African Multidisciplinary
Journal of Sciences and Artificial Intelligence

ISSN : 1595-7969
Index: Harvard, Boston, Sydney University, Dimensions, Lens, ResearchGet Scilit, Semantic, Google Scholar, Base etc

https://doi.org/10.58578/AMJSAI.v3i1.8311

Conflict and Cultivation: How Boko Haram Activities Affect Soil Fertility in Some Locations from Gombi and Hong Local Government Areas of Adamawa State, Nigeria

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Article Info:

Submitted:	Revised:	Accepted:	Published:
Oct 20, 2025	Nov 25, 2025	Dec 8, 2025	Dec 13, 2025

Abstract

The study looks into the environmental degradation caused by Boko Haram's activities, with a particular focus on soil pollution in Adamawa State's Hong and Gombi Local Government Areas. It notes a lack of prior research on the insurgency's environmental impacts, which has primarily focused on security and governance. The study assessed the effects of Boko Haram on soil physicochemical properties, heavy metal concentrations, and crop safety for consumption, in comparison to a control site with no insurgent activity. Soil samples were collected from twelve villages, including Uba, Korlea, Mararaban Mubi, and others, at varying depths using a sampling auger. Heavy metals were analyzed using X-Ray Fluorescence Spectroscopy, and the data were statistically evaluated using ANOVA and Duncan's Multiple Range Test. Significant findings show that heavy metal concentrations vary with depth, with notable increases in iron and manganese, and that lead has a negative impact on soil health. The study emphasizes the risks that heavy metals such as cadmium and mercury pose to agricultural soils and human health, as well as global contamination issues affecting food safety. It advocates for natural bioremediation methods and emphasizes the importance of continuous monitoring and regulatory measures to reduce the risks associated with heavy metals in agriculture.

Keywords: Soil Pollution; Heavy Metal Contamination; Soil Physicochemical Properties; Crop Safety; Boko Haram Insurgency

INTRODUCTION

Soil serves as the foundation for agricultural output, encompassing a diverse array of mineral constituents, including vital trace elements and hazardous substances.Among them, Zn and Cu, etc., are required for healthy functioning in humans, animals, and plants in acceptable doses, but they can be harmful at excess concentration; conversely, Cd, Hg, and As, etc., are non-essential and poisonous to organisms, even at low concentrations (Tiecher, *et al.*,2016; Rai, *et al.*,2019).These toxic elements can be absorbed by plant roots because their physiochemical properties resemble those of essential elements (Zhao and Wang, 2020).

In recent decades, rapid industrialization and overpopulation have led to the production and introduction of significant quantities of heavy metals into the soil via anthropogenic activities, resulting in soil heavy metal pollution emerging as a global concern.Reports indicate that more than five million sites globally are contaminated with heavy metals (Kumar, *et al.*,2019). In countries like China, India, and Egypt, a significant proportion of soil does not comply with quality standards for cadmium, arsenic, and lead, among others. (Emam, *et al.*,2021). Soil contamination by heavy metals can adversely affect ecosystems and human health through direct exposure to contaminated soil and the consumption of food derived from such soil (Honma *et al.*,2016).Toxic metal stress can disrupt various physiological processes in plants, including damage to cell membrane integrity, increased oxidative damage, imbalance in essential nutrient uptake, reduced photosynthetic activity, and inhibition of plant morphology and physiology (Zhao and Wang, 2020).

Accordibg to Gupta etal., (2024), toxic heavy metals absorbed by plant roots pose risks to both crops and consumers.Chaney's concept of the "soil-plant barrier" indicates that certain elements, including Cd and As, exhibit high solubility and mobility in soil, significant transport capacity within plants, and toxicity to humans and animals at low concentrations, leading to conditions such as renal failure and various cancers, including lung and skin cancers

(Emam *et al.*,2021). In certain regions, crops like rice and vegetables have consistently failed to meet food quality standards, presenting significant risks to residents in areas with high metal contamination who primarily consume locally grown produce (Zheng *et al.*,2020;,Sebastian *et al.*,2014).

Sources of Heavy Metal in Agricultural Soils

Heavy metals are introduced into the soil through natural processes and human activities.Natural activities encompass pedogenic processes, volcanic activity, and forest fires, while anthropogenic sources consist of mining, smelting, transportation, and agricultural practices, which are identified as primary contributors to heavy metal contamination in soil (ugon-Moulin *et al.*,2006). In addition to high background regions, the primary sources of heavy metals in agricultural lands include atmospheric deposition, sewage irrigation, sewage sludge, animal manure, mineral fertilizers, and pesticides (Devi *et al.*,2021). Among these, atmospheric deposition is regarded as the leading contributor to agricultural soils (Khan *et al.*,2021).

Reports by Luo *et al.*, (2009) and Ni *et al* (2018), indicate that,Atmospheric deposition contributed 43–85% of the total inputs of As, Cr, Hg, Ni, and Pb in agricultural soils from 1999 to 2005, with proportions rising to 80–94% from 2006 to 2015 in China.Conversely, animal manures accounted for 55%, 69%, and 51% of the total inputs of Cd, Cu, and Zn, respectively, from 1999 to 2005, and for 20%, 63%, and 44%, respectively, from 2006 to 2015 (Luo *et al.*, 2009; Ni *et al.*2018)]. In France, the primary sources of heavy metals in farmland are animal manures, mineral fertilizers, and pesticides. For instance, more than 50% of the total zinc, nickel, arsenic, copper, and mercury that entered agricultural lands originated from animal manures, while less than 20% resulted from atmospheric deposition (Zhoa *et al.*,2015). In contrast, approximately 50% of cadmium and chromium inputs were sourced from mineral fertilizers (Liu *et al.*,2023).

Previous research indicates that heavy metal contaminants, including Pb and Hg, in agricultural soils within certain industrial regions are primarily associated with coal combustion, industrial discharge, and vehicle emissions through atmospheric deposition. Peng *et al.*, (2016). The contribution rates of coal combustion and vehicle emissions to lead (Pb) in atmospheric dust in Northeast China were reported to be 22% and 78%, respectively. Animal manures serve as important fertilizers; however, they are significant contributors to heavy metal contamination in soil (Peng *et al.*,2020).

Heavy metal feed additives, including As, Cu, and Zn, are utilized in intensive animal production systems to enhance weight gains and egg production while also preventing disease. This practice results in elevated levels of these heavy metals in manure by-products (Peng, *et al.*,2020).our prior research indicated that the median concentrations of Cd, As, Cu, and Zn in animal manures were 2.3 (0.72), 14.0 (3.5), 282 (115), and 656 (366) mg kg^{-1}, respectively, in China (Mu *et al.*,2020). The ongoing use of chicken or pig manure resulted in the buildup of heavy metals in paddy soil, with accumulation rates of 0.006–0.026 and 0.002–0.025 mg kg^{-1} yr^{-1} for Cd, 0.15^{-1}.2 and 1.0–4.2 mg kg^{-1} yr^{-1} for Cu, and 0.54–5.5 and 1.5–9.6 mg kg^{-1} yr^{-1} for Zn, respectively [Wan *et al.*,2020).

Phosphate fertilizer is recognized as a significant source of heavy metals, particularly cadmium, derived from phosphate rocks. Analysis of 196 phosphate fertilizer samples from 12 European countries revealed average heavy metal concentrations of 7.4 $mgkg^{-1}$ for cadmium (Cd), 90 $mgkg^{-1}$ for chromium (Cr), 166 $mgkg^{-1}$ for zinc (Zn), 15 $mgkg^{-1}$ for nickel (Ni), and 2.9 $mgkg^{-1}$ for lead (Pb) (Wan *et al.*,2020). The input fluxes of chromium and cadmium from phosphate fertilizers were found to be higher than those from atmospheric deposition (Wan *et al.*,2020).

METHODS

Sample Collection

Samples soil was collected in twelve major villages of Hong and Gombi Local Government Areas of Adamawa State.in each village, samples was collected in five location . These are, Uba, Korlea , Dagza, Fachi and Mararaba Mubi in Hong Local Government and Garkida, Fota, Dzangola, Amdur and Gwallontabal in Gombi Local Government areas.

Soil Sampling and Collection

Soil was randomly collected from six different locations of the study areas. The method by Ibitoye (2006) was adopted. The soil were collected base on depth (0-10cm,11-20cm and 21-30cm). sampling auger was inserted to plough to a desirable depth, and the sample collected in desirable quantity. Bulk samples were put together and mixed to form a composite sample. Soil was spread on a paper to air-dry for about three days. Ground soil sample in mortar with pestle and sieve through 2mm sieve. This was then stored in a well labelled polyethylene bag for subsequent use. The major soil pollutant of concern in this study are heavy metals.

Sample Preparation

Determination of Heavy Metals from Soils Samples using X-Ray Fluorescence (XRF) Spectroscopy.

Major elemental oxides in soil were determined using X-ray fluorescence spectroscopic method Axion cement Pan Analytical model. 20g of each powder soil was fuse with 0.40g of stearic acid in 20ml platinum crucibles and pass with Herzog D4500 model hydraulic press to form pellet. These fused buttons was X- rayed and counted, and the major elemental oxides was determined (Das *et al.*,4024). An annular 25mCi 109Cd was used as an excitation source, which emit Ag-K X-ray (22.1KeV) in which case, the element with lower characteristics excitation energies was accessible for detection in the samples (Dutrow and Clark.2009)

Quantitative analysis of samples was carried out using the emission transmission (E – T) method, for which a number of quantification was developed and apply; these quantification methods provide different approaches to correct the matrix absorption as well as enhancement effect. In this work, quantification was carry out using a modified version of Emission-Transmission (E-T) method and the use of pure target material (Mo) was employ to measure the absorption factor in the samples. The (Mo) target served as monochromatic X-ray which was excited through the sample by primary radiation and penetrate the sample on the way to detector. The absorption factor was experimentally determined which was used by the program in the quantification of concentration of the elements. In addition, the contribution to the Mo-K peak intensity by the Zr-K was subtracted from each sample. The spectra for the sample were collected for 3000s with the 109 Cd source and the spectra were evaluated using the AXIL-QXAS program. 109Cd was used for analysis of the metal oxides. (Jamaludding and Massinar. 2017).

Statistical Analysis

All analysis was performed in triplicates. Result was presented as mean ± SD. Statistical significant Figure were establish using oneway analysis of variance. (ANOVA). Mean was separated according to Duncans Multiple Range Analysis. $P \leq 0.05$ was considered statistical significant

RESULTS

Table 1 to 5 show the Mean Concentration of Some Heavy Metals (mg/kg) in Soils Samples at Different Depths From Some Locations in Hong Local Government Area, and Gerei as a Control all in Adamawa State

The analysis of heavy metal concentrations in soil samples from Uba, in table 1 revealing that iron recorded the highest mean concentration (10.21 mg/kg), followed by manganese (2.67 mg/kg) and nickel (1.52 mg/kg), while chromium, copper, zinc, and lead showed relatively lower concentrations ranging from 0.19 to 0.30 mg/kg. This pattern indicates that iron and manganese are the predominant heavy metals in the soil profile at this location.The depth-wise distribution shown in Table 1 revealed statistically significant variations ($P < 0.05$) among depth intervals for all metals examined, as indicated by the different superscript letters.

Nickel, manganese, and iron showed significant increases with depth, with all three depth layers being significantly different from each other. Nickel rose from 1.11 mg/kg (a) in the topsoil to 1.34 mg/kg (b) at 11-20 cm and 2.10 mg/kg (c) at 21-30 cm depth, while iron increased from 8.22 mg/kg (a) to 8.85 mg/kg (b) and 13.54 mg/kg (c). Similarly, manganese exhibited significant progressive increases across all depths from 2.14 mg/kg (a) to 2.69 mg/kg (b) and 3.17 mg/kg (c). This consistent accumulation pattern at greater depths may indicate leaching processes or natural geological enrichment in subsurface layers.

The ANOVA results in Table 1 revealed contrasting patterns for chromium, copper, and zinc. Chromium showed no significant difference between the surface (0.19 mg/kg, b) and deepest layers (0.20 mg/kg, b), but both were significantly higher than the middle depth (0.16 mg/kg, a), suggesting a U-shaped distribution pattern. Copper exhibited similar behavior, with the middle layer (0.23 mg/kg, a) being significantly lower than both the surface (0.30 mg/kg, b) and deepest layers (0.36 mg/kg, c). Zinc showed significant differences across all three depths, increasing from 0.24 mg/kg (a) at the surface to 0.29 mg/kg (c) at the middle depth, then slightly decreasing to 0.27 mg/kg (b) at the deepest layer. Lead displayed irregular distribution with values of 0.22 mg/kg (ab), 0.24 mg/kg (b), and 0.17 mg/kg (a), with the deepest layer being significantly lower than the middle depth but not significantly different from the surface layer.

The coefficient of variation in Table 1 indicates that nickel exhibited the highest variability (29.61%), followed by iron (24.68%) and copper (20.00%), while chromium and zinc showed relatively uniform distribution with low variability at 10.52% and 11.11% respectively.

The mean concentrations of seven heavy metals (Cr, Ni, Cu, Mn, Fe, Pd, Zn) in soil samples collected at three different depths (0-10 cm, 11-20 cm, 21-30 cm) in Mararaban Mubi as shown in table 2, The concentrations are given in mg/kg with standard deviations, and values with different superscript letters within each metal column indicate significant differences at the 5% level according to Duncan's Multiple Range Test. Chromium (Cr) levels show a significant increase with depth, rising from 1.13 mg/kg at 0-10 cm to 1.92 mg/kg at 21-30 cm. This indicates a progressive accumulation or greater retention of Cr in deeper soil layers. The work is inline with Emam *et al.*,(2021)

Nickel (Ni) exhibits a different pattern; it peaks at 3.78 mg/kg in the deepest layer, is intermediate at 3.14 mg/kg in the shallowest layer, and has a significantly lower concentration at the middle depth of 11-20 cm (2.62 mg/kg). This variation suggests heterogeneous distribution possibly influenced by localized sources or soil properties. Copper (Cu) shows the highest concentration in the shallowest layer (0.53 mg/kg) and decreases significantly with depth to 0.43 mg/kg in the deepest layer. In contrast, manganese (Mn) remains relatively stable but with a slight increase from 3.67 mg/kg at 0-10 cm to 3.98 mg/kg at 21-30 cm, with the middle and deepest layers both statistically higher than the surface layer. This may reflect manganese mobility or natural soil enrichment characteristics.

Iron (Fe) concentrations are consistently high across all depths, ranging narrowly from 24.46 to 24.77 mg/kg, with no significant differences between depths. This suggests a stable background level of iron in the soil at this location. Palladium (Pd) shows a similar stability, though with more variability, and a slight numerical increase with depth from 0.21 mg/kg at the surface to 0.31 mg/kg at 21-30 cm — but these differences are not statistically significant.

Zinc (Zn) increases significantly with depth from 0.37 mg/kg at 0-10 cm to 0.56 mg/kg at 21-30 cm, indicating a higher accumulation in deeper layers. The overall range of concentrations for all metals suggests varying degrees of mobility and sources affecting their vertical distribution in this soil profile. Plants absorb heavy metals through their roots, which then translocate the metal to leaves and edible parts via passive diffusion and active transport mechanisms (Gupta et al.,2024).

The coefficient of variation (CV) indicates relative variability, with Pd exhibiting the highest variability (41.67%), followed by Zn and Cr, while Fe has the lowest variability

(1.30%), confirming its stable presence in the soil samples.Heavy metals differ in their soil depth distribution at Mararaban Mubi, with Cr, Ni, and Zn generally increasing with depth, Cu decreasing, Mn slightly increasing, and Fe and Pd remaining fairly constant.

The mean concentrations of seven heavy metals (Cr, Ni, Cu, Mn, Fe, Pd, Zn) measured in soil samples from Korlea, at three different depths: 0-10 cm, 11-20 cm, and 21-30 cm. As shown in table 3. Concentrations are expressed in mg/kg, with their standard deviations, and statistical significance between depths is indicated by differing superscript letters within each metal's column based on Duncan's Multiple Range Test at $P < 0.05$. Chromium (Cr) exhibits a significant increase with depth, starting at 2.06 mg/kg in the 0-10 cm layer, remaining stable at 2.16 mg/kg in the 11-20 cm layer, then rising significantly to 2.55 mg/kg in the deepest layer (21-30 cm). This pattern suggests Cr accumulates more in deeper soil layers in Korlea.

Nickel (Ni) also shows a consistent incremental increase by depth. It starts at 1.93 mg/kg at the surface, increases to 2.10 mg/kg in the middle layer, and reaches 2.58 mg/kg at the deepest layer. The statistically significant differences between all depths indicate systematic vertical variation.Copper (Cu) displays a notable upward trend with depth, starting at 0.36 mg/kg at the surface, increasing to 0.52 mg/kg at 11-20 cm, and peaking significantly at 0.84 mg/kg at 21-30 cm. This suggests enhanced copper retention deeper in the soil, potentially due to soil chemistry or contamination sources. Manganese (Mn) concentrations rise steadily from 2.18 mg/kg at the shallowest depth to 2.37 mg/kg at middle depth and further to 2.84 mg/kg at the deepest sample. The differences are significant, indicating Mn mobility or enrichment increases with soil depth.

Iron (Fe) remains relatively constant across all depths, ranging narrowly from 17.70 to 18.22 mg/kg, with no significant differences. This stability reflects a uniform natural background level of iron in the soil profile for Korlea. Palladium (Pd) shows a pronounced increase in concentration with depth, rising from 0.23 mg/kg at the surface to 0.46 mg/kg at 11-20 cm and further to 0.69 mg/kg at 21-30 cm, all significantly different. This suggests Pd is more concentrated in deeper layers, possibly reflecting deposition or geochemical factors. Zinc (Zn) presents an irregular pattern: the highest concentration is at the surface (0.42 mg/kg), drops significantly at 11-20 cm (0.27 mg/kg), and then rises again at 21-30 cm (0.38 mg/kg). These differences are statistically significant, showing heterogeneous vertical distribution likely influenced by local factors.

The coefficient of variation (CV) values reveal that Pd exhibits the highest variability (43.48%), followed by Cu (36.84%), suggesting fluctuating concentrations, while Fe has the lowest variability (2.29%), indicating consistent levels throughout the depth profile. Therefore, heavy metal concentrations in Korlea soils tend to increase with depth for Cr, Ni, Cu, Mn, and Pd, while Fe remains stable. Zn shows a fluctuating pattern, possibly reflecting complex soil dynamics or inputs.

Table 4 displays the mean concentrations of heavy metals in soil samples from Dagza at depths of 0-10 cm, 11-20 cm, and 21-30 cm. Chromium (Cr), Nickel (Ni), Copper (Cu), Manganese (Mn), Palladium (Pd), and Zinc (Zn) all show significant increases with increasing depth, suggesting accumulation or enhanced retention in deeper soil layers. Copper shows the most notable increase, from 0.11 mg/kg at the surface to 1.18 mg/kg at 21-30 cm, indicating possible localized enrichment or strong vertical mobility. Iron (Fe) concentration displays a less consistent pattern, decreasing significantly at the 11-20 cm depth (18.85 mg/kg) compared to both shallower and deeper layers (around 20.11 and 20.52 mg/kg). This may reflect geochemical variations or soil layering effects.The coefficient of variation (C.V.) highlights high variability for Copper (96.15%) and Zinc (41.30%), contrasting with relatively low variability for Chromium (7.57%) and Iron (4.14%), indicating differing consistency and distribution patterns for these metals. Overall, heavy metals in Dagza soil tend to accumulate more in deeper layers, with some metals showing strong variation likely influenced by soil characteristics or external inputs.

Table 5 present the mean concentrations of heavy metals in soil samples from Fachi at depths of 0-10 cm, 11-20 cm, and 21-30 cm . Chromium (Cr) and Nickel (Ni) display significant increases with depth, rising from 1.63 to 1.99 mg/kg for Cr and from 2.16 to 2.61 mg/kg for Ni, indicating greater accumulation in deeper layers. Manganese (Mn) shows a more complex pattern; it decreases at 11-20 cm but rises again at 21-30 cm, with all depth differences significant.Copper (Cu) exhibits very high variability (C.V. 232.04%) and an unusual pattern: an extremely high concentration at the surface (4.42 mg/kg) with large standard deviation, compared to much lower and stable concentrations at deeper layers (0.34 and 0.67 mg/kg).

Iron (Fe) concentrations increase slightly with depth, from 23.14 mg/kg at the surface to 24.71 mg/kg at 21-30 cm, showing a gradual enrichment. Palladium (Pd) varies moderately, with lower concentration at 11-20 cm compared to the shallower and deeper layers, while Zinc

(Zn) increases significantly with depth.Overall, most heavy metals in Fachi soil increase with depth except for copper, which shows irregular distribution and high variability.

Soil contamination by lead disrupts microbial communities and hinders soil health by interfering with enzyme activity, cellular functions, and nutrient cycling, which impedes organic matter decomposition and soil biomass (Gupta *et al.*,2021). Lead also negatively impacts soil structure, reducing its water-holding capacity and contributing to soil degradation (Xie *et al.,*2023). Pb is a hazardous heavy metal that damages both the environment and human health (Azevedo and Rodriguez). Its widespread use in battery manufacturing, cars, and buildings contributes to global lead contamination (Li *et al.*, 2021). Lead is released into the environment through a variety of processes, including rock weathering, volcanic activity, sea spray, lead-based paints, refinery emissions, lead-acid battery disposal, and leaded gasoline. (Ali *et al.*,2018). Lead contamination reduces microbial populations, enzyme activity, cellular function, and nutrient cycling, hence impeding organic matter breakdown and soil biomass. Lead damages soil structure and water retention capacity (Xie *et al.*,2023).

Table 1: Mean Concentration of Heavy Metals (mg/kg) in Soil Samples at Different Depths from Uba Hong Local Government Areas.

Depth	Cr	Ni	Cu	Mn	Fe	Pd	Zn
0-10cm	0. 19±0.01^{b}	1. 11±0.01^{a}	0. 30±0.01^{b}	2. 14±0.03^{a}	8. 22±0.01^{a}	0. 22±0.01^{ab}	0. 24±0.01^{a}
11-20cm	0. 16±0.01^{a}	1. 34±0.01^{b}	0. 23±0.01^{a}	2. 69±0.01^{b}	8. 85±0.05^{b}	0. 24±0.01^{b}	0. 29±0.01^{c}
21-30cm	0. 20±0.01^{b}	2. 10±0.01^{c}	0. 36±0.01^{c}	3. 17±0.05^{c}	13.54±0.03^{c}	0. 17±0.04^{a}	0. 27±0.01^{b}
Range	0. 16-0.21	1. 11-2.11	0. 23-0.37	2. 11-3.22	8. 21-13.56	0. 12-0.24	0. 23-0.30
Grand Mean	0. 19	1. 52	0. 30	2. 67	10.21	0. 21	0. 27
Standard Deviation	0. 02	0. 45	0. 06	0. 45	2. 52	0. 04	0. 03
C.V. (%)	10.52	29.61	20.00	16.85	24.68	19.05	11.11

Mean ± Standard Deviation within a column with different superscript letters are significantly different at $P < 0.05$ according to Duncan Multiple Range Test. CV = Co-efficient of Variation

Table 2: Mean Concentration of Heavy Metals (mg/kg) in Soil Samples at Different Depths from Mararaban Mubi Hong Local Government Areas

Depth	Cr	Ni	Cu	Mn	Fe	Pd	Zn
0-10cm	1. 13±0.03^{a}	3. 14±0.02^{b}	0. 53±0.01^{b}	3. 67±0.13^{a}	24.46±0.11^{a}	0. 21±0.03^{a}	0. 37±0.01^{a}
11-20cm	1. 60±0.07^{b}	2. 62±0.05^{a}	0. 45±0.01^{a}	3. 76±0.08^{a}	24.62±0.06^{a}	0. 22±0.02^{a}	0. 37±0.06^{a}
21-30cm	1. 92±0.12^{c}	3. 78±0.01^{c}	0. 43±0.02^{a}	3. 98±0.02^{b}	24.77±0.57^{a}	0. 31±0.17^{a}	0. 56±0.01^{b}
Range	1. 11-2.00	2. 58-3.79	0. 42-0.54	3. 54-4.00	24.11-25.10	0. 11-0.41	0. 30-0.56
Grand Mean	1. 55	3. 18	0. 47	3. 80	24.61	0. 24	0. 43
Standard Deviation	0. 35	0. 51	0. 05	0. 16	0. 32	0. 10	0. 10
C.V. (%)	22.58	16.04	10.64	4. 21	1. 30	41.67	23.26

Mean ± Standard Deviation within a column with different superscript letters are significantly different at $P < 0.05$ according to Duncan Multiple Range Test. CV = Co-efficient of Variation

Table 3: Mean Concentration of Heavy Metals (mg/kg) in Soil Samples at Different Depths from Korlea Hong Local Government Areas.

Depth	Cr	Ni	Cu	Mn	Fe	Pd	Zn
0-10cm	2. 06±0.11^{a}	1. 93±0.01^{a}	0. 36±0.01^{a}	2. 18±0.01^{a}	17.78±0.59^{a}	0. 23±0.01^{a}	0. 42±0.01^{c}
11-20cm	2. 16±0.01^{a}	2. 10±0.01^{b}	0. 52±0.01^{b}	2. 37±0.13^{b}	17.70±0.26^{a}	0. 46±0.03^{b}	0. 27±0.02^{a}
21-30cm	2. 55±0.01^{b}	2. 58±0.01^{c}	0. 84±0.02^{c}	2. 84±0.04^{c}	18.22±0.01^{a}	0. 69±0.02^{c}	0. 38±0.01^{b}
Range	2. 00-2.56	1. 93-2.58	0. 35-0.36	2. 17-2.87	17.09-18.23	0. 23-0.71	0. 26-0.43
Grand Mean	2. 26	2. 20	0. 57	2. 46	17.90	0. 46	0. 36
Standard Deviation	0. 23	0. 28	0. 21	0. 30	0. 41	0. 20	0. 07
C.V. (%)	10.18	12.73	36.84	12.20	2. 29	43.48	19.44

Mean ± Standard Deviation within a column with different superscript letters are significantly different at $P < 0.05$ according to Duncan Multiple Range Test. CV = Co-efficient of Variation

Table 4: Mean Concentration of Heavy Metals (mg/kg) in Soil Samples at Different Depths from Dagza Hong Local Government Areas.

Depth	Cr	Ni	Cu	Mn	Fe	Pd	Zn
0-10cm	1. 67±0.01^{a}	2. 16±0.01^{a}	0. 11±0.01^{a}	1. 91±0.01^{a}	20.11±0.01^{b}	0. 41±0.01^{a}	0. 29±0.01^{a}
11-20cm	1. 88±0.01^{b}	2. 68±0.01^{b}	0. 27±0.06^{b}	2. 16±0.01^{b}	18.85±0.58^{a}	0. 42±0.01^{a}	0. 38±0.03^{b}
21-30cm	2. 00±0.01^{c}	2. 90±0.01^{c}	1. 18±0.03^{c}	2. 56±0.01^{c}	20.52±0.23^{b}	0. 53±0.01^{b}	0. 70±0.06^{c}
Range	1. 66-2.00	2. 16-2.91	0. 11-1.21	1. 90-2.57	18.18-20.68	0. 41-0.53	0. 28-0.74
Grand Mean	1. 85	2. 58	0. 52	2. 21	19.82	0. 45	0. 46
Standard Deviation	0. 14	0. 33	0. 50	0. 29	0. 82	0. 06	0. 19
C.V. (%)	7. 57	12.79	96.15	13.12	4. 14	13.33	41.30

Mean ± Standard Deviation within a column with different superscript letters are significantly different at $P < 0.05$ according to Duncan Multiple Range Test. CV = Co-efficient of Variation

Table 5: Mean Concentration of Heavy Metals (mg/kg) in Soil Samples at Different Depths from Fachi Hong Local Government Areas.

Depth	Cr	Ni	Cu	Mn	Fe	Pd	Zn
0-10cm	1. 63±0.01^{a}	2. 16±0.01^{a}	4. 42±7.42^{a}	1. 62±0.01^{b}	23.14±0.14^{a}	0. 38±0.05^{b}	0. 45±0.01^{b}
11-20cm	1. 85±0.15^{b}	2. 38±0.05^{b}	0. 34±0.01^{a}	1. 34±0.02^{a}	24.01±0.79^{ab}	0. 27±0.02^{a}	0. 38±0.01^{a}
21-30cm	1. 99±0.01^{b}	2. 61±0.06^{c}	0. 67±0.01^{a}	1. 90±0.01^{c}	24.71±0.06^{b}	0. 43±0.01^{b}	0. 50±0.01^{c}
Range	1. 62-2.00	2. 16-2.67	0. 12-13.0	1. 32-1.91	22.98-24.93	0. 26-0.43	0. 37-0.51
Grand Mean	1. 82	2. 38	1. 81	1. 62	23.96	0. 36	0. 44
Standard Deviation	0. 18	0. 20	4. 20	0. 25	0. 79	0. 07	0. 05
C.V. (%)	9. 89	8. 40	232.04	15.43	3. 30	19.44	11.36

Mean ± Standard Deviation within a column with different superscript letters are significantly different at $P < 0.05$ according to Duncan Multiple Range Test. CV = Co-efficient of Variation

Table 6 -11: Present the Mean Concentration of Heavy Metals (mg/kg) in Soil Samples at Various Depths in all Locations from Gombi Local Government Areas with Gerei Local Government Areas as Control

Table 6 presents the mean concentrations of heavy metals in soils samples from Garkida at three depths: 0-10 cm, 11-20 cm, and 21-30 cm. Chromium (Cr), Nickel (Ni), Copper (Cu), Manganese (Mn), Iron (Fe), Palladium (Pd), and Zinc (Zn) all demonstrate significant variation by depth. Chromium increases steadily with depth from 1.78 mg/kg at the surface to 2.14 mg/kg at 21-30 cm, indicating accumulation in deeper soil layers. Nickel also shows a significant increase, from 1.11 mg/kg to 1.89 mg/kg, suggesting similar depth-related enrichment.

Copper varies less consistently but increases significantly at the deepest layer (1.56 mg/kg) compared to the middle layer (0.94 mg/kg), although the surface value (1.00 mg/kg) is comparable to the deeper level. Manganese fluctuates, being lowest at middle depth (1.46 mg/kg) and higher at both surface and deeper levels, indicating variable mobility or soil characteristics.

Iron shows a gradual and significant increase from 22.01 mg/kg at 0-10 cm to 23.77 mg/kg at 21-30 cm, reflecting stable enrichment.

Palladium shows small but significant fluctuations, with the lowest value at 11-20 cm (0.13 mg/kg) and similar concentrations at other depths. Zinc concentration is highest at the surface (0.43 mg/kg), drops significantly at 11-20 cm (0.23 mg/kg), and partially recovers at 21-30 cm (0.33 mg/kg), showing heterogeneous distribution.

The coefficient of variation (C.V.) is highest for Zinc (36.36%) and Copper (25.64%), indicating notable variability, while Chromium and Iron have lower variability, reflecting more stable concentrations.

Table 7 presents the analysis of heavy metal concentrations in soil samples from Fota, revealing that iron recorded the highest mean concentration (20.45 mg/kg), followed by copper (1.45 mg/kg) and chromium (1.21 mg/kg), while nickel, manganese, lead, and zinc showed relatively lower concentrations ranging from 0.23 to 1.04 mg/kg. The ANOVA results indicated significant variations ($P < 0.05$) among depth intervals for all metals examined, as shown by the different superscript letters.

All seven heavy metals in Table 7 exhibited significant progressive increases with depth, with each of the three layers being statistically distinct from one another. Chromium increased from 0.98 mg/kg (a) at the surface to 1.55 mg/kg (c) at the deepest layer, while copper rose from 1.11 mg/kg (a) to 1.71 mg/kg (c), and iron increased from 20.01 mg/kg (a) to 21.11 mg/kg (c). Similarly, nickel, manganese, lead, and zinc all showed consistent depth-dependent accumulation patterns, with nickel rising from 0.77 to 1.19 mg/kg, manganese from 0.86 to 1.16 mg/kg, lead from 0.12 to 0.33 mg/kg, and zinc from 0.19 to 0.42 mg/kg. This uniform accumulation pattern across all metals suggests strong leaching processes, vertical migration, or natural geological enrichment in the subsurface layers at Fota.

The coefficient of variation revealed that zinc and lead exhibited the highest variability (39.29% and 39.13% respectively), indicating highly heterogeneous distribution within the soil profile. Chromium, nickel, and copper showed moderate variability (21.49%, 19.79%, and 18.62% respectively), while iron displayed remarkably low variability (2.49%).

Table 8 presents the analysis of heavy metal concentrations in soil samples from Dzangola, revealing that iron recorded the highest mean concentration (16.94 mg/kg), followed by copper (1.74 mg/kg) and manganese (1.16 mg/kg), while chromium, nickel, lead, and zinc showed relatively lower concentrations ranging from 0.12 to 0.82 mg/kg. The ANOVA results indicated significant variations ($P < 0.05$) among depth intervals for all metals examined, as shown by the different superscript letters.

Most heavy metals in Table 8 exhibited significant progressive increases with depth, though with varying patterns. Chromium, copper, manganese, iron, and zinc showed consistent depth-dependent accumulation, with chromium increasing from 0.65 mg/kg (a) at the surface to 1.07 mg/kg (c) at the deepest layer, copper rising from 1.63 mg/kg (a) to 1.81 mg/kg (c), and zinc increasing from 0.21 mg/kg (a) to 0.46 mg/kg (c). Lead displayed a distinctive pattern, being completely absent (0.00 mg/kg, a) in the topsoil but significantly increasing to 0.13 mg/kg (b) and 0.23 mg/kg (c) in the deeper layers, suggesting minimal surface contamination and possible accumulation from geological sources or subsurface processes. Nickel exhibited an irregular distribution pattern, with the middle layer (0.71 mg/kg, c) being significantly higher than both the surface (0.52 mg/kg, a) and deepest layers (0.56 mg/kg, b), indicating complex mobility influenced by soil-specific physicochemical properties at this depth. The coefficient of variation revealed that lead exhibited exceptionally high variability (83.33%), reflecting its complete absence in the surface layer and presence in deeper layers. Chromium and zinc showed moderate variability (23.17% and 32.35% respectively), while copper and iron displayed remarkably low variability (4.60% and 4.55% respectively).

Table 9 presents the analysis of heavy metal concentrations in soil samples from Amdur, revealing that iron recorded the highest mean concentration (21.82 mg/kg), followed by chromium (1.49 mg/kg) and manganese (1.38 mg/kg), while copper, nickel, lead, and zinc showed relatively lower concentrations ranging from 0.24 to 0.99 mg/kg. The ANOVA results indicated significant variations ($P < 0.05$) among depth intervals for all metals examined, as shown by the different superscript letters.

The heavy metals in Table 9 exhibited contrasting depth distribution patterns. Chromium, copper, manganese, and iron showed significant progressive increases with depth, with chromium rising from 1.16 mg/kg (a) at the surface to 1.75 mg/kg (c) at the deepest layer, copper increasing from 0.89 mg/kg (a) to 1.12 mg/kg (c), and manganese rising from 1.12 mg/kg (a) to 1.69 mg/kg (c). Iron increased from 21.22 mg/kg (a) to 23.41 mg/kg (b), though the surface and middle layers were not significantly different. Conversely, nickel displayed a significant inverse relationship with depth, decreasing from 0.55 mg/kg (c) at the surface to 0.23 mg/kg (a) at the deepest layer, suggesting possible surface enrichment from anthropogenic sources or preferential retention in topsoil.

Zinc exhibited an irregular pattern, with the highest concentration at the surface (0.64 mg/kg, c), lowest at the middle depth (0.34 mg/kg, a), and intermediate at the deepest layer (0.44 mg/kg, b). Lead showed minimal but significant variation, increasing slightly from 0.22 mg/kg (a) to 0.25-0.26 mg/kg (b) in the deeper layers. The coefficient of variation revealed that nickel exhibited the highest variability (37.84%), followed by zinc (27.66%), indicating heterogeneous distribution within the soil profile. Chromium and manganese showed moderate variability (17.45% and 18.12% respectively), while iron, copper, and lead displayed low variability (5.82%, 10.10%, and 8.33% respectively).

Table 10 presents the analysis of heavy metal concentrations in soil samples from Gwallontabal, revealing that iron recorded the highest mean concentration (18.01 mg/kg), followed by chromium (1.26 mg/kg) and copper (0.85 mg/kg), while manganese, nickel, lead, and zinc showed relatively lower concentrations ranging from 0.13 to 0.80 mg/kg. The ANOVA results indicated significant variations ($P < 0.05$) among depth intervals for all metals examined, as shown by the different superscript letters.

The heavy metals in Table 10 exhibited diverse depth distribution patterns. Chromium, nickel, manganese, iron, and zinc showed significant progressive increases with depth, with chromium rising from 1.19 mg/kg (a) at the surface to 1.37 mg/kg (b) at the deepest layer, though the surface and middle layers were not significantly different. Nickel increased from 0.23 mg/kg (a) to 0.55 mg/kg (c), manganese rose from 0.45 mg/kg (a) to 1.12 mg/kg (c), and zinc increased from 0.66 mg/kg (a) to 0.99 mg/kg (c), with all three depths being significantly different.

Conversely, copper exhibited an irregular V-shaped pattern, with concentrations of 0.83 mg/kg (b) at the surface, decreasing significantly to 0.62 mg/kg (a) at the middle depth, then increasing to 1.08 mg/kg (c) at the deepest layer. Lead displayed a unique mid-depth concentration peak at 0.22 mg/kg (c), being significantly higher than both the surface (0.15 mg/kg, b) and deepest layers where it was completely absent (0.00 mg/kg, a), suggesting complex mobility or localized historical contamination at the 11-20 cm depth. The coefficient of variation revealed that lead exhibited the highest variability (76.92%), reflecting its absence at the deepest layer and presence in upper layers. Manganese and nickel showed high variability (36.25% and 35.71% respectively), while copper displayed moderate variability (23.53%). Chromium and iron exhibited remarkably low variability (7.14% and 7.72% respectively).

Table 11 presents the analysis of heavy metal concentrations in soil samples from Girei, which is the control site, revealing that iron recorded the highest mean concentration (11.82 mg/kg), followed by zinc (0.41 mg/kg) and manganese (0.34 mg/kg), while chromium, nickel, copper, and lead showed relatively lower concentrations ranging from 0.13 to 0.30 mg/kg. Notably, all heavy metal concentrations at the control site were substantially lower than those observed at the study sites, with iron averaging 11.82 mg/kg compared to 16.94-21.82 mg/kg at other locations. The ANOVA results indicated significant variations ($P < 0.05$) among depth intervals for all metals examined, as shown by the different superscript letters.

All seven heavy metals in Table 11 exhibited significant progressive increases with depth, demonstrating a consistent depth-dependent accumulation pattern across the soil profile. Chromium increased from 0.23 mg/kg (a) at the surface to 0.30 mg/kg (c) at the deepest layer, nickel rose from 0.11 mg/kg (a) to 0.14 mg/kg (c), and iron increased from 9.79 mg/kg (a) to 14.09 mg/kg (c). Similarly, manganese, lead, and zinc showed significant increases with depth, with manganese rising from 0.27 mg/kg (a) to 0.45 mg/kg (c), lead from 0.12 mg/kg (a) to 0.16 mg/kg (c), and zinc from 0.27 mg/kg (a) to 0.54 mg/kg (c). Copper exhibited a slightly different pattern, with the middle and deepest layers (0.32 and 0.36 mg/kg, both b) being statistically similar but both significantly higher than the surface layer (0.22 mg/kg, a).

The coefficient of variation revealed that zinc exhibited the highest variability (29.27%), followed by manganese (23.53%) and copper (20.00%), indicating moderate heterogeneity in their distribution. Chromium, nickel, and lead showed low to moderate variability (11.11%, 15.38%, and 14.29% respectively), while iron displayed remarkably low variability (1.02%).

Nickel (Ni) is an essential trace element for plants, with low concentrations supporting their growth. However, under acidic conditions (low pH), nickel availability increases, which can negatively impact plant health (Minari and Saran, 2020). Elevated levels of nickel interfere with the absorption of phosphorus, hinder root development, and reduce chlorophyll production, leading to symptoms like chlorosis (Gupta et al.,2024). Nickel is highly mobile within plants, easily moving from the soil to the leaves and seeds, where it accumulates. This bioaccumulation allows nickel to enter the food chain, posing risks to both plants and animals (Zhao et al.,2021)

Table 6: Mean Concentration of Heavy Metals (mg/kg) in Soil Samples at Different Depths in Garkida, Gombi Local Government Areas.

Depth	Cr	Ni	Cu	Mn	Fe	Pd	Zn
0-10cm	1. 78±0.01^{a}	1. 11±0.01^{a}	1. 00±0.01^{a}	1. 83±0.01^{b}	22.01±0.02^{a}	0. 17±0.02^{b}	0. 43±0.01^{c}
11-20cm	2. 00±0.01^{b}	1. 43±0.01^{b}	0. 94±0.05^{a}	1. 46±0.01^{a}	23.25±0.07^{b}	0. 13±0.01^{a}	0. 23±0.02^{a}
21-30cm	2. 14±0.01^{c}	1. 89±0.01^{c}	1. 56±0.01^{b}	1. 97±0.03^{c}	23.77±0.10^{c}	0. 20±0.01^{c}	0. 33±0.15^{ab}
Range	1. 78-2.15	1. 11-1.90	0. 90-1.57	1. 45-2.00	22.0-23.89	0. 13-0.21	0. 22-0.50
Grand Mean	1. 98	1. 48	1. 17	1. 75	23.01	0. 17	0. 33
Standard Deviation	0. 16	0. 34	0. 30	0. 23	0. 78	0. 03	0. 12
C.V. (%)	8. 08	22.97	25.64	13.14	3. 39	17.65	36.36

Mean ± Standard Deviation within a column with different superscript letters are significantly different at $P < 0.05$ according to Duncan Multiple Range Test. CV = Co-efficient of Variation

Table 7: Mean Concentration of Heavy Metals (mg/kg) in Soil Samples at Different Depths in Fota, Gombi Local Government Areas.

Depth	Cr	Ni	Cu	Mn	Fe	Pd	Zn
0-10cm	0. 98±0.01^{a}	0. 77±0.01^{a}	1. 11±0.01^{a}	0. 86±0.01^{a}	20.01±0.06^{a}	0. 12±0.01^{a}	0. 19±0.01^{a}
11-20cm	1. 11±0.01^{b}	0. 93±0.01^{b}	1. 54±0.01^{b}	1. 10±0.01^{b}	20.23±0.01^{b}	0. 23±0.01^{b}	0. 22±0.01^{b}
21-30cm	1. 55±0.01^{c}	1. 19±0.03^{c}	1. 71±0.06^{c}	1. 16±0.01^{c}	21.11±0.01^{c}	0. 33±0.02^{c}	0. 42±0.01^{c}
Range	0. 97-1.56	0. 76-1.23	1. 11-1.78	0. 86-1.17	20.00-21.12	0. 12-0.35	0. 19-0.42
Grand Mean	1. 21	0. 96	1. 45	1. 04	20.45	0. 23	0. 28
Standard Deviation	0. 26	0. 19	0. 27	0. 14	0. 51	0. 09	0. 11
C.V. (%)	21.49	19.79	18.62	13.46	2. 49	39.13	39.29

Mean ± Standard Deviation within a column with different superscript letters are significantly different at $P < 0.05$ according to Duncan Multiple Range Test. CV = Co-efficient of Variation.

Table 8: Mean Concentration of Heavy Metals (mg/kg) in Soil Samples at Different Depths in Dzangola, Gombi Local Government Areas.

Depth	Cr	Ni	Cu	Mn	Fe	Pd	Zn
0-10cm	0. 65±0.03^{a}	0. 52±0.01^{a}	1. 63±0.01^{a}	0. 98±0.01^{a}	16.01±0.01^{a}	0. 00±0.00^{a}	0. 21±0.01^{a}
11-20cm	0. 73±0.01^{b}	0. 71±0.01^{c}	1. 76±0.02^{b}	1. 17±0.01^{b}	17.03±0.05^{b}	0. 13±0.01^{b}	0. 34±0.01^{b}
21-30cm	1. 07±0.01^{c}	0. 56±0.01^{b}	1. 81±0.01^{c}	1. 33±0.01^{c}	17.78±0.01^{c}	0. 23±0.01^{c}	0. 46±0.02^{c}
Range	0. 62-1.08	0. 52-0.71	1. 63-1.82	0. 97-1.34	16.0-17.79	0. 0-0.23	0. 21-0.47
Grand Mean	0. 82	0. 60	1. 74	1. 16	16.94	0. 12	0. 34
Standard Deviation	0. 19	0. 09	0. 08	0. 15	0. 77	0. 10	0. 11
C.V. (%)	23.17	15.00	4. 60	12.93	4. 55	83.33	32.35

Mean ± Standard Deviation within a column with different superscript letters are significantly different at $P < 0.05$ according to Duncan Multiple Range Test. CV = Co-efficient of Variation

Table 9: Mean Concentration of Heavy Metals (mg/kg) in Soil Samples at Different Depths in Amdur, Gombi Local Government Areas.

Depth	Cr	Ni	Cu	Mn	Fe	Pd	Zn
0-10cm	1. 16±0.01^{a}	0. 55±0.01^{c}	0. 89±0.01^{a}	1. 12±0.01^{a}	21.22±0.01^{a}	0. 22±0.01^{a}	0. 64±0.01^{c}
11-20cm	1. 55±0.02^{b}	0. 33±0.01^{b}	0. 96±0.01^{b}	1. 34±0.02^{b}	20.83±0.26^{a}	0. 25±0.01^{b}	0. 34±0.01^{a}
21-30cm	1. 75±0.03^{c}	0. 23±0.01^{a}	1. 12±0.01^{c}	1. 69±0.01^{c}	23.41±0.74^{b}	0. 26±0.01^{b}	0. 44±0.01^{b}

Depth	Cr	Ni	Cu	Mn	Fe	Pd	Zn
Range	1. 15-1.78	0. 23-0.56	0. 88-1.13	1. 12-1.70	20.6-24.23	0. 21-0.26	0. 34-0.64
Grand Mean	1. 49	0. 37	0. 99	1. 38	21.82	0. 24	0. 47
Standard Deviation	0. 26	0. 14	0. 10	0. 25	1. 27	0. 02	0. 13
C.V. (%)	17.45	37.84	10.10	18.12	5. 82	8. 33	27.66

Mean ± Standard Deviation within a column with different superscript letters are significantly different at $P < 0.05$ according to Duncan Multiple Range Test. CV = Co-efficient of Variation

Table 10: Mean Concentration of Heavy Metals (mg/kg) in Soil Samples at Different Depths in Gwallontabal Gombi Local Government Areas

Depth	Cr	Ni	Cu	Mn	Fe	Pd	Zn
0-10cm	1. 19±0.01^a	0. 23±0.02^a	0. 83±0.01^b	0. 45±0.01^a	16.20±0.03^a	0. 15±0.03^b	0. 66±0.01^a
11-20cm	1. 23±0.01^a	0. 47±0.01^b	0. 62±0.05^a	0. 83±0.02^b	18.67±0.41^b	0. 22±0.01^c	0. 77±0.01^b
21-30cm	1. 37±0.05^b	0. 55±0.02^c	1. 08±0.05^c	1. 12±0.01^c	19.16±0.01^c	0. 00±0.00^a	0. 99±0.01^c
Range	1. 18-1.43	0. 21-0.57	0. 44-0.46	0. 44-1.13	16.18-19.17	0. 00-0.23	0. 65-1.00
Grand Mean	1. 26	0. 42	0. 85	0. 80	18.01	0. 13	0. 80
Standard Deviation	0. 09	0. 15	0. 20	0. 29	1. 39	0. 10	0. 14
C.V. (%)	7. 14	35.71	23.53	36.25	7. 72	76.92	17.50

Mean ± Standard Deviation within a column with different superscript letters are significantly different at $P < 0.05$ according to Duncan Multiple Range Test. CV = Co-efficient of Variation

Table 11: Mean Concentration of Heavy Metals (mg/kg) in Soil Samples at Different Depths in Girei As Control

Depth	Cr	Ni	Cu	Mn	Fe	Pd	Zn
0-10cm	0. 23±0.01^a	0. 11±0.01^a	0. 22±0.01^a	0. 27±0.01^a	9. 79±0.01^a	0. 12±0.01^a	0. 27±0.01^a
11-20cm	0. 28±0.02^b	0. 13±0.01^b	0. 32±0.01^b	0. 31±0.01^b	11.62±0.02^b	0. 13±0.01^b	0. 43±0.01^b
21-30cm	0. 30±0.01^c	0. 14±0.01^c	0. 36±0.01^b	0. 45±0.02^c	14.09±0.01^c	0. 16±0.01^c	0. 54±0.01^c
Range	0. 22-0.31	0. 11-0.15	0. 21-0.23	0. 27-0.46	9. 78-14.10	0. 11-0.17	0. 27-0.54
Grand Mean	0. 27	0. 13	0. 30	0. 34	11.82	0. 14	0. 41
Standard Deviation	0. 03	0. 02	0. 06	0. 08	0. 12	0. 02	0. 12
C.V. (%)	11.11	15.38	20.00	23.53	1. 02	14.29	29.27

Mean ± Standard Deviation within a column with different superscript letters are significantly different at $P < 0.05$ according to Duncan Multiple Range Test. CV = Co-efficient of Variation

DISCUSSION

Heavy metals like cadmium (Cd), lead (Pb), arsenic (As), and mercury (Hg) are becoming more widely recognized as important contaminants in agricultural soils (Khan *et al* 2021). These components, introduced through industrial operations, mining, wastewater irrigation, and excessive pesticide use, endanger soil health, crop productivity, and human well-being (Das *et al.*,2024). Heavy metals change soil's physical and chemical properties, diminishing fertility and water retention capacity (Sompura *et al.*,2024). They also alter microbial populations that are crucial for nutrient cycling. According to Xie *et al.*, (2023) these metals interfere with enzyme activity and microbial diversity, resulting in compromised soil functions and decreased agricultural sustainability (Lahori et al.,2017),

Plants absorb heavy metals from contaminated soils, which can then accumulate in edible tissues. This bioaccumulation not only inhibits plant growth, but it also transfers hazardous substances into the food chain. According to Xie *et al.*, (2023), approximately 17% of worldwide croplands are contaminated, posing a hazard to food safety and increasing consumer risk of chronic diseases (Gao *et al.*,2021). Long-term exposure to heavy metals from soil-grown food has been related to major health problems including as renal damage, neurological diseases, and developmental delays (Wan *et al.*,2020). Vulnerable groups, particularly those living in rural areas, are at a higher risk since they rely on local agriculture (Jomova *et al.*,2024). Recent research has emphasized natural bioremediation strategies such as phytoremediation, microbial remediation, and soil amendments for reducing heavy metal toxicity (Devi *et al.,*2024). Research by Xie *et al.*, (2023), highlight the potential of employing hyperaccumulator plants and beneficial bacteria to restore soil health without adding additional contaminants.

CONCLUSION

Heavy metal concentrations in the soil of some locations in the Gombi and Hong Local Government Areas were mostly safe throughout the study period. The findings highlight the importance of continuous monitoring and regulation of environmental pollution to ensure food safety.Although trace metal concentrations such as iron, chromium, manganese, copper, nickel, cobalt, and zinc are within permissible limits, the presence of contaminants such as lead and paladium in certain areas necessitates further investigation.

To protect public health, it is critical to identify sources of pollution, evaluate alternative exposure pathways, and investigate the impact of environmental factors on food safety.Policymakers and stakeholders must work together to develop and implement more stringent regulations, oversight mechanisms, and corrective measures. Public awareness campaigns can help farmers and consumers understand potential risks and promote safe agricultural practices. Continuous research and strict environmental management are required to ensure that vegetables remain a safe and dependable source of nutrients.(Emam *et al.*,2021)

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