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Exposure and Health Risks of Cadmium, Chromium, Lead, Copper, and Zinc in Common Cereals from Bauchi State, Nigeria

Abdulkadir Nafisat *, Abdulhameed Ahmad, Gaya E.A. and Buba Toma

Department of Ecology, faculty of science, Abubakar Tafawa Balewa University, Bauchi State, Nigeria
* Correspondence: nafisafuk13@gmail.com

Abstract

Cereals are a staple component of the Nigerian diet; however, their contamination with heavy metals raises serious public health concerns. This study evaluated the concentrations, contamination levels, and associated non-carcinogenic and carcinogenic risks of cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), and zinc (Zn) in commonly consumed cereals; maize, millet, sorghum, and wheat sold in Wunti Market, Bauchi State, Nigeria. Composite samples were collected and analyzed using atomic absorption spectrophotometry after acid digestion. Contamination factors (CF) and standard human health risk assessment models were employed to estimate exposure via ingestion, inhalation, and dermal contact for both adults and children. The results indicated that Cd and Pb concentrations in all cereal samples exceeded recommended permissible limits, whereas Cu and Zn remained within acceptable thresholds. Cadmium showed particularly high contamination factors, especially in maize and millet, indicating significant environmental accumulation. Exposure assessments revealed that children had higher estimated intake levels than adults across all exposure pathways, reflecting their greater vulnerability. Although ingestion pathways suggested low non-carcinogenic risk overall, inhalation and dermal exposure routes demonstrated elevated hazard quotient (HQ) and hazard index (HI) values, particularly for Cd, Cr, and Pb. Furthermore, the estimated total carcinogenic risk for both adults and children surpassed the acceptable threshold established by regulatory agencies, with maize contributing the highest risk levels among the cereals studied. These findings suggest that both consumption and handling of contaminated cereals may pose substantial long-term health risks, especially for children. The study underscores the need for routine monitoring of heavy metal contamination in food products, adoption of safer agricultural practices, and stricter regulation of agrochemical use.

Keywords: carcinogenic; non-carcinogenic; health risk; exposure heavy metal

1. Introduction

Food is essential for sustaining life and supporting physiological processes such as growth, maintenance, and development [1,2]. Among food sources, cereals and legumes are widely consumed and serve as major nutrient providers across Nigeria [3]. In Northern Nigeria, agriculture constitutes the primary livelihood, with the region significantly contributing to national and cross-border food supply [4,5]. To enhance productivity, farmers rely heavily on pesticides, which play important roles in pest control, soil management, and disease prevention, thereby supporting food security and increased agricultural output [6,7].

However, the excessive and improper use of pesticides, driven partly by inadequate knowledge among farmers, has led to environmental contamination, particularly of soil and water systems [8,9]. These practices result in the persistence of residues in soil ecosystems, negatively affecting biodiversity and promoting the bioaccumulation of toxic substances, including heavy metals, in food crops [4,10].

Human exposure to these contaminants occurs through multiple pathways. Ingestion of contaminated food accounts for over 90% of total exposure. Additionally, inhalation of airborne particulates during post-harvest processes such as threshing, milling, and transportation exposes individuals to heavy metal-laden dust. Dermal exposure also occurs through direct contact during handling, sorting, and marketing of cereals, particularly in informal settings lacking protective measures. These exposure pathways align with established human health risk assessment frameworks, including those of the USEPA.

Heavy metals are also directly linked to pesticide formulations, including compounds such as methyl mercuric chloride, sodium arsenate, calcium arsenate, and zinc phosphide [11]. Although naturally present in soils, their concentrations have been significantly altered by anthropogenic activities [12]. These metals pose serious health risks: lead affects neurological and cardiovascular systems [13], cadmium causes organ damage and cancer [14], mercury impacts the nervous system [15], and arsenic is associated with cancers and developmental disorders [16].

The presence of heavy metals reduces the nutritional value of cereals and raises significant public health concerns, prompting regulatory agencies such as EFSA and the U.S. FDA to establish permissible limits. Continuous monitoring is therefore essential. Consequently, this study evaluates the concentrations of cadmium, chromium, copper, lead, and zinc in maize, millet, and sorghum sold in Wunti Market, Bauchi State, and assesses their associated health risks.

2. Materials and Methods

2.1. Sample Collection and Preparation

Basket market survey was conducted in Wunti market in Bauchi, where three samples of each cereal (Maize, Millet, and Sorghum) were collected. The samples were bulked together to form composite samples as described by Aroro et al., [17]. The collected cereals were handpicked and crushed using a blender and sieved using a 2 µm standard sieve and stored in a well labeled paper bag prior to heavy metal analysis.

2.2. Heavy Metal Analysis

One gram (1 g) of each powdered cereal sample was digested in 15ml combination of three acids (70% high-purity Sigma Aldrich (nitric acid) HNO3, 65% (per chloric acid) HClO4, and 70% (sulfuric acid) H2SO4 in 5:1:1 ratio). At 80°C, the solution was digested using a hot plate until it became translucent. The resulting solution was sieved and diluted with 50 mL distilled water before being analyzed. With the use of an atomic absorption spectrophotometer (AAS), the digests were examined for cadmium, chromium, copper, lead and zinc concentrations as described by Zhong et al., [18]

2.3. Contamination Factor

The contamination factor (CF) is utilized for assessing the level of contamination in sample from each heavy metal. It is calculated using the following equation:

$$CF = \frac{Ci}{Bi}$$

where Ci and Bi stand for measured metal concentrations and background value for specific metal, respectively. CF is classified into four groups to measure the degree of contamination in the sample as follows: CF <1 (low contamination), 1 ≤ CF < 3 (moderate contamination), 3 ≤ CF <6 (considerable contamination), and 6 ≥ CF (high contamination) [19].

2.4. Health Risk Assessment

The risk that pollution poses to humans can be estimated by using an efficient model called the human health risk model. Differences in physiology and behavior of adults compared with children keep them separate. The study estimated the potential of non-carcinogenic and carcinogenic health risks for the two age groups.

2.5. Exposure Assessment

The primary routes of exposure for children and adults to heavy metals are through ingestion (ADI_{ing}), inhalation of suspended particles (ADI_{inh}), and dermal contact (ADI_{der}). The dose received through each of the three pathways from maize, millet and sorghum was calculated using the following equations [20].

$$ADI_{ing} = \frac{CA \times IR \times EF \times ED \times CF}{BW \times AT}$$

$$ADI_{inh} = \frac{CA \times InhR \times ET \times EF \times ED}{PEF \times BW \times AT}$$

$$ADI_{der} = \frac{CA \times SA \times AF \times ABS \times EF \times ED \times CF}{BW \times AT}$$

where: ADI_{ing} is the average daily intake of heavy metals (HMs) ingested in mg/kg/day. ADI_{inh} is the average daily intake of HMs inhaled in mg/kg/day. ADI_{der} is the exposure dose via dermal contact in mg/kg/day. CA is the concentration of HMs available in cereals (mg kg-1). IR is cereals ingestion rate. BW is the body weight. EF is the exposure frequency. ED is the exposure duration. ATc is the carcinogenic risk average time. ATnc is the non-carcinogenic risk average time. SA is the skin surface area available for contact. CF is the conversion factor. AF is the soil-to-skin adherence factor. ABS is the absorption factor. InhR is the inhalation rate. ET is the cereal exposure time. PEF is the particle emission factor, and ET is the exposure time (h/day) [21].

2.6. Non-Carcinogenic Risk

The non-carcinogenic health risk of a substance is determined by estimating the likelihood of adverse health effects at a specific dosage within a specific timeframe using the hazard quotient and hazard index. The hazard quotient (HQ) is referred to as the quotient of ADI divided by the chronic reference dose (RfD) of a certain heavy metal in mg/kg/day. The potential hazard quotient (HQ) for each metal was calculated by using the following equation [22].

$$HQ = \frac{ADI}{RfD}$$

If $HQ < 1$, it means that there are no adverse health consequences, whereas $HQ > 1$ suggests that there are probably harms [23].

The population's non-carcinogenic response to a certain number of heavy metals is the total of all the HQs caused by each heavy metal known as the Hazard Index HI [24]. It was calculated using the equation below:

$$HI = \sum_{i=1}^{n} (HQ)$$

The value of $HI \leq 1$ indicates that there is no significant risk of non-carcinogenic effects. On the other hand, there is a chance that non-carcinogenic effects may occur. When $HI > 1$, and the probability increases as the value of the HI increases [25].

2.7. Carcinogenic Risk Index

Carcinogen risks are computed as the incremental probability that a person would get cancer during their lifetime as a result of exposure to the probable carcinogen [26]. It was computed as:

$$(CR) = ADI \times CSF$$

where ADI (mg/kg/day) and CSF (mg/kg/day) represent the average daily intake and cancer slope factor, respectively.

The carcinogenic slope factor (CSF) indicates the maximum probable carcinogenic risk in an individual exposed to a specific carcinogenic substance dose.

A total cancer risk (TCR) was calculated by the sum of CR from all carcinogens in the studied cereals as follows:

$$\text{Risk(total) (TCR)} = \text{Risk(ing)} + \text{Risk(inh)} + \text{Risk(dermal)}$$

where $\text{Risk}_{(\text{ing})}$, $\text{Risk}_{(\text{inh})}$, and $\text{Risk}_{(\text{dermal})}$ are risk contributions through ingestion, inhalation, and dermal pathways, respectively. The USEPA recommends risk values less than 1.00E-06 are regarded as negligible, whereas a risk exceeding 1.00E-04 is likely to be harmful to human health. If the 1.00E-06 < TCR < 1.00E-04, the cancer risk is acceptable [27].

3. Result and Discussion

Permissible limit by WHO: Cd= 0.1, Cr= NS, Cu= 10, Pb=0.1 and Zn= 50

The mean concentrations of cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), and zinc (Zn) in millet, maize, sorghum, and wheat (Figure 1) reveal varying levels of contamination across the cereals. Cadmium concentrations ranged from 0.325 mg/kg in sorghum to 1.495 mg/kg in maize, exceeding the WHO permissible limit of 0.1 mg/kg in all samples. This indicates widespread Cd contamination, particularly in maize and millet, likely linked to phosphate fertilizer use and contaminated soils [28,29].

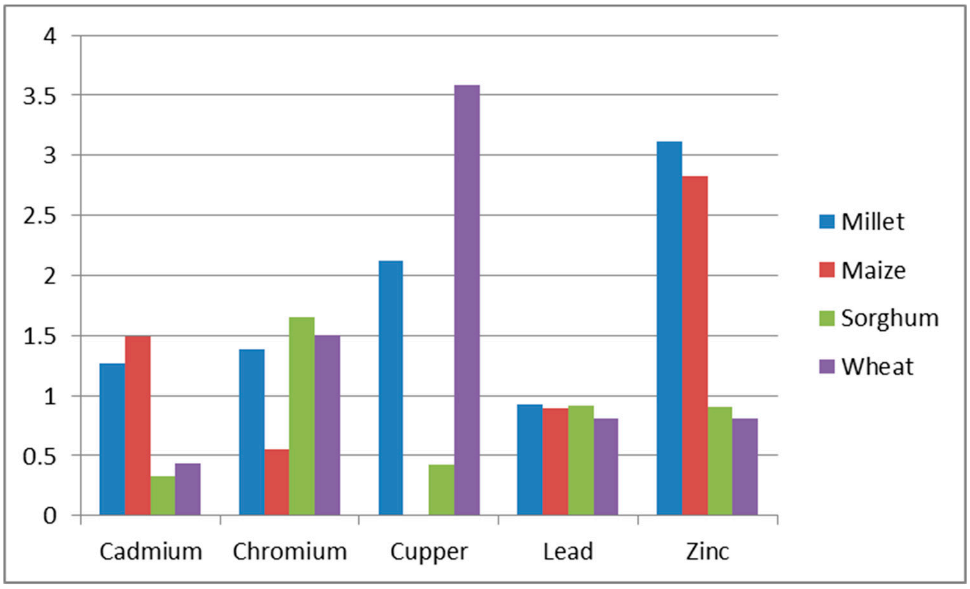

Figure 1. heavy metals (Cd, Cr, Cu, Pb and Zn) mean concentrations in millet, maize, sorghum and wheat.

Chromium levels ranged from 0.55 mg/kg in maize to 1.65 mg/kg in sorghum. Although no specific WHO limit exists for chromium in cereals, its presence even at low concentrations poses toxicological risks, especially in its hexavalent form. The observed levels may be attributed to industrial emissions, wastewater irrigation, and agrochemical inputs [29,30].

Copper concentrations ranged from 0.425 mg/kg in sorghum to 3.58 mg/kg in wheat, with maize showing levels below detection limits. All values were within the WHO permissible limit of 10 mg/kg, suggesting no immediate toxicity risk. However, relatively higher levels in wheat may be associated with the application of copper-based pesticides and fungicides [31].

Lead concentrations ranged from 0.805 mg/kg in wheat to 0.925 mg/kg in millet, exceeding the WHO limit of 0.1 mg/kg in all cereals. This widespread Pb contamination is a significant public health concern, particularly for children, and may result from atmospheric deposition, contaminated irrigation sources, vehicular emissions, and milling processes [32].

Zinc concentrations ranged from 0.81 mg/kg in wheat to 3.115 mg/kg in millet and remained within the WHO permissible limit of 50 mg/kg. As an essential micronutrient, these levels likely reflect natural soil composition and fertilizer use rather than contamination [33].

4. Contamination Factor

CF <1 (low contamination), CF < 3 (moderate contamination), CF <6 (considerable contamination), and 6 ≥ CF (high contamination) [19].

The contamination factor analysis (Figure 2) revealed extremely high CF values for cadmium across all cereals, ranging from 6.5 in sorghum to 29.9 in maize, indicating high contamination according to Shen et al., [19]. Chromium CF values ranged from 5.5 to 16.5, reflecting considerable to high contamination**,** while copper, lead, and zinc generally showed low to moderate contamination**.**

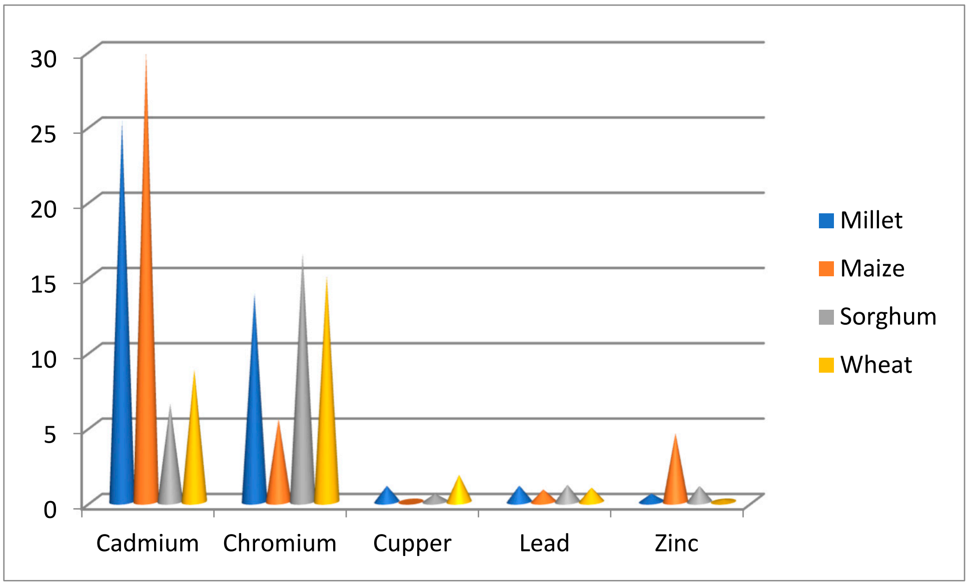

Figure 2. heavy metals (Cd, Cr, Cu, Pb and Zn) contamination factor (CF) in millet, maize, sorghum and wheat.

The dominance of Cd contamination aligns with reports that phosphate fertilizers and wastewater irrigation are major sources of cadmium accumulation in agricultural soils in developing countries [34,35]. The elevated CF values for chromium further suggest persistent anthropogenic inputs and limited soil buffering capacity in the study area.

4.1. Health Risk Assessment

Based on the heavy metal concentrations, risk evaluation for carcinogenic and non-carcinogenic effects was performed. Humans are exposed to heavy metals primarily through three routes: inhalation through the nose, ingestion through the mouth, and dermal absorption through skin contacts.

4.2. Exposure Assessment

WHO/FAO (Codex) acceptable limit (mg/kg/day) Cd=0.001, Cr= 0.3 Cu= 0.9 Pb= No significant concentration via ingestion, Zn=40.

Figure 3 indicates that ingestion exposure levels were consistently higher in children than in adults across all metals and cereal types, primarily due to children's lower body weight and higher food intake relative to body mass (36). Cadmium (Cd) exposure in children exceeded permissible limits, particularly through millet (0.0204), maize (0.028), and wheat (0.0024), aligning with findings from Nigeria and Egypt where Cd intake surpassed FAO/WHO tolerable daily intake thresholds

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[37,38]. Chronic Cd exposure is associated with renal dysfunction, skeletal damage, and carcinogenic effects [39].

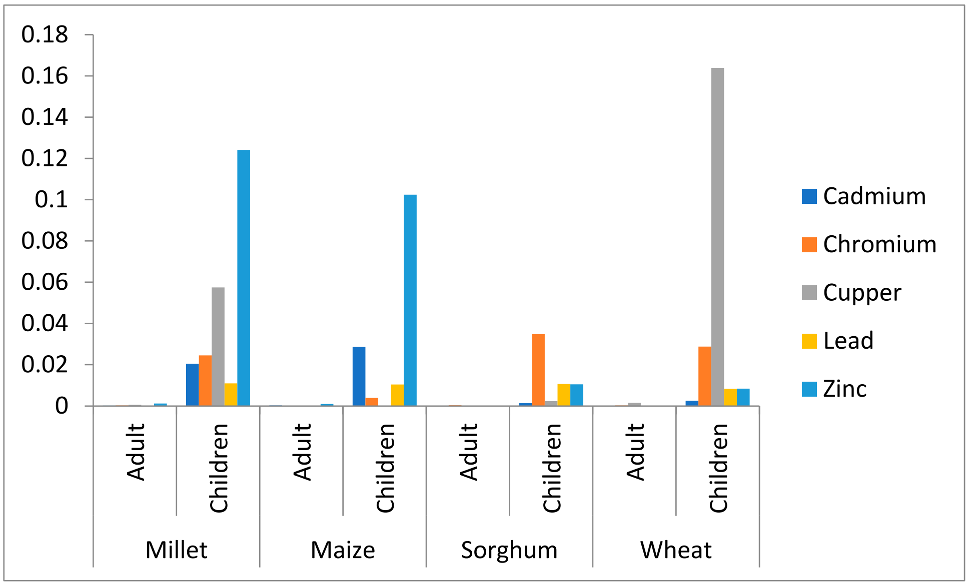

Figure 3. heavy metals exposure assessment via ingestion.

Chromium (Cr) ingestion for both adults and children remained within permissible limits, ranging from 0.0000357–0.000321 in adults and 0.000321–0.0348 in children. Despite this, prolonged exposure to low concentrations, particularly hexavalent chromium, may induce oxidative stress and DNA damage [30]. The relatively higher Cr intake in maize may be linked to soil adsorption and translocation processes in irrigated agricultural systems [40].

Copper (Cu) exposure was also higher in children than adults but remained within safe limits, with values ranging from 0.0000213–0.00151 in adults and 0.0023–0.16 in children. Elevated Cu levels, especially in wheat, may result from contaminated soils or excessive agrochemical application [31].

Lead (Pb) exposure showed low values in adults (0.0000761–0.000101) but significantly higher levels in children (0.0082–0.010), reflecting its persistence and toxicity. Pb poses serious risks to children's neurological development even at low concentrations, with similar trends reported in cereal-based diets in Pakistan and Ethiopia [41].

Zinc (Zn) exposure remained within permissible limits for both groups, ranging from 0.0000774–0.00114 in adults and 0.0083–0.124 in children. While Zn is essential, excessive intake may disrupt iron and copper metabolism [33].

Among cereals, millet showed the highest ingestion exposure in children, particularly for Zn (0.124059) and Cu (0.057463), while adult exposure remained minimal. Sorghum exhibited relatively low adult exposure but notable child exposure to Cr (0.034808) and Pb (0.010623). Wheat recorded the highest Cu ingestion in children (0.163863), highlighting its significant contribution to copper intake.

Inhalation exposure (Figure 4) generally resulted in higher estimated doses than ingestion, particularly for cadmium (Cd) and chromium (Cr). Children consistently exhibited greater inhalation exposure than adults, likely due to higher respiratory rates and increased contact with contaminated dust during cereal handling, processing, and storage [42,43]. Although cereals are mainly consumed orally, activities such as milling, open-air drying, and storage can generate airborne particulates, contributing to elevated inhalation risks.

For millet, adult inhalation exposure ranged from 0.005049 (Pb) to 0.057258 (Zn), while children showed higher levels, especially for zinc (0.124059). Maize followed a similar trend, with children recording elevated Cd (0.028576) and Zn (0.102397). In sorghum, adult exposure remained moderate, but children had notable Cr (0.034808) and Pb (0.010623) levels. Wheat showed a pronounced pattern, with children recording the highest copper (Cu) inhalation exposure (0.163863), consistent with ingestion patterns.

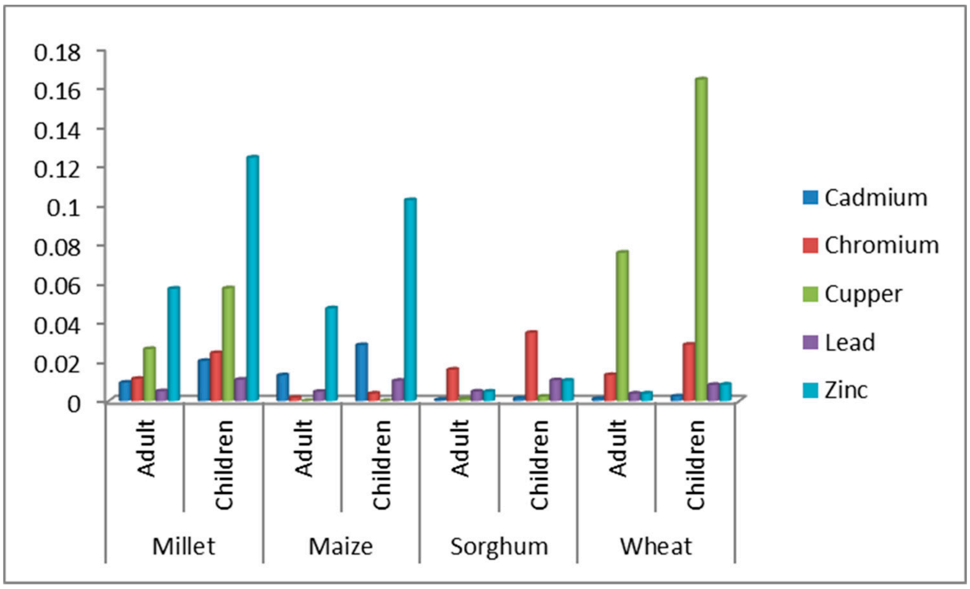

Figure 4. heavy metals exposure assessment via inhalation.

These findings align with reports of elevated Cd exposure from inhaled agricultural dust in northern Nigeria [44] and similar observations in India and Pakistan, where atmospheric deposition and farming activities contributed significantly to Cd exposure among children [35,40]. Chronic inhalation of Cd-contaminated particles is associated with pulmonary and renal toxicity [39].

Although Cr exposure remained within acceptable limits, prolonged exposure particularly to hexavalent chromium may cause respiratory inflammation, oxidative stress, and DNA damage [30]. Elevated Cr levels in millet may be linked to contaminated soils and wastewater irrigation, as reported in Kano and Kaduna States and comparable findings in Ethiopia [41,45].

Copper exposure was generally within safe limits for both adults and children, indicating low inhalation risk, though localized elevations may arise from soil contamination and dust resuspension [31]. Lead (Pb) exposure was higher in children and may be associated with urban pollution, vehicular emissions, and contaminated processing environments [33]. Pb remains highly toxic, particularly affecting neurological development in children [38]. Zinc (Zn) levels were within tolerable limits, though excessive exposure may interfere with copper metabolism and enzymatic functions [33].

Dermal exposure levels were generally lower than ingestion and inhalation pathways for both adults and children; however, children consistently exhibited higher exposure across all cereals and metals. This pattern reflects children’s increased vulnerability due to their higher surface area-to-body weight ratio and thinner skin, which enhances dermal absorption of contaminants [46,47].

In millet, children recorded the highest dermal exposure for zinc (0.006947) and copper (0.003218), while adult values remained significantly lower. Although zinc and copper are essential trace elements, excessive exposure may lead to adverse effects such as skin irritation and interference with metabolic processes [48,49]. Elevated copper exposure in children may be linked to prolonged contact during handling and interaction with contaminated dust [31], while higher zinc levels are consistent with natural soil enrichment and fertilizer application in cereal production [50].

Maize showed generally low dermal exposure for all metals, with copper undetected, indicating negligible non-carcinogenic risk via this pathway. Sorghum also exhibited minimal dermal exposure overall, although children recorded slightly elevated chromium (0.001949) and lead (0.000595) levels. In wheat, children showed relatively higher copper exposure (0.009176), suggesting increased contact during processing and handling activities.

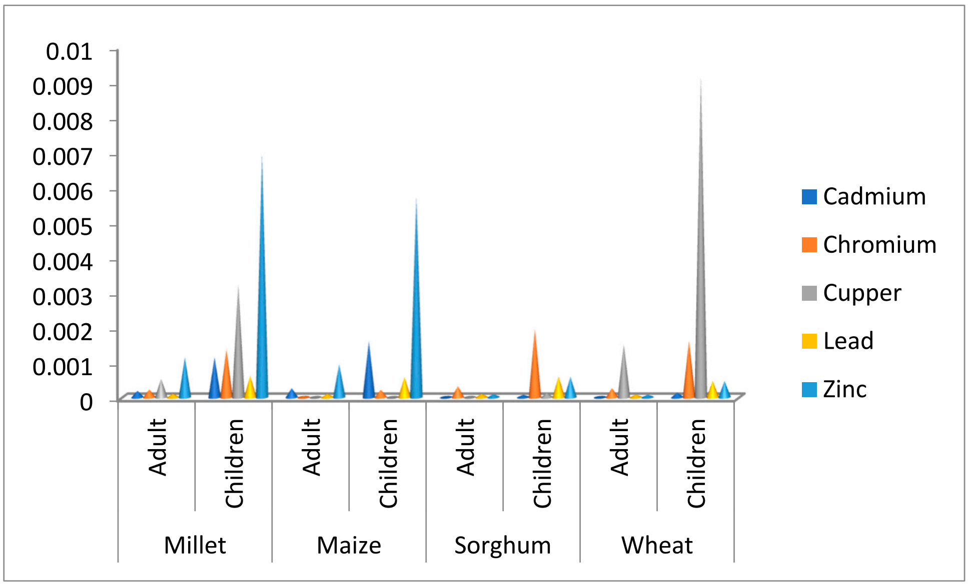

Figure 5. heavy metals exposure assessment via dermal contact.

Comparable studies from Ghana and Egypt reported dermal chromium exposure within safe limits but highlighted the risk of cumulative effects from prolonged contact [34,38]. Elevated chromium levels in sorghum may be associated with contaminated soils or phosphate fertilizers containing trace metals [51]. Even at low concentrations, dermal exposure to chromium, particularly hexavalent forms, can cause skin irritation and allergic reactions [52].

Lead exposure through dermal contact, though relatively low, remains concerning due to its neurotoxicity and potential for accumulation with repeated exposure [53,54]. Similar trends have been reported in Nigeria and Ethiopia, where dermal Pb exposure was low but not negligible [32,41]. Cadmium exposure, although within WHO limits, may still contribute to long-term health risks such as nephrotoxicity and bone damage, particularly in children [37,39,44]. Notably, the absence of established international reference doses for dermal exposure complicates comprehensive risk assessment [55].

5. Non Carcinogenic Health Risk

The non-carcinogenic health risks associated with exposure to cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), and zinc (Zn) through consumption of millet, maize, sorghum, and wheat were evaluated using the Hazard Quotient (HQ) approach. Hazard quotients were calculated separately for ingestion (HQ_ing), inhalation (HQ_inh), and dermal contact (HQ_derm) for both adults and children.

Figure 6 shows that cadmium (Cd) posed the greatest non-carcinogenic health risk among the analyzed metals. For adults, the hazard quotient via ingestion (HQ_ing) for Cd was below unity (0.1889), indicating minimal dietary risk; however, inhalation (HQ_inh = 944.28) and dermal exposure (HQ_derm = 7.54) far exceeded safe limits. In children, the risk was substantially higher, with Cd HQ_inh reaching 2045.95 and HQ_derm 45.83, indicating severe non-carcinogenic risk. Chromium (Cr) also exhibited elevated inhalation risk, with HQ_inh values of 113.19 in adults and 245.25 in children. Although copper (Cu), lead (Pb), and zinc (Zn) showed HQ_ing values below 1, their inhalation HQ values exceeded unity, particularly among children. The consistently low HQ_ing values across both age groups suggest that millet consumption does not pose significant non-carcinogenic risk through ingestion, consistent with findings that cereal grains generally exhibit low bioaccumulation of heavy metals [56,57].

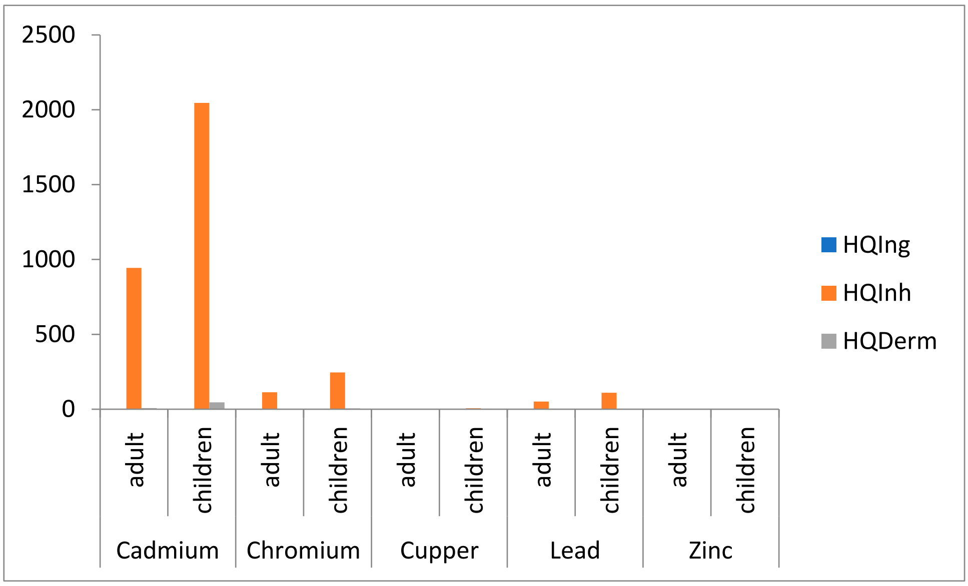

Figure 6. hazard quotient via ingestion, inhalation and dermal contact with millet.

Cadmium and chromium were identified as the primary contributors to non-carcinogenic risk via inhalation and dermal pathways, especially in children. This is attributed to children's higher sensitivity, lower body weight, and increased exposure rates per unit body mass [58]. Similar elevated inhalation-related HQ values have been reported in agricultural regions of Asia and Africa, where exposure to contaminated dust during cereal processing significantly increases health risks [42,43].

Dermal exposure to Cd, Cr, and Pb also presents potential toxicity risks, particularly for children frequently in contact with contaminated cereal dust. These metals exhibit higher dermal permeability compared to Cu and Zn, which have lower skin bioavailability [59,60]. Comparable studies in Nigeria and other regions have reported similar HQ patterns, emphasizing inhalation as a critical exposure pathway [61,62]. Additional studies across West Africa, China, India, and Brazil have also identified Cd and Cr as major contributors to elevated HQ values in cereals, often linked to soil contamination, fertilizer use, atmospheric deposition, and storage conditions [16,63,65–67].

According to EPA (55) guidelines, HQ values greater than one indicates potential non-carcinogenic health effects, highlighting the significance of non-dietary exposure pathways in assessing overall risk.

Figure 7 indicates that hazard quotients (HQs) for ingestion of cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), and zinc (Zn) in maize were all below unity for both adults and children, suggesting negligible non-carcinogenic risk from dietary intake. This implies that maize consumption in the study area does not pose immediate health concerns, consistent with studies reporting low bioavailability of heavy metals in cereal grains [56,68]. However, children showed relatively higher ingestion HQs than adults due to lower body weight and higher intake rates [58]. Similar findings from Nigeria and other regions confirm that ingestion-related HQ values for cereals typically remain below safety thresholds [46,50,69–72].

In contrast, inhalation exposure presented significantly higher risks. Cadmium showed extremely elevated HQ_inh values, reaching 1318.88 in adults and 2857.57 in children the highest among all cerealsindicating substantial non-carcinogenic risk. Chromium inhalation posed moderate to high risk, particularly in children (HQ_inh = 38.66). Lead also exceeded safe limits via inhalation, with HQ values of 47.80 in adults and 103.56 in children, despite low ingestion HQs. Copper showed no risk (HQ = 0) due to non-detection in maize, while zinc remained within safe limits across all pathways. These elevated inhalation risks suggest that environmental factors such as dust exposure, atmospheric deposition, poor storage conditions, unpaved roads, and open waste burning may significantly contribute to overall exposure beyond dietary intake.

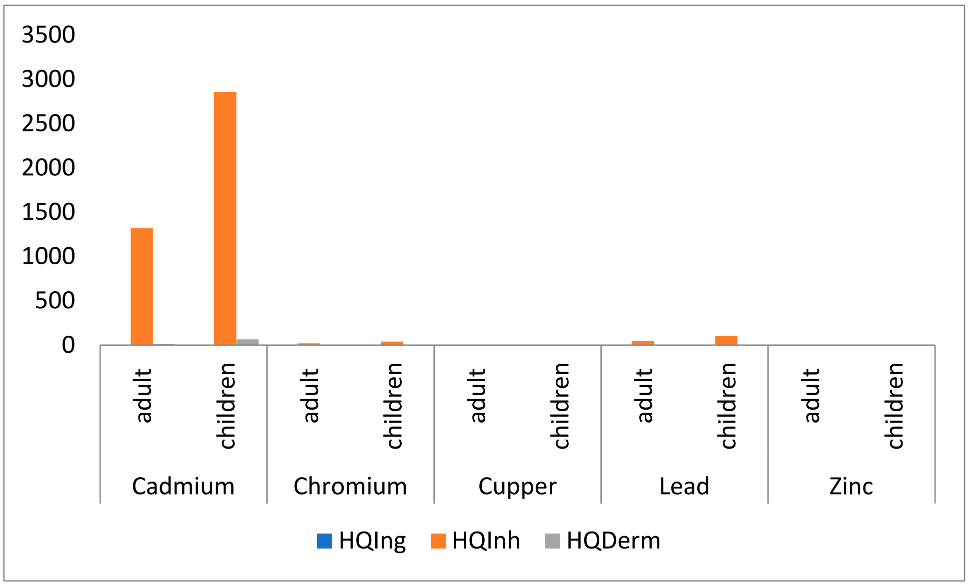

Figure 7. hazard quotient via ingestion, inhalation and dermal contact with maize.

These findings align with studies identifying inhalation of contaminated dust during cereal processing and handling as a major exposure pathway [42,43]. The particularly high Cd inhalation risk underscores its strong airborne toxicity, often linked to environmental deposition and post-harvest contamination [73].

Dermal exposure results further indicate that children are more vulnerable to Cd, Cr, and Pb due to greater skin permeability and higher contact frequency [59,60]. Similar patterns of low ingestion but elevated inhalation and dermal risks have been reported in Bangladesh and Iran, particularly in areas influenced by urban and industrial activities [71,74].

Figure 8 shows that hazard quotients (HQs) via ingestion for cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), and zinc (Zn) in sorghum were below unity for both adults and children, indicating minimal non-carcinogenic risk from dietary intake. While adults are unlikely to experience immediate health effects, children remain more vulnerable due to lower body weight, higher intake per unit body mass, and developing physiological systems that enhance metal absorption [71,72]. These findings are consistent with studies reporting low ingestion risks in cereals from non-industrial regions [69,70]. However, relatively higher ingestion HQs in children align with reports from northern Nigeria and other regions where Cd and Pb exposure in children approached or exceeded safe limits [46,50].

In contrast, inhalation exposure presented significant risks, particularly for children. Cadmium and chromium exhibited elevated HQ_inh values, with chromium reaching 160.65 in adults and 348.08 in children. Lead inhalation HQs also exceeded unity in both age groups, while copper and zinc remained within safe limits across all pathways. These results highlight inhalation as the dominant exposure route, likely influenced by environmental contamination such as dust, vehicular emissions, industrial fallout, and poor storage conditions. Similar findings have been reported in Nigeria and other countries, where airborne particulates from agricultural and environmental sources significantly increased heavy metal exposure [42,43,72,74].

Dermal exposure further revealed elevated HQ values for Cd, Cr, and Pb, particularly in children, with values exceeding the safety threshold. This indicates potential health risks associated with frequent contact with contaminated sorghum residues. Children’s higher susceptibility is linked to increased dermal absorption, frequent outdoor activities, and hand-to-mouth behaviors [75]. Comparable studies have shown that dermal exposure can significantly contribute to overall risk in environments with contaminated soils [76].

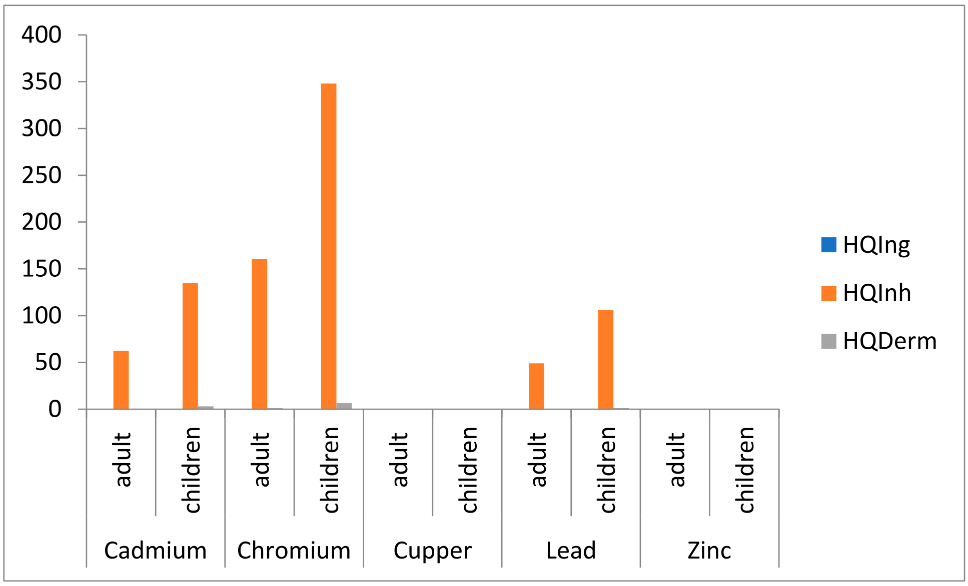

Figure 8. hazard quotient via ingestion, inhalation and dermal contact with sorghum.

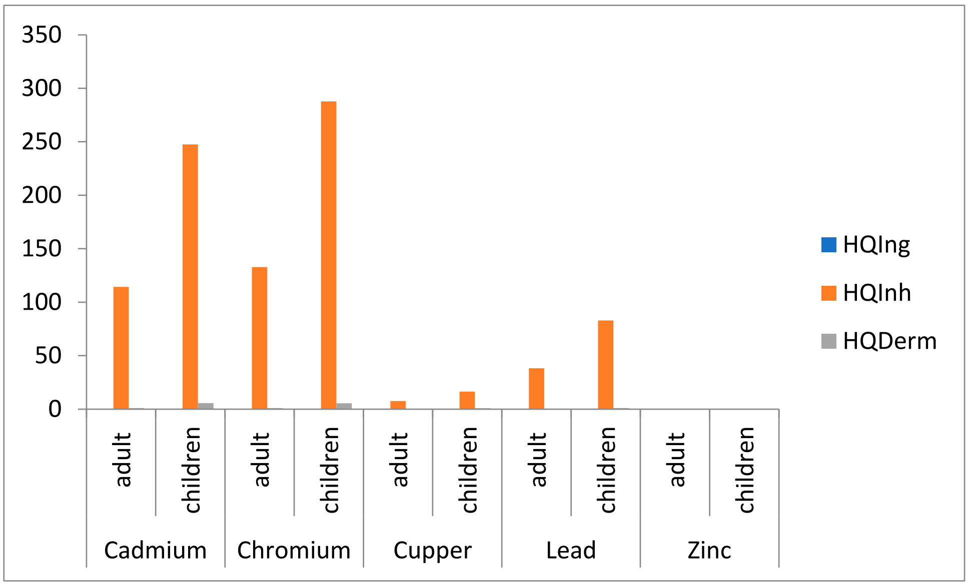

Figure 8. hazard quotient via ingestion, inhalation and dermal contact with wheat.

Wheat HQ values for all the heavy metals were below the threshold level of 1, Cd (0.0228- 0.056), Cr (0.088-0.022), Cu (0.378-0.094), Pd (0.012-0.0544) and Zn (0.00025- 0.000643). Similar findings were reported in Ghana and northern Nigeria, where ingestion HQs for cereals remained within acceptable limits due to low soil-to-grain transfer rates [69]. Low HQ(ing) values can be explained by moderate metal mobility in soil, limited use of phosphate fertilizers, and post-harvest cleaning that removes surface dust. Wheat generally exhibits lower Cd and Pb uptake than rice or maize, which may explain the observed safety margin [59]. However, continuous cultivation near industrial or trafficked areas could increase HQ(ing) over time, emphasizing the importance of soil and irrigation-water monitoring to maintain food safety. The relatively higher ingestion HQs for cadmium in children highlight their increased vulnerability to dietary cadmium exposure, consistent with findings by Gupta et al. [58] and Kumar et al. [77]. These results suggest that wheat is relatively safe for direct dietary intake, but cadmium bioaccumulation remains a potential concern over long-term exposure.

However, inhalation exposure hazard quotients resulted in high HQ values above the 1 in cadmium, chromium, copper and lead for both adult and children suggesting non carcinogenic risk.

Zinc did not pose significant health risks across all pathways. Elevated HQ(inh) suggests that airborne particulates adhering to grains during open-air drying or milling may constitute a dominant risk pathway. Comparable findings in cereal markets across Africa and Asia demonstrate that dust from traffic and biomass combustion substantially increases inhalation exposure [78,79]. Children, who inhale more air per body mass, are especially vulnerable. High HQ(inh) values therefore reflect both environmental deposition and occupational dust exposure among vendors and processors. Inhalation exposure resulted in very high HQ values for copper in adults (7.56) and children (16.39). Cadmium and chromium also showed inhalation HQ values far exceeding unity in both age groups. Children recorded particularly high HQ values for cadmium (247.53) and chromium (287.67) through inhalation. The very high inhalation HQs for cadmium suggest that inhalation of contaminated particulates from wheat during handling, processing, or storage could cause adverse health effects. These findings are consistent with Saleem et al. [43], who reported that inhalation of heavy-metal-laden dust from cereals is a neglected but critical route of exposure, particularly affecting children due to their higher breathing rates relative to body weight [73].

Dermal exposure hazard quotients were below the threshold level of 1 across all the metals for adult and children except for cadmium (5.544563) and chromium (5.369863) that are above the permissible limit. This aligns with reports from North Africa and the Middle East where dermal absorption from grains contributes less than 5 % to total heavy-metal exposure [80].

Hazard Index (HI) Assessment

The cumulative non-carcinogenic health risks associated with exposure to heavy metals through millet, maize, sorghum, and wheat were evaluated using the Hazard Index (HI), which represents the summation of hazard quotients for multiple metals within a single exposure pathway. The HI was assessed separately for ingestion (HI ingestion, inhalation and dermal contact) for adults and children. According to the United States Environmental Protection Agency (USEPA), an HI value less than one (HI < 1) indicates an acceptable level of non-carcinogenic risk, whereas values equal to or greater than one (HI ≥ 1) suggest potential adverse health effects arising from combined exposure to multiple contaminants.

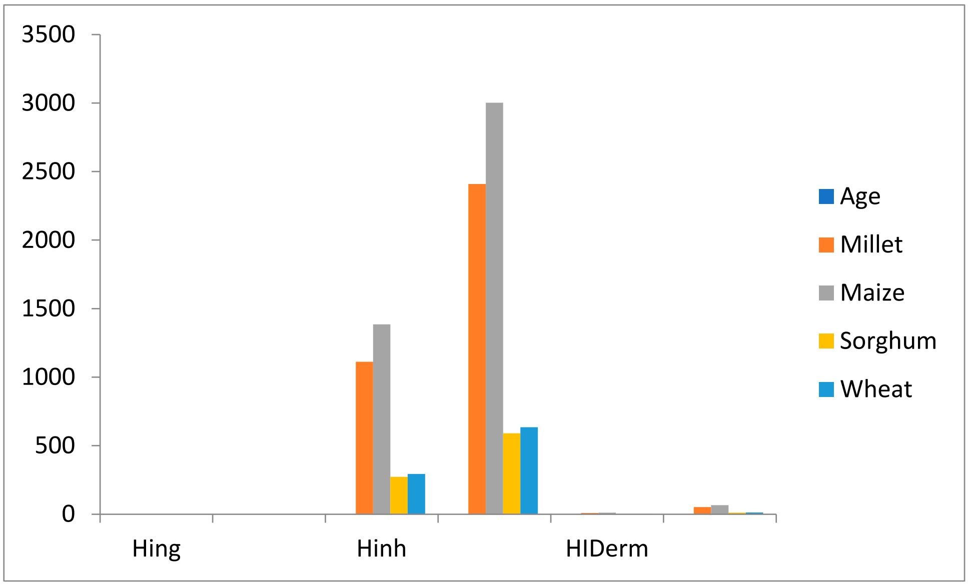

Figure 10. hazard index via ingestion, inhalation and dermal contact with millet, maize, sorghum and wheat.

The hazard index (HI) results show that ingestion-based cumulative non-carcinogenic risks for all cereals were below unity for both adults and children, indicating acceptable safety levels. Adult HI_ing values ranged from 0.153 (sorghum) to 0.512 (wheat), while children's values ranged from 0.130 (sorghum) to 0.736 (maize). Despite remaining within safe limits, children consistently exhibited higher HI values, particularly for maize and millet, reflecting their greater vulnerability due to higher food intake relative to body weight and developing physiological systems. Similar trends have been reported in Nigerian studies, where ingestion HI values for adults were typically below unity, while children often approached or exceeded the threshold, especially for cadmium and lead.

In contrast, inhalation-based HI values were extremely high for all cereals and both age groups. Adult HI_inh values ranged from approximately 272 (sorghum) to 1385 (maize), while children's values ranged from about 590 (sorghum) to over 3000 (maize), indicating theoretically severe non-carcinogenic risk. However, these elevated values are unlikely to reflect realistic exposure scenarios, as cereals are primarily consumed through ingestion. Inhalation exposure occurs indirectly via contaminated dust during handling or processing. Thus, the high HI_inh values are likely due to conservative modeling assumptions, low inhalation reference doses, or high particulate exposure factors. Similar overestimations of inhalation risks have been reported in previous food-based health risk assessments, emphasizing ingestion as the most relevant exposure pathway.

Dermal HI values also exceeded unity for all cereals in both adults and children, with children again showing higher values. Adult HI_derm ranged from 1.76 (sorghum) to 100.84 (maize), while children's values ranged from 10.68 (sorghum) to 65.93 (maize), suggesting potential non-carcinogenic risks from cumulative dermal exposure. Nonetheless, dermal contact is a secondary exposure route for cereals and may not accurately represent real-life risk under typical consumption conditions. Elevated dermal HI values likely result from conservative assumptions related to skin adherence, exposure duration, and contamination levels. Existing studies similarly indicate that dermal exposure contributes minimally to total heavy metal intake from food crops compared to ingestion, particularly in rural settings.

6. Carcinogenic Risk

Carcinogenic risk (CR) estimates the incremental lifetime probability of developing cancer due to exposure to carcinogenic metals, while total carcinogenic risk (TCR) represents the combined risk from multiple exposure pathways. According to USEPA guidelines, acceptable lifetime cancer risk ranges from 1×10^{-6} (one additional cancer case per one million people) to 1×10^{-4} (one additional cancer case per ten thousand people). Values above 1×10^{-4} are considered unacceptable and indicative of significant carcinogenic concern.

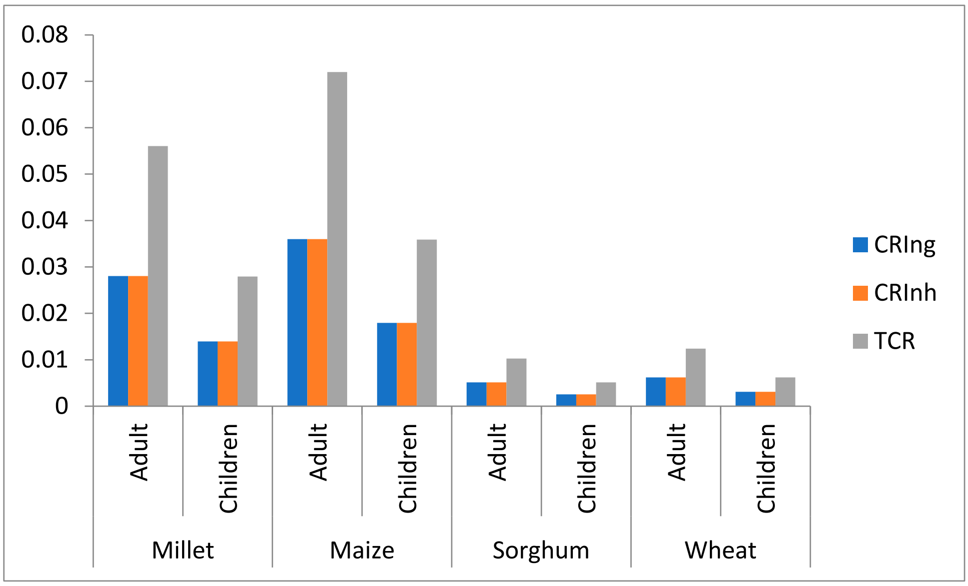

Figure 11. Carcinogenic risk and total carcinogenic risk assessment via ingestion & inhalation of heavy metals in millet, maize, sorghum and wheat.

The total carcinogenic risk (TCR) values for all cereals exceeded the acceptable USEPA limit (1 × 10^{-4}) for both adults and children, indicating potential lifetime cancer risks associated with their consumption. Adult TCR values ranged from 0.00126 (sorghum) to 0.07198 (maize), while children's values ranged from 0.00511 (sorghum) to 0.03587 (maize), demonstrating levels several orders of magnitude above safe thresholds.

Maize exhibited the highest carcinogenic risk for both age groups, followed by millet and wheat, while sorghum showed the lowest risk. The elevated risk levels are largely attributed to the presence of cadmium and chromium, as well as contamination during pre- and post-harvest handling and storage. Adults generally recorded higher TCR values than children, reflecting longer cumulative exposure durations over time.

The high carcinogenic risk can be linked to multiple environmental and agricultural factors. These include the continuous use of phosphate fertilizers, pesticides, and untreated wastewater, which introduce heavy metals such as Cd and Pb into soils and facilitate their uptake by crops. Additionally, atmospheric deposition from vehicular emissions, industrial activities, and open waste burning contributes to contamination during cultivation and processing stages. Poor storage conditions further increase exposure through contact with contaminated dust and residues.

Children were identified as particularly vulnerable due to their lower body weight and higher food intake per unit body mass, making them more susceptible to chronic exposure effects. Similar findings have been reported by Adebayo et al. [81]and Mlangeni et al. [82], highlighting increased cancer risks in children from prolonged dietary exposure to Cd and Pb in cereals.

These results are consistent with other Nigerian studies, where carcinogenic risks above acceptable limits have been reported by Ikem [29] documented elevated cancer risks for Cd and Pb in rice and maize, while Bawa [5] linked such risks in cereals and vegetables to persistent contamination from wastewater irrigation and heavy metal accumulation in agricultural systems.

7. Conclusion

This study demonstrates significant contamination of cereals sold in Bauchi State with cadmium and lead, resulting in elevated non-carcinogenic and carcinogenic health risks, particularly for children. Although dietary exposure alone appears acceptable, cumulative exposure through inhalation and dermal contact may pose serious long-term health concerns. Regular monitoring of cereals, enforcement of safe agrochemical use, and public awareness on food handling practices are recommended to reduce heavy-metal exposure and protect public health.

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