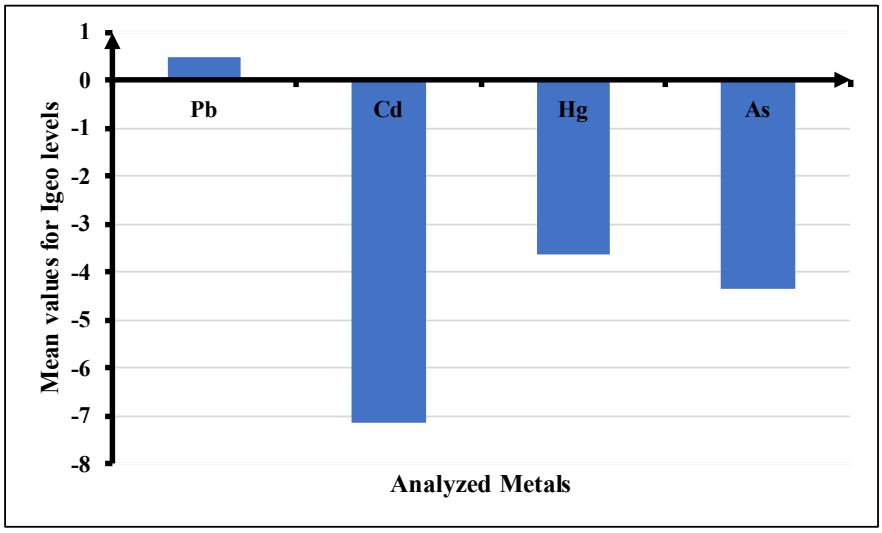

Figure 17. Mean I_{geo} levels for all analysed metals.

3.5. Ecological Risk Assessment

Figure 18 shows a graph of ecological risk index for all sample points. The highest RI value is from B1 at 36.3864, while the lowest is from A3 at 6.1858, this indicates a relatively low concern for all samples.

The RI values (6.1858 - 36.3864) indicate that all samples (RI < 150) are in the low-risk category, suggesting that there is minimal health risks associated with exposure to the contaminants measured in these samples.

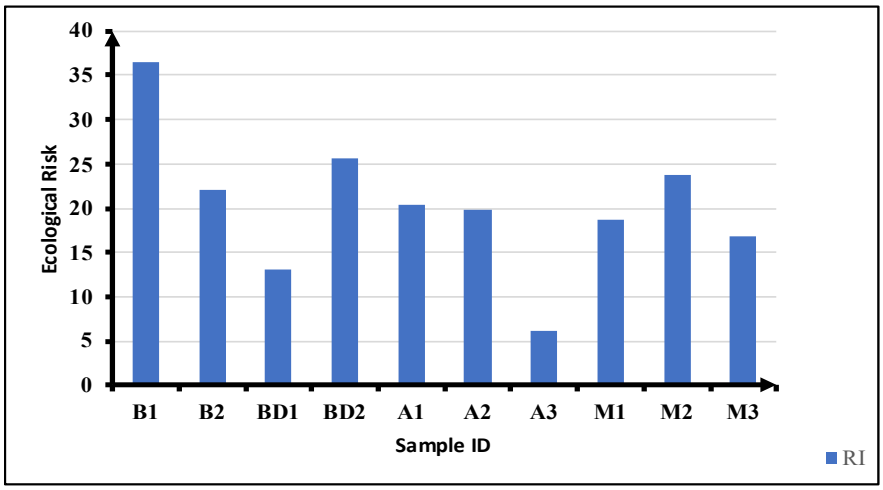

Figure 18. Risk Index for all sample points.

3.6. Human Risk Assessment

3.6.1. Carcinogenic (Children)

The CRing for Pb exceeds the threshold (10^{-6}) at 2.52E−06, suggesting a potential carcinogenic risk for children in the Tebrebie community. However, CRinh and CRderm are below the threshold, indicating negligible risks through inhalation and dermal exposure (Table 4). All CR values for As (CRing, CRinh, and CRderm) are above the 10^{-6} threshold, indicating significant carcinogenic risks associated with exposure to Arsenic through ingestion, inhalation, and dermal contact for children in the Tebrebie community. Similarly, all CR values for Cd are below the threshold of 10^{-6}, indicating negligible carcinogenic risks for children in the Tebrebie community.

3.6.2. Non-Carcinogenic (Children)

All heavy metals (Pb, As, Hg, Cd) have HI values well below 1, suggesting no significant non-carcinogenic health risks from exposure for children in the Tebrebie community (Table 4).

Table 4. Non-carcinogenic and carcinogenic risks of heavy metals in soils (Children).

Heavy Metal	Non-carcinogenic risks				Carcinogenic risks		
	HQing	*HQinh*	*HQderm*	HI	*Cring*	CR*inh*	CR*derm*
Pb	1.62E−02	2.98E−08	3.03E−04	1.65E−02	2.52E−06	4.66E−07	1.43E−07
As	5.21E−02	4.30E−07	4.38E−03	5.65E−02	1.22E−04	5.10E−06	1.14E−05
Hg	1.73E−03	8.34E−07	2.43E−05	1.76E−03	-	-	-
Cd	2.56E−05	9.59E−07	7.16E−06	3.37E−05	8.4E−07	3.15E−08	2.24E−08

3.6.3. Carcinogenic (Adult)

For adults, CR values for Pb and Cd are all below the threshold of 10^{-6}, indicating negligible carcinogenic risks from exposure to Pb. On the contrary, all CR values

for As exceed the threshold of 10^{-6}, indicating significant carcinogenic risks associated with exposure to As for adults in the Tebrebie community (Table 5). The highest risk is through ingestion (CRing), but inhalation and dermal contact also pose significant risks.

3.6.4. Non-Carcinogenic (Adult)

All heavy metals (Pb, As, Hg, Cd) have HI values well below 1, suggesting that the non-carcinogenic health risks for adults in the Tebrebie community are minimal (Table 5).

Table 5. Non-carcinogenic and carcinogenic risks of heavy metals in soils (Adult).

Heavy Metal	Non-carcinogenic risks				Carcinogenic risks		
	HQing	*HQinh*	*HQderm*	**HI**	*Cring*	CR*inh*	CR*derm*
Pb	1.74E−03	1.32E−08	4.70E−05	1.78E−03	2.70E−07	2.06E−07	2.22E−08
As	5.58E−03	1.91E−07	6.80E−04	6.26E−03	1.31E−05	2.26E−06	1.77E−06
Hg	1.86E−04	1.93E−06	3.77E−06	1.92E−04	-	-	-
Cd	2.74E−06	2.74E−06	1.11E−06	6.60E−06	9.00E−08	1.40E−08	3.48E−09

4. Conclusion

The following conclusions are drawn from the study:

1) The heavy metal concentrations including Pb > As > Hg > Cd in urban soils from Tebrebie have been determined as follows: Pb concentrations range from 2.011 to 6.117 mg/kg, while As levels range from 0.001 to 3.694 mg/kg, Hg concentrations vary between 0.001 and 0.088 mg/kg and Cd levels remain constant at 0.002 mg/kg across all samples.

2) As, Pb, and Hg exhibit localised hotspots, particularly in the central to northern regions, suggesting potential sources of pollution.

3) The Pollution Load Index (PLI) results indicate that all the sampled locations are uncontaminated, as all PLI values were less than the threshold value of 1. This suggests that the combined concentrations of the analyzed heavy metals have not resulted in significant overall soil pollution across the study area.

4) Arsenic presents the highest concentration among the assessed toxic elements, making it the primary concern for both children and adults in terms of potential cancer risk but children are particularly vulnerable.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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