

Assessment of Heavy Metal Contamination in Agricultural Soils of Bauchi State, Nigeria: Sources, Spatial Distribution, and Risk Index Evaluation

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Abstract: This study investigates the concentration, spatial variability, and associated health risks of selected heavy metals (Cd, Cr, As, Pb, and Cu) in agricultural soils across the Northern Agricultural Zone of Bauchi State, Nigeria. Twenty-one composite soil samples were analyzed using standardized geochemical protocols, and results were benchmarked against international regulatory thresholds set by the USEPA and EU. The mean concentrations of Cd (14.97 mg/kg) and As (10.43 mg/kg) substantially exceeded permissible limits, indicating possible anthropogenic enrichment linked to agricultural inputs and artisanal mining. Spatial distribution maps revealed discrete hotspots, particularly in areas of high cultivation intensity and proximity to mineralized geological formations. Risk assessment metrics, including Annual Daily Intake (ADI) and Hazard Quotients (HQ), demonstrated elevated non-carcinogenic risks for children, particularly via oral ingestion of Cd and Cr. Inhalation data exhibited anomalous values likely due to computational artifacts, warranting further methodological review. Despite copper and lead levels remaining below regulatory limits, their cumulative ecological and physiological impacts remain relevant, especially under prolonged exposure scenarios. These findings underscore the urgent need for regulatory oversight of agrochemical practices, community-level health surveillance, and implementation of soil remediation strategies in vulnerable zones.

Keywords: Heavy Metals, Soil Contamination, Agricultural Soils, Health Risk Assessment, Hazard Quotient (HQ), Annual Daily Intake (ADI)

1 Introduction

The contamination of soils by heavy metals is an escalating concern worldwide, particularly in regions experiencing rapid industrialization and urban expansion. Metals such as cadmium, chromium, arsenic, lead, and copper are especially worrisome because of their persistence in the environment and potential to cause adverse health effects even at low concentrations [1, 2]. These contaminants often accumulate through human activities such as mining, industrial emissions, and the application of agrochemicals, creating long-lasting pollution challenges [3].

In Nigeria, expanding industrial activities and population growth have contributed to increasing levels of heavy metals in soils, especially in areas near industrial hubs and mining sites [4-6]. Despite these challenges, comprehensive local data on soil contamination and associated health risks

remain limited, which hinders the development of targeted remediation and regulatory frameworks [6].

Exposure to these metals occurs through several pathways, primarily ingestion, inhalation, and dermal contact, with children often being more vulnerable due to their behavior and physiology [7]. Health risk assessments using indicators like hazard quotients and indices help quantify potential non-carcinogenic and carcinogenic risks, guiding environmental management decisions [8, 9]. Given regional variations in contamination sources and exposure scenarios, localized studies are critical for accurate risk profiling [10].

This research focuses on assessing heavy metal concentrations in soil samples from Bauchi State, Nigeria, with a specific emphasis on evaluating health risks for children and adults through different exposure pathways. By comparing findings with previous studies in Nigeria and other regions, this study seeks to provide essential data to

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support environmental health protection and sustainable soil use policies.

2 Materials and Methods

Study Area

This investigation was carried out within the Northern Agricultural Zone of Bauchi State, located in northeastern Nigeria. This zone comprises several Local Government Areas (LGAs), including Gamawa, Zaki, Itas/Gadau, Jama'are, Giade, Shira, and Katagum. Geographically, this part of the state is bordered by Jigawa and Kano States to the northwest, Yobe State to the northeast, and Gombe State to the southeast, forming a strategically significant agricultural corridor with both ecological and socio-economic diversity [11].

The area lies within two major geological formations: the Chad Basin sediments and the Basement Complex terrain. The Chad Formation is predominantly composed of loosely packed sand, silt, gravel, and clay materials that influence the leaching and retention capacities of soils. Below this sedimentary layer lies the crystalline Basement Complex, which consists primarily of granites, gneisses, and schists, often associated with mineralization of substances like limestone, quartz, iron ore, and granite [12, 13].

Climatically, the zone experiences a tropical savanna climate, with distinct seasonal cycles. The dry season, extending from November to May, brings high temperatures, often exceeding 30°C . From June to October, the wet season sets in, contributing approximately 800 mm of annual rainfall. A cooler, dust-laden harmattan season also occurs between December and February, driven by dry winds from the Sahara Desert [14].

The economy of the study area is deeply rooted in agriculture. Farmers cultivate cereals and legumes such as millet, sorghum, maize, and cowpea, while also raising livestock like cattle, goats, sheep, and poultry. In addition to farming, small-scale mining activities targeting quartz, limestone, and iron ore are also prevalent, potentially contributing to metal pollution in soils [15]. Local market economies thrive on agricultural produce and artisanal crafts, reinforcing the community's dependence on natural resources.

The selection of this zone as the study location stems from its geological complexity, agricultural intensity, and presence of unregulated mining practices, all of which can influence the accumulation of toxic heavy metals in soils. The presence of Yankari Game Reserve and Wikki Warm Springs, although ecotouristic, underscores the environmental importance of this region.

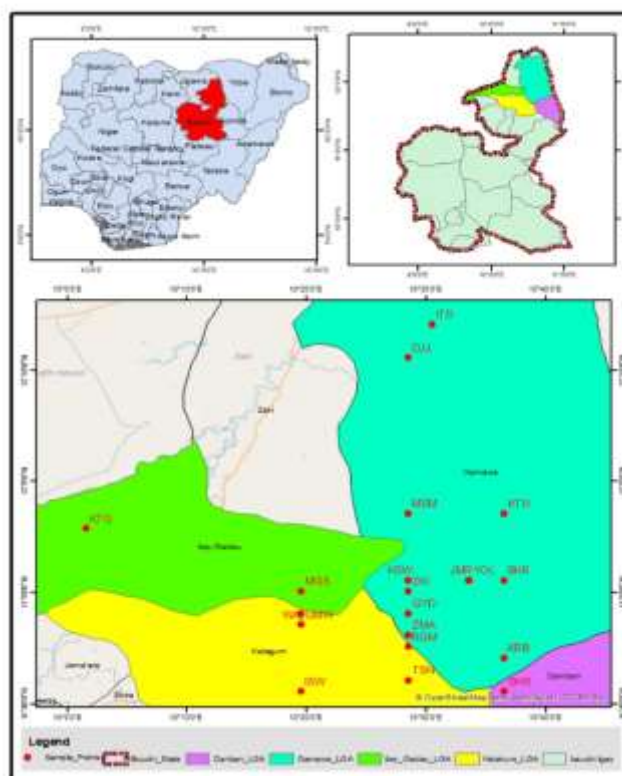


Fig. 1: Map of the study area and sampling locations.

Method of Soil Sample Collection

The Worldwide Positioning System (GPS) was used to take the coordinates of the sampling points within the study region. A total of twenty (21) soil samples were collected from farms in the selected locations in the study area. These soil samples were collected randomly from each sampling farms in the study area. The method applied in sampling is simple random sampling to achieve statistical sensitivity of sampling. A shovel was used to collect soil samples to a depth of about 10cm. The method applied in sampling is simple random sampling to achieve statistical sensitivity of sampling. Each composite soil sample

collected is expected to weigh about 400g of mass, separately collected and placed in a well-labeled polythene bag, and then sealed to avoid cross-contamination of the samples during transportation to the laboratory.

Method of Soil Sample Preparation

The soil samples were prepared through a process of open-air drying at room temperature to remove moisture, and would later be oven dried at a temperature of $500 - 1100^{\circ}\text{C}$ to obtain uniform weight. Stony soil samples were ground into a powdery form separately and singly using a mortar and pestle and sieved with a wire mesh with holes of thickness 0.5mm to obtain homogeneity of sample size. The

samples are expected to weigh approximately 300g. The samples for heavy metal concentration analysis were sent immediately to the laboratory, where Atomic Absorption spectrometry (AAS) analysis was carried out on the samples.

Method of Data Analysis

The data on heavy metal concentration from soil samples were analyzed. The hazard indices and soil to the presence of heavy metals and activity concentration, level, respectively, were determined to ascertain the potential risk associated with the samples. Using MS Excel for the data analysis.

Hazard indices: Determination of Heavy Metals Concentration Analysis.

The potential exposure pathways for heavy metals in contaminated soils are calculated based on recommendations by several U.S Environmental Protection Agency [16]. ADI (mg/kg-day) for the different pathways were calculated using the following exposure Equations (1) to (3) as prescribed by [17].

The ingestion of Heavy Metals through Soil (ADI_{ing}), Inhalation of Heavy Metals via Soil Particulates (ADI_{inh}), and Dermal Contact with Soil (ADI_{derm}) are given in equations (2), (3), and (4), respectively.

$$ADI_{ing} = \frac{C \times IR \times EF \times ED \times CF}{BW \times AT} \quad (1)$$

Where ADI_{ing} is the average daily intake of heavy metals ingested from soil in mg/kg-day, C is the concentration of heavy metal in mg/kg for soil. IR in mg/day is the ingestion rate, EF in days/year is the exposure frequency, ED is the exposure duration in years, BW is the body weight of the exposed individual in kg, and AT is the period over which the dose is averaged in days. CF is the conversion factor in kg/mg.

$$ADI_{inh} = \frac{C \times IR_{air} \times EF \times ED}{BW \times AT \times PEF} \quad (2)$$

Where ADI_{inh} is the average daily intake of heavy metals inhaled from soil in mg/kg-day, CS is the concentration of heavy metal in soil in mg/kg, IR_{air} is the inhalation rate in m³/day, and PEF is the particulate emission factor in m³/kg. EF, ED, BW, and AT are as defined earlier in Equation (1).

$$ADI_{dems} = \frac{C \times S \times F \times E \times A \times F \times A \times B \times S \times E \times F \times E \times D \times C \times F}{BW \times AT} \quad (3)$$

Where ADI_{dems} is the exposure dose via dermal contact in mg/kg/day. C_s is the concentration of heavy metal in soil in mg/kg, SA is the exposed skin area in cm², FE is the fraction of the dermal exposure ratio to soil, AF is the soil adherence factor in mg/cm², and ABS is the fraction of the

applied dose absorbed across the skin. EF, ED, BW, CF, and AT are as defined earlier in Equation (1). Table 2 shows the exposure parameters used for the health risk assessment for the standard residential exposure scenario through different exposure pathways.

Table 1: Exposure parameter used for the health risk assessment through different exposure pathways for soil [18]

Parameter	Unit	Child	Adult
Body weight (BW)	Kg	15	70
Exposure Frequency (EF)	Days/years	350	350
Exposure duration (ED)	Years	6	30
Ingestion rate (IR)	mg/day	200	100
Inhalation rate (IR_{air})	m ³ /day	10	20
Skin surface area (SA)	cm ²	2100	5800
Soil adherence factor (AF)	mg/cm ²	0.2	0.07
Dermal absorption factor (ABS)	None	0.1	0.1
Dermal exposure ratio (FE)	None	0.61	0.61
Particulate emission factor (PEF)	m ³ /kg	1.3x10 ⁹	1.3x10 ⁹
Conversion factor (CF)	kg/mg	10 ⁻⁶	10 ⁻⁶
Average time (AT) for carcinogens	Days	365x70	365x70
Average time (AT) for non-carcinogens	Days	365xED	365xED

Non- Non-Carcinogenic Risk Assessment

Non-carcinogenic hazards are characterized by a term called hazard quotient (HQ). HQ is a unitless number that is expressed as the probability of an individual suffering an adverse effect. It is defined as the quotient of ADI or dose divided by the toxicity threshold value, which is referred to as the chronic reference dose (RfD) in mg/kg-day of a specific heavy metal, as shown in Equation (3);

$$HQ = \frac{ADI}{RFD} \quad (4)$$

For n number of heavy metals, the non-carcinogenic effect to the population is a result of the summation of all the HQs due to individual heavy metals. This is considered to be another term called the Hazard Index (HI) as described by the USEPA document [17]. Equation (4) shows the mathematical representation of this parameter:

$$HI = \sum_{k=1}^n HQ_k = \sum_{k=1}^n \frac{ADI_k}{RfD_k} \quad (5)$$

Where HQ_k , ADI_k , and RfD_k are values of heavy metal k . If the HI value is less than one, the exposed population is unlikely to experience adverse health effects. If the HI value exceeds one, then there may be concern for potential non-carcinogenic effects [17].

Carcinogenic Risk Assessment

For carcinogens, the risks are estimated as the incremental probability of an individual developing cancer over a lifetime as a result of exposure to the potential carcinogen. The equation for calculating the excess lifetime cancer risk is:

$$Risk_{pathway} = \sum_{k=1}^n ADI_k CSF_k \quad (6)$$

where Risk is a unitless probability of an individual developing cancer over a lifetime. ADI_k (mg/kg/day) and CSF_k (mg/kg/day)⁻¹ are the average daily intake and the cancer slope factor, respectively, for the k th heavy metal, for n number of heavy metals. The slope factor converts the estimated daily intake of the heavy metal, averaged over a lifetime of exposure, directly to the incremental risk of an individual developing cancer.

The total excess lifetime cancer risk for an individual is finally calculated from the average contribution of the individual's heavy metals for all the pathways using the following equation:

$$Risk_{(total)} = Risk_{(ing)} + Risk_{(inh)} + Risk_{(dems)} \quad (7)$$

where $Risk_{(ing)}$, $Risk_{(inh)}$, and $Risk_{(dermal)}$ are risk contributions through ingestion, inhalation, and dermal pathways.

Both non-carcinogenic and carcinogenic risk assessment of heavy metals are calculated using RfD and CSF values derived largely from the Department of Environmental Affairs (South Africa) and USEPA, as shown in Table 3.2.

3 Results and Discussion

The results of Heavy Metals Concentration Level in mg/kg of Soil Samples collected from the Study Area are presented in Figure 4, respectively. The levels of Cd, Cr, As, Pb, and Cu samples collected are determined

The analysis of soil samples from 21 locations in the northern agricultural zone of Bauchi State revealed elevated concentrations of heavy metals, notably Cd (14.97 mg/kg), Cr (18.70 mg/kg), As (10.43 mg/kg), Pb (16.97 mg/kg), and Cu (30.43 mg/kg) (see Figure 2). These levels raise environmental and health concerns when compared with international standards.

Cadmium levels were especially high (14.97 mg/kg), exceeding both EU (3 mg/kg) and USEPA (0.3 mg/kg) thresholds [19]. Such contamination is likely linked to

phosphate-based fertilizers, which are known Cd sources in farmlands [20]. Arsenic with an average of 10.43 mg/kg levels also surpassed safety limits (USEPA: 0.68 mg/kg), posing significant risks due to its persistence and carcinogenic nature [21].

While average lead levels (16.97 mg/kg) remained below the USEPA critical limit (400 mg/kg), they exceeded natural background values, likely due to informal mining and traffic emissions [22, 23]. Copper concentrations (peaked at 72.68 mg/kg and averaged 30.43 mg/kg), though within regulatory limits (USEPA: 3100 mg/kg; EU: 140 mg/kg), may still impair soil biological activity at elevated levels [24].

Chromium concentrations averaged 18.70 mg/kg, with a peak of 44.34 mg/kg—within permissible limits, yet the potential presence of toxic Cr(VI) raises ecological concerns [25].

Comparative studies highlight regional variability. For example, Cd levels reported by Adebayo and Olayinka [26] in southwestern Nigeria were lower (<5 mg/kg), suggesting that local agricultural and mining practices may intensify contamination in Bauchi. Conversely, soils in Zamfara's mining areas showed even higher levels [27], pointing to broader anthropogenic influences.

Spatial patterns suggest certain locations (e.g., ITSS, JMRS, GMWS) act as contamination hotspots, likely due to land use intensity or proximity to pollutant sources. These findings support the urgent need for remediation strategies like phytoremediation and organic amendments [28]. Additionally, regular soil monitoring and stricter agrochemical regulation are essential to protect soil health and agricultural sustainability in the region.

The findings indicate that ingestion is the primary exposure route for heavy metals in children, with Cd, Cu, and Pb showing the most significant intake levels. Adults, while less affected, still demonstrate concerning exposure to Cu and Cd, particularly via dermal contact. The inhalation data requires validation due to evident anomalies. These results underscore the urgent need for soil remediation, public health monitoring, and pollution source control in the study area to mitigate long-term health risks, especially among children. This study evaluated the Mean Annual Daily Intake (ADI) of five heavy metals (Cd, Cr, As, Pb, Cu) through ingestion, inhalation, and dermal pathways in children and adults (see Table 3).

Following ingestion exposure, Children exhibited notably higher ADIs than adults, consistent with their physiological vulnerability and higher intake relative to body weight [29, 30]. Cu (3.89×10^{-3} mg/kg/day) and Pb (2.10×10^{-3} mg/kg/day) were the most significant, surpassing values from similar regions [31]. Adults had lower ADIs, with Cu (4.17×10^{-4} mg/kg/day) within safe limits [32], although Cd levels approached risk thresholds [33].

Reported inhalation ADIs were implausibly high (e.g., As: 4.85×10^{18} mg/kg/day), indicating likely unit or input errors. These values greatly exceed standard references [34], requiring data review and correction.

Both age groups showed comparable dermal ADIs, with Cu being highest overall. Children had elevated Pb dermal exposure (2.69×10^{-4} mg/kg/day), likely due to behavioral

Compared to studies in regions like Southwestern Nigeria [36] and Jebba [6], this study recorded higher ADIs, especially for Cd and Cu, suggesting localized pollution sources. Ingestion remains the primary exposure route, particularly for children. Adults face moderate risk, mainly via dermal contact. The inhalation data must be revised. These findings underscore the need for remediation, monitoring, and stricter pollution control.

Table 2: Reference Doses (RfD) and Cancer Slope Factors (CSF) for the different Heavy Metals [17, 18].

Heavy metal	Oral RfD	Dermal RfD	Inhalation RfD	Oral CSF	Dermal CSF	Inhalation CSF
As	3.0×10^{-4}	3.0×10^{-4}	3.0×10^{-4}	1.5	1.5	15
Pb	3.6×10^{-3}	NA	NA	8.5×10^{-3}	NA	4.2×10^{-2}
Cd	5.0×10^{-4}	5.0×10^{-4}	5.7×10^{-5}	NA	NA	6.3
Ni	2.0×10^{-2}	5.6×10^{-3}	NA	NA	NA	NA
Zn	3.0×10^{-1}	7.5×10^{-2}	NA	NA	NA	NA
Cu	4×10^{-2}	NA	NA	NA	NA	NA
Cr	3×10^{-3}	NA	NA	5×10^{-1}	NA	NA

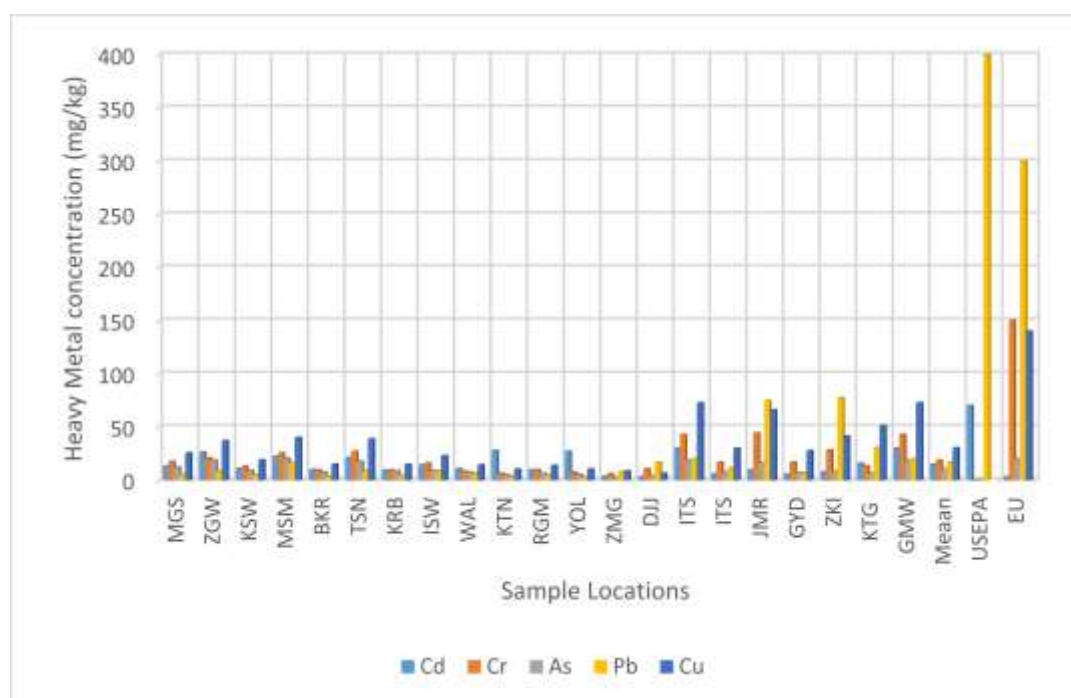


Fig. 2: Comparison of Heavy Metals Concentration Level in mg/kg of Soil Samples collected from the Study Area

factors. Cu's bioavailability in soils supports its prominence [29, 35], while As also poses dermal risks due to its skin permeability [33].

Table 3: Mean Annual Daily Intake (ADI) of Heavy Metals

Receptor Pathway	Mean Annual Daily Intake (mg.kg ⁻¹ .day ⁻¹)		
	Cd	Cr	As
Ingestion Child	1.91E-03	2.39E-03	1.33E-03
Ingestion Adult	2.05E-04	2.56E-04	1.43E-04
Inhalation Child	6.31E-11	7.88E-11	4.85E+18
Inhalation Adult	1.49E+10	1.26E+10	1.04E+19

Table 4 summarizes average Hazard Quotient (HQ) values via ingestion, inhalation, and dermal exposure for children and adults in the study area. An HQ above 1 signals potential health concerns [19].

Child ingestion HQs for cadmium ($Cd = 3.83$) and chromium ($Cr = 2.39$) exceed the safe limit, suggesting significant risk. This aligns with findings from Malik et al. [37], who reported HQ values above 2 for Cd in industrial–agricultural soils. Chromium’s elevated child HQ exceeds the 1.5 threshold noted in Zhang et al. [38]. In contrast, HQs for arsenic (As), lead (Pb), and copper (Cu) were below 0.001, suggesting no immediate non-carcinogenic concern via ingestion.

Adult ingestion HQs remain below 1 for all metals, with the highest for Cr (0.256), indicating negligible risk for older populations. This differential between age groups mirrors results from Li et al. [29], who attributed higher child exposure to greater soil ingestion per body weight.

Child inhalation HQs for Cd (1.11×10^{-15}) and Cr (2.63×10^{-8}) are in expected ranges; however, values for As, Pb, and Cu are extremely high (10^{15} – 10^{19}), likely due to calculation or unit errors. In properly conducted studies, inhalation HQs remain well below 1 for all ages in non-industrial regions (Liang et al., 2024). The adult inhalation HQ values (10^{19} – 10^{21}) are similarly implausible, underscoring a need to re-evaluate calculations or unit conversions.

Dermal HQs remain below 1 for both children and adults. Chromium shows the highest dermal HQ (0.15–0.16), reflecting its relatively higher dermal absorption potential [39]. Other metals registered negligible dermal HQ values (<0.0003), consistent with prior observations by Wang et al. [40] regarding low skin penetration of heavy metals in contaminated soils.

Overall, ingestion presents the primary non-carcinogenic risk for children, driven by Cd and Cr. This pattern is echoed in comparable investigations of soil contamination in rural agricultural settings [29]. Before concluding, troubleshooting inhalation values is essential.

Table 5 presents calculated risk values across three primary exposure routes (ingestion, inhalation, dermal contact) for children and adults, focusing on five heavy metals: Cd, Cr, As, Pb, and Cu. Summing risk scores across all metals and exposure routes highlights ingestion as the dominant pathway, especially for children.

Child ingestion risk is highest for arsenic (0.200), followed by cadmium (0.184) and copper (0.004), culminating in a total ingestion risk of 0.392. These values surpass their adult equivalents (0.152 total), particularly for arsenic (child: 0.200 vs. adult: 0.021), due to children's higher exposure rates per unit body weight. This aligns with observations in Punjab, Pakistan, where arsenic ingestion risk among children exceeded adult estimates by nearly tenfold [41–48].

The inhalation pathway results are invalid, featuring astronomically high values ($>10^{19}$) for adults and exaggerations in children. Such magnitudes are physically

implausible and far exceed typical environmental exposure levels, which are generally $\leq 10^{-3}$ for non-industrial soils [38]. This discrepancy indicates likely calculation or data entry errors that must be rectified before drawing meaningful interpretations.

Dermal exposure risks are low across both demographics. Children’s total dermal risk is 0.027, while adults’ is 0.027, primarily driven by arsenic absorption, likely due to its skin permeability. These findings mirror those of Li et al. [29], who reported dermal risks below 0.05 for similar metals in agricultural areas. The similarity between child and adult dermal risks is expected, given the shared exposure context and only slight variation in body weight and surface area parameters [49].

4 Conclusions

The present investigation reveals significant contamination of agricultural soils in northern Bauchi State with heavy metals, particularly cadmium and arsenic, exceeding international safety thresholds and posing tangible risks to environmental and human health. The elevated levels of Cd and Cr in child exposure pathways point to ingestion as the dominant route of concern, exacerbated by localized factors such as fertilizer usage and unregulated mining. Although other metals like Cu and Pb remain within global acceptable ranges, their potential for bioaccumulation and long-term toxicity cannot be dismissed. Spatial analysis confirms heterogeneous contamination, with specific sampling points emerging as pollution hotspots likely driven by both anthropogenic and geogenic factors. The unusually high inhalation HQ values observed for several metals suggest inconsistencies in exposure modeling that require methodological refinement. Overall, the data highlight a pressing need for multi-pronged interventions comprising soil quality monitoring, public awareness, regulatory control of agro-inputs, and deployment of remediation technologies to mitigate ongoing exposure and prevent future soil degradation in this vital agricultural corridor. Strengthening institutional capacity and policy frameworks will be critical in translating scientific insights into sustainable land management practices in the region.

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