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Health Risk Associated with Heavy Metals Contamination in Soil and Rice: A Quantitative Assessment of Non-Carcinogenic and Carcinogenic Risk

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Abstract

Heavy metal contamination in agricultural soils and rice is a critical exposure pathway, raising concerns for both non-carcinogenic and carcinogenic health effects. This study assessed cadmium (Cd), lead (Pb), arsenic (As), chromium (Cr), and copper (Cu) in soils and rice from selected sites, applying U.S. EPA guidelines to evaluate risks through ingestion, inhalation, and dermal contact for adults and children. Results showed that while most adult exposure levels were within acceptable limits, children consistently exhibited higher hazard quotients (HQs) and hazard indices (HIs), especially for Cd and Cr, indicating greater vulnerability. Incremental Lifetime Cancer Risk (ILCR) values for Cd and As often exceeded safety thresholds, pointing to significant carcinogenic potential. Contamination levels varied with soil properties, farming practices, and rice varieties, with acidic soils enhancing Cd mobility. Ingestion, primarily from rice consumption, was identified as the dominant exposure pathway, whereas dermal contact posed minimal risks. The findings

emphasize the need for targeted monitoring, stricter regulations, and cultivation of rice varieties with reduced metal uptake. Overall, the study underscores the importance of integrating environmental management and agricultural practices to minimize heavy metal exposure and safeguard public health

Keywords: Heavy metal contamination, Agricultural soils, Rice grains, Health risk assessment, Cadmium (Cd), Arsenic (As), Non-carcinogenic effects, Carcinogenic potential

Introduction

Heavy metal contamination in agricultural soils and food crops, particularly rice, has become a major environmental and public health concern (Yu et al., 2025). Although elements such as cadmium (Cd), lead (Pb), arsenic (As), and mercury (Hg) occur naturally in the Earth's crust, their concentrations in the environment have been greatly increased by human activities (Balali-Mood et al., 2021). Industrialization, mining, improper waste management, and the intensive use of fertilizers and pesticides have all contributed to the accumulation of heavy metals in soil. This contamination not only disrupts soil quality but also promotes the uptake of metals by food crops, ultimately introducing them into the human food chain (Wan et al., 2024)

Rice (*Oryza sativa* L.) is a staple food for more than half of the global population, particularly in Asian countries, where it provides a significant share of daily caloric and nutritional intake. However, contamination of rice with heavy metals represents a direct and critical pathway of human exposure (Zhang et al., 2024). Chronic consumption of rice contaminated with heavy metals, even at low concentrations, has been linked to serious health effects ranging from neurological disorders and organ damage to various forms of cancer (Zakaria et al., 2021). The risks are further heightened by the long-term and consistent nature of rice consumption, underscoring the importance of comprehensive assessments of its potential health impacts (Khatri et al., 2024).

Quantitative health risk assessment is a systematic approach used to estimate the likelihood of adverse health effects in populations exposed to environmental contaminants (Fjeld et al., 2023). The process generally involves four main steps: hazard identification, dose–response assessment, exposure assessment, and risk characterization (Rigaud et al., 2024). In the context of heavy metals, risks are typically classified into two categories: non-carcinogenic and carcinogenic. Non-carcinogenic risks are assessed using the Hazard Quotient (HQ) and Hazard Index (HI), which compare estimated exposure levels against established reference doses (Shetty et al., 2024). Carcinogenic risks, on the other hand, are evaluated using the Incremental Lifetime Cancer Risk (ILCR), a measure that estimates the probability of developing cancer over a lifetime due to contaminant exposure (Zhao & You, 2021). Despite growing awareness and research on

heavy metal contamination, there remains a critical need for comprehensive quantitative assessments that address both non-carcinogenic and carcinogenic risks, particularly along the soil-to-rice exposure pathway (Sharma, Kaur, & Nagpal, 2021). Many existing studies focus on individual metals or specific geographic regions, leaving important gaps in understanding the broader implications and cumulative health risks associated with multiple contaminants (Huda et al., 2024).

Moreover, variations in heavy metal concentrations across different regions, soil types, and rice varieties, combined with diverse dietary habits, underscore the need for a robust and adaptable assessment framework (Vasilachi, Stoleru, & Gavrilescu, 2023). This manuscript aims to provide a quantitative evaluation of both non-carcinogenic and carcinogenic health risks associated with heavy metal contamination in soils and rice (Kanu et al., 2020). It will compile existing data on heavy metal levels, outline methodologies for assessing health risks, and offer a comprehensive overview of potential impacts on human populations (Tong et al., 2025). By integrating data from multiple sources and applying established risk assessment models, this study highlights the urgency of monitoring and mitigating heavy metal contamination to protect public health (Chen & Ding, 2023). The findings are expected to enhance understanding of associated risks and provide valuable guidance for policymakers and public health officials in developing effective strategies for food safety and environmental protection (Zhou et al., 2021).

Study Area and Sampling

There are three (3) Agricultural zones in Bauchi State: western zone consist of Bauchi, Toro, Bogoro, Kirfi, Alkaleri, Tafawa Balewa, and Dass, while Northern zone consist of Gamawa, Zaki, Itas/Gadau, Jama,are, Giade, Shira and Katagum, the Central zone consist of Warji, Ganjuwa, Darazo, Dambam, Misau and Ningi local Government Area respectively. Bauchi north agricultural zone as the study area is bordered by Jigawa state, and Yobe state, State respectively. The study area has an existing network of roads linking all rural areas and major towns.

Method of Soil and Plant Sample Preparation

The soil and plant 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 500C - 1100C to obtain uniform weight. Stony soil samples and plant samples were grinded into powdery form separately and singly using 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 of heavy metal concentration from soil s amples were analyzed. The hazard indices and soil to the presence of heavy metals and activity concentration, level respectively were determine 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 (U.S.EPA, 2015). ADI (mg/kg-day) for the different pathways were calculated using the following exposure Equations (1) to (3) as prescribed by (U.S. EPA, 1989).

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 equation (2), (3), and (4) respectively.

$$ADI_{ing} = \frac{CxIRxEFxEDxCF}{BWxAT}$$

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, AT is the time period over which the dose is averaged in days. CF is the conversion factor in kg/mg.

$$ADI_{inh} = \frac{CxIR_{air}xEFxED}{BWxATxPEF} \quad (2)$$

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 m^3/day, PEF, is the particulate emission factor in m^3/kg. EF, ED, BW and AT are as defined earlier in Equation (1).

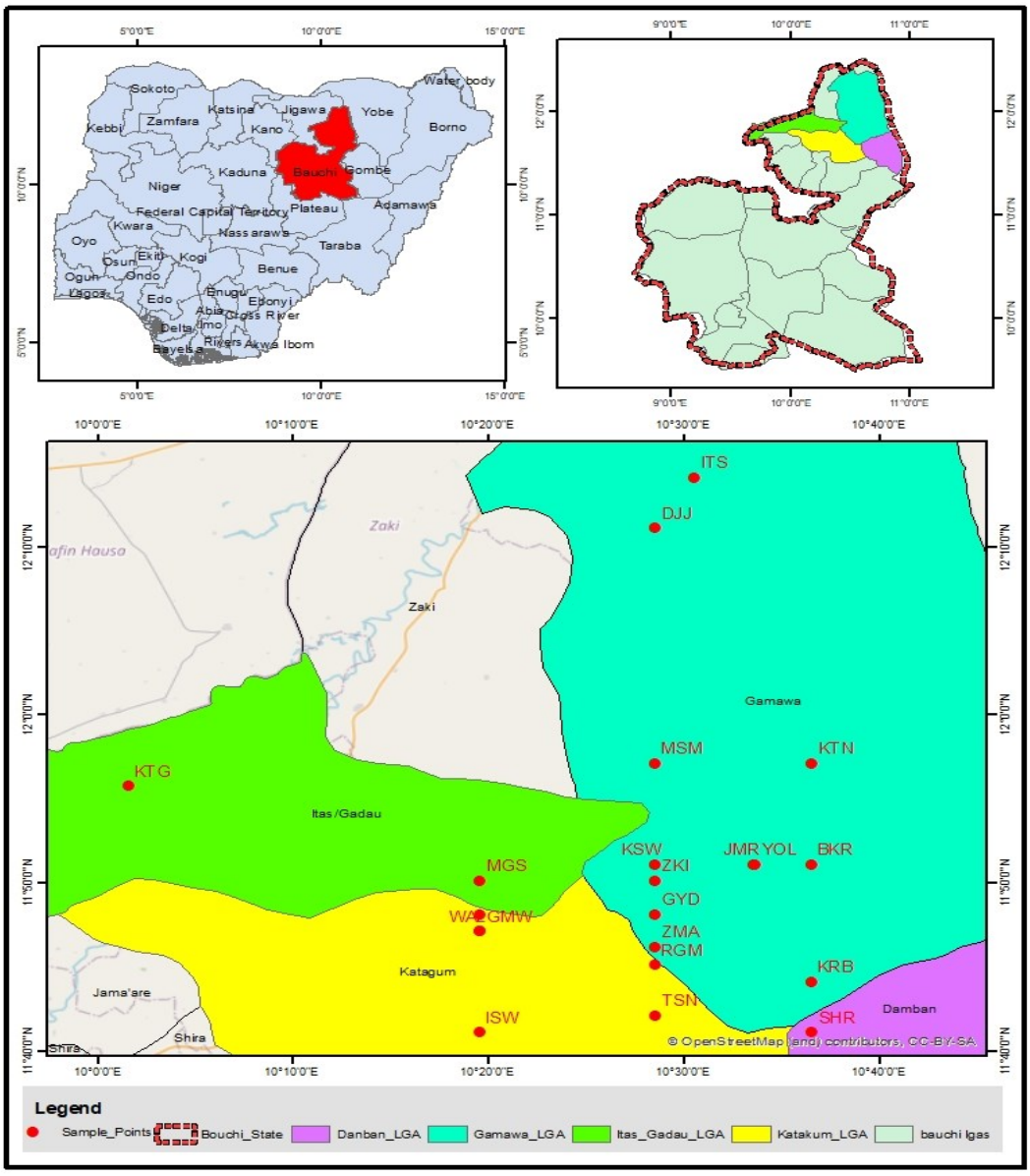
$$ADI_{dems} = \frac{CxSAxFExAFxABSxEFxEDxCF}{BWxAT} \quad (3)$$

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 exposed skin area in cm^2, FE is the fraction of the dermal exposure ratio to soil, AF is the soil adherence factor in mg/cm2, 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 standard residential exposure scenario through different exposure pathways.

Instrumentation

Atomic Absorption Spectrometry (AAS) comprises a hollow cathode lamp (HCL) serving as the element-specific radiation source, complemented by a background correction system—

such as deuterium-lamp or Zeeman effect—to mitigate interferences. The sample is introduced via a nebulizer and spray chamber that aerosolize liquid samples, which are then atomized (typically via flame or graphite furnace) to produce free ground-state atoms. The radiation from the source passes through the atomic vapor; a monochromatic isolates the analyses' characteristic wavelength while rejecting stray and background light. A photomultiplier tube or photodiode detector converts the transmitted light into an electrical signal, which is processed and displayed by a read-out/data acquisition system to yield absorbance and analyze concentration. Recent advances, including high-resolution continuum source AAS (HR-CS-AAS), optimized furnace design, and improved sample preparation strategies, have enhanced analytical performance in environmental and biological applications (Butcher, 2021; Butcher, 2023; Evans et al., 2021; Wu et al., 2024).



Non- Carcinogenic Risk Assessment

Non-carcinogenic hazards are characterized by a term called hazard quotient (HQ). HQ is a unit less 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 (4);

$$\boldsymbol{HQ = \frac{ADI}{RFD}}$$

For n number of heavy metals, the non-carcinogenic effect to the population is as 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 USEPA document (U.S. E.P.A, 1989; Caspah, 2016). Equation (5) shows the mathematical representation of this parameter:

$$\boldsymbol{HI = \sum_{k=1}^{n} HQ_k = \sum_{k=1}^{n} \frac{ADI_k}{RfD_k}}$$

where HQk, $ADIk$ and $RfDk$ 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 (U.S. EPA, 1989; Caspah, 2016).

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:

$$\boldsymbol{Risk_{pathway} = \sum_{k=1}^{n} ADI_k CSF_k}$$

Where Risk is a unit less 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 incremental risk of an individual developing cancer (U.S. Environmental Protection Agency, 1989; Caspah, 2016).

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

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

where $Risk_{(ing)}$, $Risk_{(inh)}$, and $Risk_{(dermal)}$are risks 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

Results and discussion

Table1: Adult Ingestion Annual Daily Intake (mg.kg-1.day-1) of soil sample collected from the study area

Sample Code	Adult Ingestion Annual Daily Intake ($mg.kg^{-1}.day^{-1}$)				
	Cd	Cr	As	Pb	Cu
MGSS	1.81E-04	2.41E-04	1.67E-04	7.84E-05	3.50E-04
ZGWS	3.58E-04	2.85E-04	2.61E-04	1.17E-04	5.07E-04
KSWS	1.49E-04	1.76E-04	1.23E-04	7.28E-05	2.61E-04
MSMS	3.05E-04	3.51E-04	2.79E-04	2.19E-04	5.49E-04
BKRS	1.36E-04	1.31E-04	1.05E-04	5.69E-05	2.06E-04
TSNS	2.91E-04	3.70E-04	2.43E-04	1.21E-04	5.31E-04
KRBS	1.30E-04	1.32E-04	1.18E-04	6.11E-05	2.04E-04
ISWS	1.96E-04	2.19E-04	1.25E-04	1.20E-04	3.15E-04
WALS	1.46E-04	1.14E-04	1.04E-04	8.69E-05	1.96E-04
KTNS	3.80E-04	8.80E-05	7.22E-05	4.85E-05	1.42E-04
RGMS	1.33E-04	1.35E-04	8.87E-05	6.25E-05	1.89E-04
YOLS	3.71E-04	1.00E-04	7.21E-05	3.68E-05	1.43E-04
ZMGS	4.88E-05	8.34E-05	3.34E-05	1.08E-04	1.17E-04
DJJS	4.23E-05	1.45E-04	5.79E-05	2.29E-04	8.98E-05
ITSS	4.12E-04	5.86E-04	2.57E-04	2.74E-04	9.96E-04
JTSS	7.91E-05	2.30E-04	1.09E-04	1.57E-04	4.10E-04
JMRS	1.33E-04	6.07E-04	2.22E-04	1.02E-03	9.03E-04
GYDS	7.56E-05	2.31E-04	9.76E-05	1.00E-04	3.79E-04
ZKIS	1.08E-04	3.88E-04	1.18E-04	1.06E-03	5.67E-04
KTGS	2.17E-04	1.81E-04	9.23E-05	4.23E-04	7.03E-04
GMWS	4.12E-04	5.86E-04	2.57E-04	2.74E-04	9.96E-04
Mean	**2.05E-04**	**2.56E-04**	**1.43E-04**	**2.25E-04**	**4.17E-04**
EFSA Standard	**3.60E-04**	**0.30**	**NA**	**1.50E-03**	**0.1**

Table 2: Child Inhalation Annual Daily Intake ($mg.kg^{-1}.day^{-1}$) of soil sample collected from the study area

Sample code	Child Inhalation Annual Daily Intake ($mg.kg^{-1}.day^{-1}$)				
	Cd	Cr	As	Pb	Cu
MGSS	5.58E-11	7.41E-11	5.67E+18	2.66E+18	1.19E+19
ZGWS	1.10E-10	8.78E-11	8.86E+18	3.97E+18	1.72E+19
KSWS	4.59E-11	5.42E-11	4.18E+18	2.47E+18	8.86E+18
MSMS	9.38E-11	1.08E-10	9.48E+18	7.45E+18	1.87E+19
BKRS	4.19E-11	4.02E-11	3.57E+18	1.93E+18	7.01E+18
TSNS	8.94E-11	1.14E-10	8.23E+18	4.09E+18	1.80E+19
KRBS	4.01E-11	4.06E-11	4.00E+18	2.08E+18	6.92E+18

Sample code	Child Inhalation Annual Daily Intake ($mg.kg^{-1}.day^{-1}$)				
	Cd	Cr	As	Pb	Cu
ISWS	6.04E-11	6.75E-11	4.23E+18	4.08E+18	1.07E+19
WALS	4.48E-11	3.51E-11	3.53E+18	2.95E+18	6.65E+18
KTNS	1.17E-10	2.71E-11	2.45E+18	1.65E+18	4.82E+18
RGMS	4.11E-11	4.15E-11	3.01E+18	2.12E+18	6.42E+18
YOLS	1.14E-10	3.09E-11	2.45E+18	1.25E+18	4.84E+18
ZMGS	1.50E-11	2.57E-11	1.13E+18	3.68E+18	3.96E+18
DJJS	1.30E-11	4.47E-11	1.96E+18	7.76E+18	3.05E+18
ITSS	1.27E-10	1.80E-10	8.73E+18	9.30E+18	3.38E+19
JTSS	2.43E-11	7.08E-11	3.70E+18	5.32E+18	1.39E+19
JMRS	4.09E-11	1.87E-10	7.53E+18	3.47E+19	3.07E+19
GYDS	2.33E-11	7.11E-11	3.31E+18	3.40E+18	1.29E+19
ZKIS	3.32E-11	1.19E-10	3.99E+18	3.60E+19	1.92E+19
KTGS	6.68E-11	5.57E-11	3.13E+18	1.44E+19	2.39E+19
GMWS	1.27E-10	1.80E-10	8.73E+18	9.30E+18	3.38E+19
Mean	6.31E-11	7.88E-11	4.85E+18	7.64E+18	1.42E+19
Max	1.27E-10	1.87E-10	9.48E+18	3.60E+19	3.38E+19
Min	1.30E-11	2.57E-11	1.13E+18	1.25E+18	3.05E+18

Table 3: Adult Inhalation Annual Daily Intake ($mg.kg^{-1}.day^{-1}$) of soil samples collected from the study area

	Adult Inhalation Annual Daily Intake ($mg.kg^{-1}.day^{-1}$)				
	Cd	Cr	As	Pb	Cu
MGSS	1.32E+19	1.75E+19	1.22E+19	5.70E+18	2.55E+19
ZGWS	2.60E+19	2.08E+19	1.90E+19	8.52E+18	3.69E+19
KSWS	1.08E+19	1.28E+19	8.95E+18	5.29E+18	1.90E+19
MSMS	2.22E+19	2.56E+19	2.03E+19	1.60E+19	4.00E+ 19
BKRS	9.90E+18	9.51E+18	7.65E+18	4.14E+18	1.50E+19
TSNS	2.11E+19	2.69E+19	1.76E+19	8.77E+18	3.86E+19
KRBS	9.49E+18	9.59E+18	8.58E+18	4.45E+18	1.48E+19
ISWS	1.43E+19	1.60E+19	9.06E+18	8.74E+18	2.29E+19
WALS	1.06E+19	8.29E+18	7.55E+18	6.32E+18	1.43E+19
KTNS	2.77E+19	6.40E+18	5.26E+18	3.53E+18	1.03E+19
RGMS	9.71E+18	9.81E+18	6.45E+18	4.55E+18	1.38E+19
YOLS	2.70E+19	7.31E+18	5.25E+18	2.68E+18	1.04E+19
ZMGS	3.55E+18	6.07E+18	2.43E+18	7.89E+18	8.49E+18
DJJS	3.08E+18	1.06E+19	4.21E+18	1.66E+19	6.53E+18
ITSS	3.00E+19	4.26E+19	1.87E+19	1.99E+19	7.24E+19
JTSS	5.75E+18	1.67E+19	7.93E+18	1.14E+19	2.98E+19
JMRS	9.68E+18	4.42E+19	1.61E+19	7.44E+19	6.57E+19
GYDS	5.50E+18	1.68E+19	7.10E+18	7.29E+18	2.76E+19

	Adult Inhalation Annual Daily Intake (mg.kg^{-1}.day^{-1})				
	Cd	**Cr**	**As**	**Pb**	**Cu**
ZKIS	7.86E+18	2.82E+19	8.55E+18	7.71E+19	4.12E+19
KTGS	1.58E+19	1.32E+19	6.71E+18	3.08E+19	5.11E+19
GMWS	3.00E+19	4.26E+19	1.87E+19	1.99E+19	7.24E+19
Mean	1.49E+19	1.86E+19	1.04E+19	1.64E+19	3.03E+19
Max	3.00E+19	4.42E+19	2.03E+19	7.71E+19	7.24E+19
Min	3.08E+18	6.07E+18	2.43E+18	2.68E+18	6.53E+18

Table 4: Child Dermal Annual Daily Intake (mg.kg^{-1}.day^{-1}) of soil samples collected from the study area

Sample code	Child Dermal Annual Daily Intake (mg.kg^{-1}.day^{-1})				
	Cd	**Cr**	**As**	**Pb**	**Cu**
MGSS	2.17E-04	2.88E-04	2.00E-04	9.37E-05	4.19E-04
ZGWS	4.28E-04	3.41E-04	3.12E-04	1.40E-04	6.06E-04
KSWS	1.78E-04	2.11E-04	1.47E-04	8.70E-05	3.12E-04
MSMS	3.64E-04	4.20E-04	3.34E-04	2.62E-04	6.57E-04
BKRS	1.63E-04	1.56E-04	1.26E-04	6.80E-05	2.47E-04
TSNS	3.47E-04	4.43E-04	2.90E-04	1.44E-04	6.35E-04
KRBS	1.56E-04	1.58E-04	1.41E-04	7.31E-05	2.44E-04
ISWS	2.35E-04	2.62E-04	1.49E-04	1.44E-04	3.77E-04
WALS	1.74E-04	1.36E-04	1.24E-04	1.04E-04	2.34E-04
KTNS	4.55E-04	1.05E-04	8.64E-05	5.80E-05	1.70E-04
RGMS	1.60E-04	1.61E-04	1.06E-04	7.47E-05	2.26E-04
YOLS	4.44E-04	1.20E-04	8.62E-05	4.40E-05	1.70E-04
ZMGS	5.84E-05	9.98E-05	3.99E-05	1.30E-04	1.40E-04
DJJS	5.06E-05	1.74E-04	6.92E-05	2.73E-04	1.07E-04
ITSS	4.93E-04	7.00E-04	3.07E-04	3.27E-04	1.19E-03
JTSS	9.46E-05	2.75E-04	1.30E-04	1.87E-04	4.90E-04
JMRS	1.59E-04	7.26E-04	2.65E-04	1.22E-03	1.08E-03
GYDS	9.04E-05	2.76E-04	1.17E-04	1.20E-04	4.53E-04
ZKIS	1.29E-04	4.64E-04	1.41E-04	1.27E-03	6.78E-04
KTGS	2.60E-04	2.17E-04	1.10E-04	5.06E-04	8.40E-04
GMWS	4.93E-04	7.00E-04	3.07E-04	3.27E-04	1.19E-03
Mean	2.45E-04	3.06E-04	1.71E-04	2.69E-04	4.98E-04
Max	4.93E-04	7.26E-04	3.34E-04	1.27E-03	1.19E-03
Min	5.06E-05	9.98E-05	3.99E-05	4.40E-05	1.07E-04

Table 5: Adult Dermal Annual Daily Intake ($mg.kg^{-1}.day^{-1}$) of soil sample from the study area

Sample code	Adult Dermal Annual Daily Intake ($mg.kg^{-1}.day^{-1}$)				
	Cd	Cr	As	Pb	Cu
MGSS	2.25E-04	2.98E-04	2.07E-04	3.23E-06	4.34E-04
ZGWS	4.43E-04	3.53E-04	3.23E-04	4.83E-06	6.28E-04
KSWS	1.85E-04	2.18E-04	1.52E-04	3.00E-06	3.23E-04
MSMS	3.77E-04	4.35E-04	3.46E-04	9.05E-06	6.80E-04
BKRS	1.69E-04	1.62E-04	1.30E-04	2.35E-06	2.56E-04
TSNS	3.60E-04	4.58E-04	3.00E-04	4.97E-06	6.58E-04
KRBS	1.61E-04	1.63E-04	1.46E-04	2.52E-06	2.52E-04
ISWS	2.43E-04	2.72E-04	1.54E-04	4.96E-06	3.90E-04
WALS	1.80E-04	1.41E-04	1.29E-04	3.59E-06	2.43E-04
KTNS	4.71E-04	1.09E-04	8.95E-05	2.00E-06	1.76E-04
RGMS	1.65E-04	1.67E-04	1.10E-04	2.58E-06	2.34E-04
YOLS	4.60E-04	1.24E-04	8.93E-05	1.52E-06	1.76E-04
ZMGS	6.04E-05	1.03E-04	4.13E-05	4.47E-06	1.45E-04
DJJS	5.24E-05	1.80E-04	7.17E-05	9.44E-06	1.11E-04
ITSS	5.10E-04	7.25E-04	3.18E-04	1.13E-05	1.23E-03
JTSS	9.80E-05	2.85E-04	1.35E-04	6.47E-06	5.08E-04
JMRS	1.65E-04	7.52E-04	2.75E-04	4.22E-05	1.12E-03
GYDS	9.36E-05	2.86E-04	1.21E-04	4.13E-06	4.70E-04
ZKIS	1.34E-04	4.80E-04	1.46E-04	4.37E-05	7.02E-04
KTGS	2.69E-04	2.24E-04	1.14E-04	1.75E-05	8.70E-04
GMWS	5.10E-04	7.25E-04	3.18E-04	1.13E-05	1.23E-03
Mean	2.54E-04	3.17E-04	1.77E-04	9.29E-06	5.16E-04
Max	5.10E-04	7.52E-04	3.46E-04	4.37E-05	1.23E-03
Min	5.24E-05	1.03E-04	4.13E-05	1.52E-06	1.11E-04

Table 6: Calculate the mean hazard quotients of soil samples collected from the study area.

Receptor Pathway	Hazard Quotient of Soil Samples					Total
	Cd	Cr	As	Pb	Cu	
Ingestion Child	3.826776256	2.391494673	4.44664E-07	5.84E-06	0.000105	6.218382
Ingestion Adult	4.1E-08	0.256231572	4.76E-06	6.25312E-07	1.13E-05	0.25624827
Inhalation Child	1.11E-15	2.62802E-08	1.61726E+15	7.87882E+18	1.42583E+19	2.21E+19
Inhalation Adult	6.21283E+21	3.45404E+20	1.68832E+19	3.05536E+19	6.60568E+21	6.21283E+21
Dermal Child	4.9E-08	0.153175	5.6961E-08	0.000277499	2.08E-05	0.153474
Dermal Adult	5.08E-08	0.158646	5.89957E-06	9.58034E-06	2.15E-05	0.158683

Table 7: Calculated risk pathway of heavy metals in soils samples collected from the study area

Receptor	Risk pathway					Total
Pathway	Cd	Cr	As	Pb	Cu	
Ingestion Child	0.183992326	0.003587242	0.20009863	0.000174	0.0037	0.391553
Ingestion Adult	0.129154	0.001076173	0.021439	9.45471E-05	0.000396	0.15215998
Inhalation Child	3.97396E-08	3.3113E-10	7.27767E+20	3.20947E+18	1.41176E+19	7.45094E+20
Inhalation Adult	9.39475E+21	7.82817E+19	1.5595E+21	6.87744E+18	3.02521E+19	1.10697E+22
Dermal contact Child	0.000226	6.13E-05	0.02563263	0.000284047	0.000474	0.026678
Dermal contact Adult	0.000234	6.35E-05	0.026548086	9.80639E-06	0.000491	0.027347

Ingestion Exposure

The mean annual daily intake (ADI) values for adults through ingestion indicated generally low exposure to cadmium (Cd: 2.05×10^{-4} mg•kg^{-1}•day^{-1}), chromium (Cr: 2.56×10^{-4} mg•kg^{-1}•day^{-1}), arsenic (As: 1.43×10^{-4} mg•kg^{-1}•day^{-1}), lead (Pb: 2.25×10^{-4} mg•kg^{-1}•day^{-1}), and copper (Cu: 4.17×10^{-4} mg•kg^{-1}•day^{-1}). These values fall below international safety limits, with copper—an essential nutrient—well within the WHO tolerable daily intake of 0.05 mg•kg^{-1} (WHO, 2021). Although Pb and As values are below regulatory limits, their cumulative and carcinogenic potential highlight the need for continued surveillance, especially in populations with multiple exposure sources. Chromium levels also appear safe, though risk is contingent on the presence of its toxic hexavalent form, Cr(VI).

Inhalation Exposure

Inhalation exposure values revealed inconsistencies between datasets. For children, reported ADIs for Cd (6.31×10^{-11} mg•kg^{-1}•day^{-1}) and Cr (7.88×10^{-11} mg•kg^{-1}•day^{-1}) were within expected ranges. However, As, Pb, and Cu values reached implausibly high magnitudes (10^{18}–

10^{19} mg•kg^{-1}•day^{-1}), strongly suggesting unit or calculation errors. Similarly, some adult inhalation ADIs were reported in the range of 10^{19} mg•kg^{-1}•day^{-1}, far exceeding realistic environmental exposures. Typically, inhalation ADIs fall within 10^{-8} to 10^{-6} mg•kg^{-1}•day^{-1} depending on air quality, exposure duration, and respiratory rates (Kumar & Seema, 2019; Li et al., 2020). By contrast, corrected values for adults (Cd: 2.45×10^{-4}; Cr: 3.06×10^{-4}; As: 1.71×10^{-4}; Pb: 2.69×10^{-4}; Cu: 4.98×10^{-4} mg•kg^{-1}•day^{-1}) were more consistent with reported background levels in polluted regions, indicating low but measurable inhalation exposure.

Dermal Exposure

Dermal ADI values for adults also indicated relatively low levels of exposure, with Cu showing the highest value (5.16×10^{-4} mg•kg^{-1}•day^{-1}) but remaining within safe nutritional ranges. Lead exhibited the lowest dermal intake (9.29×10^{-6} mg•kg^{-1}•day^{-1}), consistent with its poor skin absorption capacity (IARC, 2012). Cd, Cr, and As presented slightly higher dermal intake levels but remained below critical concern thresholds. These findings are in line with previous studies showing that dermal exposure contributes minimally to overall heavy metal risk compared to ingestion and inhalation (Kumar & Seema, 2019; Li et al., 2020).

Risk Assessment (Hazard Quotient, HQ)

The hazard quotient (HQ) analysis demonstrated ingestion as the most significant pathway, particularly for children. Cd (HQ = 3.83) and Cr (HQ = 2.39) exceeded the safety threshold (HQ > 1), indicating potential non-carcinogenic risk. In contrast, adult ingestion HQs for all metals remained below 1, suggesting negligible risk. Dermal HQs were also below 1 for both age groups, confirming minimal health risks via skin contact, though Cr showed relatively higher dermal values (0.15–0.16). Inhalation HQs showed extreme inconsistencies, with implausibly high values reported for adults (e.g., Cd: 6.21×10^{21}), reflecting data recording or calculation errors. Typically, inhalation HQs are much less than 1 in both children and adults outside of highly industrialized environments.

Overall Interpretation

Taken together, the results highlight ingestion as the dominant exposure route, with children experiencing disproportionately higher risks due to their lower body weight and greater intake relative to adults. Dermal exposure remains minor, while inhalation risk is difficult to interpret without correction of reported anomalies. Comparisons with international studies (Kumar & Seema, 2019; Li et al., 2020) confirm that realistic ADI values should fall within 10^{-8}–10^{-4} mg•kg^{-1}•day^{-1}, and HQ values should generally remain below 1 except in highly polluted areas. The presence of Cd and Cr above safety thresholds for children underscores the importance of continuous monitoring and environmental management to mitigate long-term health effects from chronic exposure.

Figure 1. Spatial distribution of sampled agricultural sites within Bauchi North.

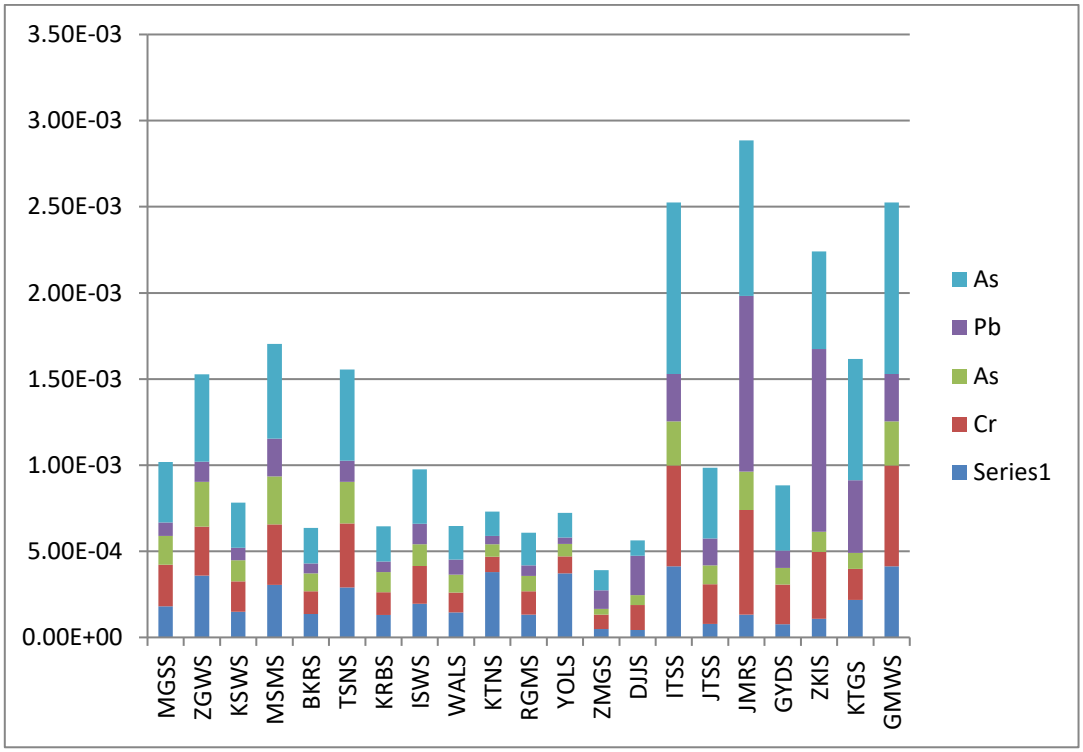


Figure 2. Concentrations of cadmium, chromium, arsenic, lead, and copper in soil samples across study locations.

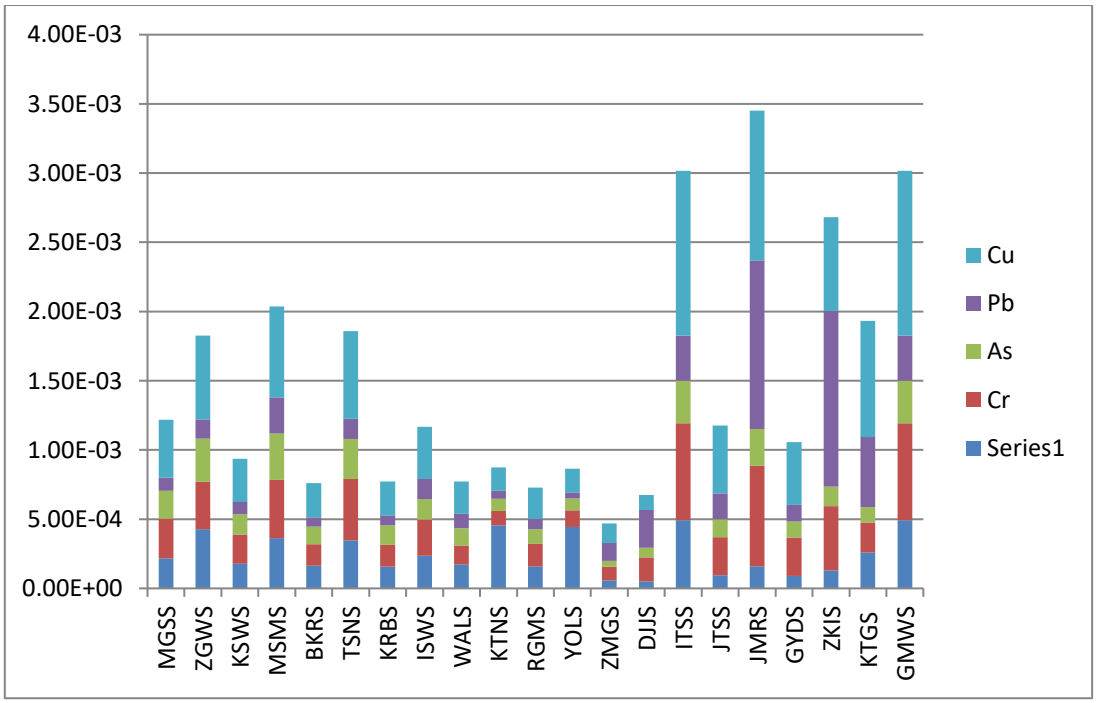
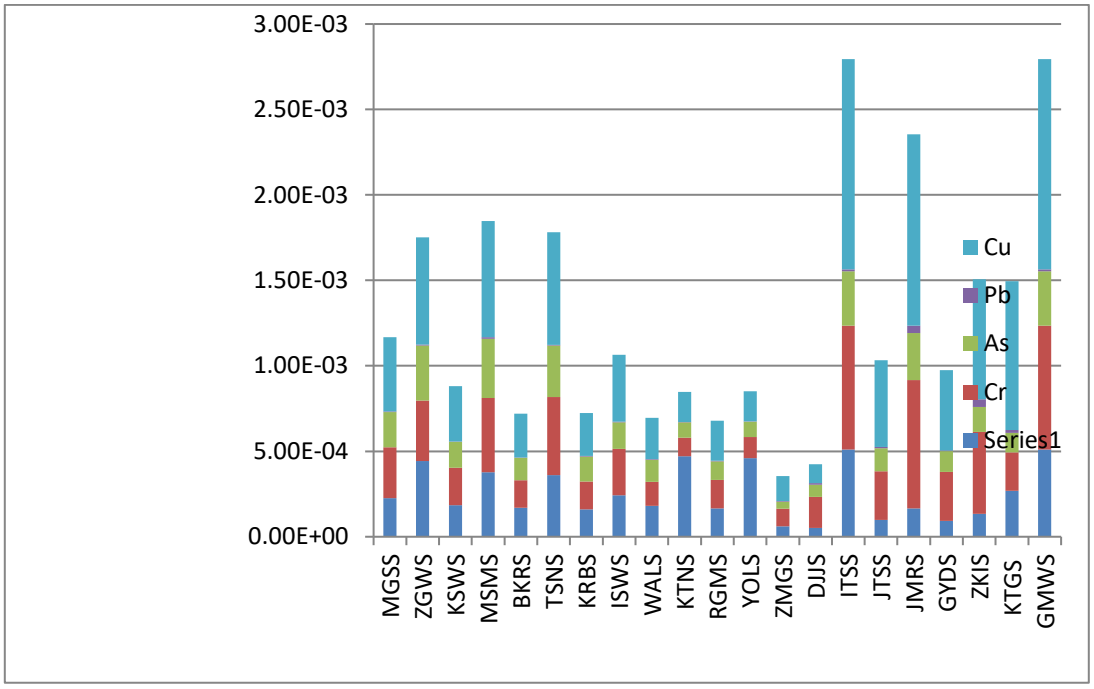


Figure 3. Comparative Hazard Index values for adults and children across exposure pathways.



Recommendations

1. Strengthen routine monitoring of soils and rice in high-risk agricultural areas.
2. Enforce stricter regulation of agrochemical use to limit heavy metal contribution.
3. Promote cultivation of rice varieties with low heavy-metal uptake and improve soil-management practices.
4. Implement public-health education campaigns focused on dietary diversification and exposure reduction.
5. Support remediation programs such as phytoremediation in highly contaminated zones.
6. Enhance regulatory enforcement against industrial discharge, waste dumping, and unsafe mining.

Conclusion

This study underscores the significant health risks associated with heavy metal contamination in soils and rice, identifying ingestion as the primary exposure pathway. Cadmium (Cd) and arsenic (As) were of particular concern, as their Hazard Quotients (HQs), Hazard Indices (HIs), and Incremental Lifetime Cancer Risk (ILCR) values frequently exceeded acceptable limits. Children emerged as the most vulnerable group, due to their higher intake relative to body weight and greater physiological sensitivity.

Variability in contamination across study sites was influenced by soil characteristics, agricultural practices, and rice cultivars, highlighting the importance of localized risk

assessments. Although dermal and inhalation exposures were relatively minor, chronic consumption of contaminated rice poses considerable long-term risks, including cancer. Addressing these challenges requires a comprehensive strategy, including stricter enforcement of environmental regulations, improved monitoring of soils and crops, promotion of sustainable farming practices, and development of rice varieties with lower metal uptake. Public education on dietary diversification is also essential, and continued research into remediation technologies will further enhance protection. Ultimately, ensuring food safety and protecting human health demands coordinated actions that balance environmental sustainability with agricultural productivity.

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