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EVALUATION OF HEAVY METALS CONTAMINATION AND ASSOCIATED HEALTH RISKS IN PASTEURIZED AND UNPASTEURIZED COW MILK IN GASHUA, YOBE STATE, NIGERIA

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ABSTRACT

Milk is a vital source of nutrients but may also serve as a pathway for toxic heavy metal exposure. This study assessed cadmium, chromium, lead, and mercury in cow milk consumed in Gashua, Yobe State, Nigeria. To determine the levels of Cd, Cr, Pb, and Hg in pasteurized and unpasteurized cow milk, compare the findings with WHO limits, and evaluate associated health risks. A cross-sectional study was conducted using 10 milk samples (5 pasteurized, 5 unpasteurized) collected from sales points through a stratified random sampling technique. Atomic absorption spectrophotometry was used to determine heavy metal concentrations. Health risk assessment was performed using estimated daily intake (EDI), target hazard quotient (THQ), hazard index (HI), and incremental lifetime cancer risk (ILCR) based on United States Environmental Protection Agency (USEPA) standards. Data were analyzed using descriptive statistics. Mean concentrations of Cd (0.012–0.017 mg/L), Cr (0.153 mg/L), and Pb (0.220–0.228 mg/L) exceeded WHO permissible limits, while Hg (0.0026–0.003 mg/L) remained within safe levels. Health risk assessment showed that EDI, THQ, and HI values were <1, indicating no immediate non-carcinogenic risks. However, ILCR values approached the upper acceptable limit, particularly in children. Pasteurized and unpasteurized cow milk in Gashua, Yobe State, is contaminated with Cd, Cr, and Pb above safe limits. Although immediate non-carcinogenic risks appear low, the potential long-term carcinogenic risks, especially in children, warrant routine monitoring and preventive interventions. Strengthen regulatory frameworks and establish routine monitoring systems to ensure milk safety and protect public health is suggested.

Keywords: Heavy Metals, Milk, Health, Evaluation, Risk

INTRODUCTION

Heavy metals occur in the environment both from natural sources and anthropogenic sources (Jaishankar *et al.,* 2014). Increased industrial and agricultural activities have led to the significant release of different wastes containing high amounts of pollutants including heavy metals. Therefore, the industrial and agricultural activities could cause an increase in the concentrations of heavy metal compounds in the air, water, and soils, as well as their passage to the tissues and milk of grazing animals (Maas *et al.,* 2011). Most of the metals taken up by plants and animals can then enter the food chain, such as through dairy products (Ogabiela *et al.*, 2011). A strong relationship between contaminated drinking water with heavy metals such as Pb, Cd, Cu, Mo, Ni, Cr and chronic diseases such as renal failure, kidney stones, liver cirrhosis, hair loss, and chronic anemia has continued to be a threat to the population of Gashua, Bade LGA, Yobe state (Suleiman, 2021). In the livestock system, milk and dairy products are considered major sources of nutritious foods providing essential macro and micronutrient that support growth and immune functions in both animals and humans (Leksir *et al.*, 2019; Malbe *et al.*, 2010). Several elements in milk like iron (Fe), zinc (Zn), and copper (Cu) are essential for the human body and play a crucial role in metabolism. These elements are considered as co-factors in many enzymatic reactions showing a variety of biochemical functions in the living organism. Nevertheless, the levels of these components above the sanitary recommendations may become toxic to human health (Gall *et al.,* 2015; Licata *et al.,* 2012; Varol *et al.,* 2020). Other heavy metals such as cadmium (Cd), lead (Pb), and mercury (Hg) are nonessential elements and can cause metabolic disorders with toxic effects even at very low concentrations (Varol *et al.,* 2020). Besides the impact on human health, the presence of heavy metals can impact the health of cows and directly or indirectly affect milk composition (Zhou *et al.,* 2017). Therefore, the presence of these compounds in milk, in addition to being an indirect indicator of the contamination of the environment in which the dairy cows are housed, is a direct indicator of its hygienic quality (Gonzalez-montana *et al.,* 2012). In Gashua a region characterized by intensive agricultural activities, local communities rely heavily on cow milk for daily nutrition. Concurrently, the water used for drinking and irrigation has been found to contain elevated levels of heavy metals, including cadmium (Cd), lead (Pb), chromium (Cr). Studies have reported present of heavy metals contaminants in water and vegetables across multiple location of Gashua, Bade local government area, Yobe state. Studies also link these contaminants to chronic kidney disease among residents in the study area (Waziri *et al.,* 2017; Sulaiman *et al.,* 2019;

Suleiman *et al.*, 2021). The contamination of the environment by heavy metal is of great concern globally because metals do not break down into less harmful substances and present a number environmental risk (Li *et al.*, 2004). Metals like Copper and Zinc are essential metals for plant growth and productivity. However, plants may accumulate heavy metals present in soil water, like Cadmium (Cd), Nickel (Ni), Chromium (Cr) and Lead (Pb) which are not essential growth and this may pose threat environment (Mitsios, *et al*. 2005). This current study is to evaluate the levels of heavy metal contaminants and associated health risks in pasteurized and unpasteurized cow milk consumed in Gashua, Yobe State, Nigeria.

MATERIALS AND METHODS

Study Area

The town Gashua in Bade Local Government area of Yobe State is located between latitude 120 52' 05 N and 120 87'11 N and longitude 110 57'26 E and 110 02'47 E. Among the towns in Bade, Gashua is one of the largest having an area of 3,336 square kilometers and a population of 139,804 as of the 2006 census; male was 73,709 and female 66,095. (Census, 2006). Gashua town lies in the plain region of the savannah and the town has a fertile soil which supports the cultivation of Rice, Millet, Groundnut, Guinea corn, and Sorghum. The vast land within the LGA supports the rearing of animals. The climate is characterized by high amount of temperature and low annual rainfall towards the northern region (Kimmage, 2012). Rainfall ranges between 400 mm and 800 mm with an annual mean rainfall of 750 mm. The Mean annual temperature is usually around 39^{O} C and the mean monthly value range is between 27^{O} C in the coolest month of December to January and 32^{O} C in the hottest month of April to May. The major river that flows in Gashua and the adjoining area is the River Komadugu Yobe (Kimmage, 2012).

Study Design

This study used a descriptive cross-sectional study design to assess the levels of heavy metal contamination in pasteurized and unpasteurized cow milk from different sources.

Sampling Technique

A stratified random sampling technique was employed to ensure representative inclusion of both pasteurized and unpasteurized cow milk samples.

Sample Collection

A total of 10 samples of 300mL of pasteurized and unpasteurized cow milk from different milk sales point were collected. The samples were poured into sterile samples container and the samples was transported in cool chain into Yobe state University chemistry research laboratory for chemical analysis.

Sample Digestion and Analysis of Metals

The optimized microwave digestion procedure was adopted for the preparation of milk samples. Three milliliters (3.0 mL) of each liquid milk sample were transferred into a 60 mL Teflon digestion vessel. Subsequently, 6 mL of 70% nitric acid (HNO_3) and 1 mL of 30% hydrogen peroxide (H_2O_2) were added. The mixture was gently shaken and allowed to stand for 10 minutes before sealing the vessel. Digestion was carried out in a microwave system using the optimized conditions: 50 W at 165°C for 10 minutes, followed by 80 W at 190°C for 20 minutes, and finally 0 W at 50°C for 10 minutes. After digestion, the samples were cooled to room temperature to prevent foaming and loss of volatile components. Each digest was then diluted to 25 mL with deionized water and filtered where necessary. Reagent blanks and reference materials were digested alongside the samples to ensure quality control and reliability of analytical results. The resulting digests were analyzed for the concentrations of Cadmium (Cd), Chromium (Cr), Mercury (Hg), and Lead (Pb) using Atomic Absorption Spectrophotometer (AAS) under appropriate analytical conditions.

Health Risk Assessment

The potential health risks associated with the consumption of heavy metals from pasteurized and unpasteurized cow milk were assessed based on the Estimated Daily Intake (EDI), Target Hazard Quotient (THQ), Hazard Index (HI), and Target Cancer Risk (TCR), following standard protocols.

Estimated Daily Intake (EDI)

The EDI of metals refers to the amount of a substance in food expressed on a body mass basis (mg/kg body weight/day) that humans can ingest daily over a lifetime without significant health risks (Benard *et al.,* 2020). In this study, the EDI of cadmium, chromium, lead, and mercury through the consumption of pasteurized and unpasteurized cow milk in the study area was determined using the formula:

$$EDI = \frac{C \text{ x } QFC}{BW}$$

where C = mean concentration of Cd, Cr, Pb, or Hg in milk (mg/kg); BW = average body weight in kg (children 0–17 years = 30 kg; adults ≥18 years = 60 kg); and QFC = estimated quantity of milk consumed daily (kg/person/day), taken as 0.0345 kg.

The computed EDI values were compared with their respective provisional tolerable daily intake (PTDI) values set by FAO/WHO (2011), for example 0.001 mg/kg/day for Cd and 0.002 mg/kg/day for Pb.

Target Hazard Quotient (THQ)

The THQ represents the non-carcinogenic health risks posed by heavy metals (Njoga *et al.,* 2021). It was estimated according to the USEPA (2021) method as:

$$THQ = \frac{EF \text{ x } ED \text{ x } QFC \text{ x } C}{RFD \text{ x } BW \text{ X } AT}$$

where EF = exposure frequency (365 days/year), ED = exposure duration (set as 55 years, the average life expectancy in Nigeria; Benard *et al.,* 2020), QFC = daily milk consumption (0.0345 kg/person/day), C = mean concentration of Cd, Cr, Pb, or Hg in milk (mg/kg), RfD = oral reference dose (mg/kg/day) for the respective metal, BW = average body weight (kg), and AT = averaging time (days), equal to $ED \times 365$ for non-carcinogenic effects. A THQ value < 1 indicates little or no non-carcinogenic health risk, whereas THQ ≥ 1 suggests the possibility of adverse health effects.

Hazard Index (HI)

The HI determines the potential risk from combined exposure to multiple metals with similar toxic effects. It is the sum of the individual THQs:

$$HI = THQCd + THQCr + THQPb + THQHg$$

An HI value < 1 suggests negligible risk, while HI ≥ 1 indicates a possibility of non-carcinogenic health effects (Njoga *et al.,* 2021).

Target Cancer Risk (TCR)

TCR was calculated to assess the carcinogenic risks associated with lifetime exposure to Cd, Cr, Pb, and Hg using the formula:

TCR = CDI x CSF

where *CDI* is the chronic daily intake (mg/kg/day) averaged over a lifetime, and *CSF* is the cancer slope factor ((mg/kg/day) $^{-1}$) for each metal, as defined by USEPA (2021). For example, CSF values used were 0.38 for Cd and 0.008 for Pb. A TCR < 1×10^{-6} is considered negligible, 1×10^{-6} to 1×10^{-4} indicates an acceptable or tolerable risk, while TCR > 1×10^{-4} suggests a potential public health concern (Naseri *et al.*, 2021).

Data Analysis

The data were first entered and cleaned in Microsoft Excel, after which statistical analyses were performed. Descriptive statistics, including mean, median, range, and standard deviation, were conducted using the Statistical Package for the Social Sciences (SPSS) version 22 (IBM). A 95% confidence interval was calculated using VassarStats computational statistics software.

RESULTS AND DISCUSSIONS

Results

Table 1: The Heavy Metals Concentration in Pasteurized Cow Milk (mg/L)

Sample Id	Cadmium (Cd) (mg/L)	Chromium (Cr) (mg/L)	Mercury (Hg) (mg/L)	Lead (Pb) (mg/L)
A1	0.008	0.15	0.003	0.24
A2	0.015	0.12	0.002	0.17
A3	0.005	0.18	0.003	0.32
A4	0.021	0.095	0.004	0.28
A5	0.011	0.22	0.001	0.13

The concentrations of Cadmium, Chromium, Mercury, and Lead across the five samples (A1–A5) of pasteurized cow milk are presented in the table 1. Sample A1 recorded 0.008 mg/L of Cadmium, 0.15 mg/L of Chromium, 0.003 mg/L of Mercury, and 0.24 mg/L of Lead. In Sample A2, the values were 0.015 mg/L Cadmium, 0.12 mg/L Chromium, 0.002 mg/L Mercury, and 0.17 mg/L Lead. Sample A3 contained 0.005 mg/L Cadmium, 0.18 mg/L Chromium, 0.003 mg/L Mercury, and 0.32 mg/L Lead. For Sample A4, the concentrations were 0.021 mg/L Cadmium, 0.095 mg/L Chromium, 0.004 mg/L Mercury, and 0.28 mg/L Lead. Lastly, Sample A5 showed 0.011 mg/L Cadmium, 0.22 mg/L Chromium, 0.001 mg/L Mercury, and 0.13 mg/L Lead.

Table 2: The Heavy Metals Concentration in Unpasteurized Cow Milk

Sample Id	Cadmium (Cd) (mg/L)	Chromium (Cr) (mg/L)	Mercury (Hg) (mg/L)	Lead (Pb) (mg/L)
B1	0.03	0.08	0.005	0.21
B2	0.006	0.25	0.003	0.09
B3	0.025	0.13	0.002	0.35
B4	0.018	0.195	0.004	0.26
B5	0.004	0.11	0.002	0.19

The concentrations of heavy metals in samples B1 to B5 of unpasteurized cow milk are presented in the table 2. Sample B1 contained 0.03 mg/L of Cadmium, 0.08 mg/L of Chromium, 0.005 mg/L of Mercury, and 0.21 mg/L of Lead. In Sample B2, the measured values were 0.006 mg/L Cadmium, 0.25 mg/L Chromium, 0.003 mg/L Mercury, and 0.09 mg/L Lead. Sample B3 showed 0.025 mg/L Cadmium, 0.13 mg/L Chromium, 0.002 mg/L Mercury, and 0.35 mg/L Lead. For Sample B4, the concentrations were 0.018 mg/L Cadmium, 0.195 mg/L Chromium, 0.004 mg/L Mercury, and 0.26 mg/L Lead. Finally, Sample B5 had 0.004 mg/L Cadmium, 0.11 mg/L Chromium, 0.002 mg/L Mercury, and 0.19 mg/L Lead.

Table 3: The Mean Heavy Metals Concentration in Pasteurized Cow Milk

Metals	Mean ± SD	95% CI(Lower)	95% CI(Higher)	WHO Standard Limit
Cadmium (Cd)	0.012 ±0.0062	0.007	0.017	0.003
Chromium (Cr)	0.153±0.0492	0.116	0.192	0.05
Lead (Pb)	0.228±0.0779	0.168	0.288	0.001
Mercury (Hg)	0.0026±0.0011	0.0004	0.0015	0.010

The mean concentration of Cadmium in the pasteurized milk samples was 0.012 ± 0.0062 mg/L with a 95% confidence interval (CI) of 0.007–0.017 mg/L, which is above the WHO standard limit of 0.003 mg/L. Chromium recorded a mean concentration of 0.153 ± 0.0492 mg/L (95% CI: 0.116–0.192 mg/L), also exceeding the WHO permissible limit of 0.05 mg/L. Lead showed the highest deviation, with a mean value of 0.228 ± 0.0779 mg/L (95% CI: 0.168–0.288 mg/L) compared to the WHO limit of 0.001 mg/L. Mercury, on the other hand, had a mean concentration of 0.0026 ± 0.0011 mg/L (95% CI: 0.0004–0.0015 mg/L), which was within the WHO permissible limit of 0.01 mg/L as presented in table 3.

Table 4: The Mean Heavy Metals Concentration in Unpasteurized Cow Milk

Metals	Mean ± SD	95% CI(Lower)	95% CI(Higher)	WHO Standard Limit
Cadmium (Cd)	0.017±0.0114	0.008	0.026	0.003
Chromium (Cr)	0.153±0.0687	0.104	0.211	0.05
Lead (Pb)	0.220±0.0954	0.150	0.294	0.001
Mercury (Hg)	0.003±0.0013	0.002	0.004	0.010

The mean concentration of Cadmium in unpasteurized milk samples was 0.017 ± 0.0114 mg/L with a 95% confidence interval (CI) of 0.008–0.026 mg/L, which is higher than the WHO permissible limit of 0.003 mg/L. Chromium recorded a mean concentration of 0.153 ± 0.0687 mg/L (95% CI: 0.104–0.211 mg/L), also exceeding the WHO standard of 0.05 mg/L. Lead showed the highest deviation, with a mean value of 0.220 ± 0.0954 mg/L (95% CI: 0.150–0.294 mg/L) compared to the WHO safe limit of 0.001 mg/L. Mercury, however, had a mean concentration of 0.003 ± 0.0013 mg/L (95% CI: 0.002–0.004 mg/L), which remained below the WHO permissible limit of 0.01 mg/L.

Table 5: Estimated Daily Intake (EDI) of Heavy Metals in Pasteurized and Unpasteurized Cow Milk

Metals	Pasteurized(adult)	Pasteurized(children)	Unpasteurized(adult)	Unpasteurized(children)
Cadmium (Cd)	8.60×10^{-5}	2.00×10^{-4}	1.21×10^{-4}	2.83×10^{-4}
Chromium (Cr)	1.09×10^{-3}	2.55×10^{-3}	1.09×10^{-3}	2.55×10^{-3}
Lead (Pb)	1.63×10^{-3}	3.80×10^{-3}	1.57×10^{-3}	3.67×10^{-3}
Mercury (Hg)	1.86×10^{-5}	4.33×10^{-5}	2.14×10^{-5}	5.00×10^{-5}

The estimated daily intake (EDI) of heavy metals in pasteurized and unpasteurized cow milk showed that children had higher exposure levels than adults due to their lower body weight. In pasteurized milk, the EDI values ranged from 1.86×10^{-5} mg/kg·day (Hg) to 3.80×10^{-3} mg/kg·day (Pb) in children, while in adults, values ranged from 8.60×10^{-5} mg/kg·day (Cd) to 1.63×10^{-3} mg/kg·day (Pb). In unpasteurized milk, a similar trend was observed, with children recording the highest EDI for Pb (3.67×10^{-3} mg/kg·day) and the lowest for Hg (5.00×10^{-5} mg/kg·day). Overall, Pb and Cr showed the highest daily intake values across both age groups, while Hg consistently showed the lowest, as presented in Table 5.

Table 6: Target Hazard Quotient (THQ) and Hazard Index (Hi)

Metals	Pasteurized(adult)	Pasteurized(children)	Unpasteurized(adult)	Unpasteurized(children)
Cadmium (Cd)	0.043	0.100	0.061	0.142
Chromium (Cr)	0.004	0.009	0.004	0.009
Lead (Pb)	0.041	0.096	0.039	0.092
Mercury (Hg)	0.0006	0.001	0.0007	0.002
HI (∑THQ)	0.088	0.206	0.105	0.245

The target hazard quotient (THQ) analysis indicated that for both adults and children, all metals had THQ values well below the safety threshold of 1 in both pasteurized and unpasteurized milk. The hazard index (HI), which represents the cumulative non-carcinogenic risk, was also below 1 across all groups, with values of 0.088 and 0.105 for adults (pasteurized and unpasteurized, respectively) and 0.206 and 0.245 for children. These findings suggest that consumption of cow milk, whether pasteurized or unpasteurized, does not pose significant non-carcinogenic health risks from the studied metals. However, children showed relatively higher HI values compared to adults, indicating greater susceptibility due to lower body weight.

Table 7: Incremental Lifetime Cancer Risk (ILCR) of Heavy Metals in Cow Milk

Metals	Pasteurized(adult)	Pasteurized(children)	Unpasteurized(adult)	Unpasteurized(children)
Cadmium (Cd)	4.30×10^{-6}	1.00×10^{-5}	6.05×10^{-6}	1.42×10^{-5}
Chromium (Cr)	1.64×10^{-5}	3.83×10^{-5}	1.64×10^{-5}	3.83×10^{-5}
Lead (Pb)	8.16×10^{-6}	1.90×10^{-5}	7.85×10^{-6}	1.83×10^{-5}
Total ILCR	2.89×10^{-5}	6.73×10^{-5}	3.03×10^{-5}	7.08×10^{-5}

The incremental lifetime cancer risk (ILCR) assessment showed that for adults, the total ILCR values were 2.89×10^{-5} (pasteurized) and 3.03×10^{-5} (unpasteurized), while for children, they were higher at 6.73×10^{-5} (pasteurized) and 7.08×10^{-5} (unpasteurized). All these values fall within the generally acceptable risk range of 1×10^{-6}–1×10^{-4}, although children's values approach the upper bound, indicating relatively higher vulnerability. Among the studied metals, chromium contributed the most to the overall cancer risk, followed by cadmium and lead. Mercury was not included in the ILCR analysis, as it is not considered carcinogenic in this context. These findings suggest that while the cancer risk from milk consumption is within acceptable limits, continuous monitoring is advisable, especially for children, who exhibited comparatively higher ILCR values.

Discussion

The current findings of this study revealed the presence of heavy metals (Cadmium, Chromium, Mercury, and Lead) in both pasteurized and unpasteurized cow milk samples collected in Gashua, Yobe State, Nigeria. The concentrations of Cadmium, Chromium, and Lead in both milk types exceeded the World Health Organization (WHO) permissible limits, while Mercury concentrations remained within safe levels. The higher findings are likely due to a combination of environmental contamination (soil, water, feed), anthropogenic activities, and possible contamination during processing. Our study revealed that cadmium (Cd) levels in both pasteurized (0.012 mg/L) and unpasteurized milk (0.017 mg/L) were significantly higher than the WHO standard of 0.003 mg/L. Chronic cadmium exposure is associated with kidney dysfunction, skeletal damage, and an increased risk of cancer. The elevated concentrations suggest contamination from environmental sources such as polluted water, fodder, or industrial activities. This finding is consistent with reports from Pakistan (Mohammed *et al.,* 2013), Bangladesh (Muhib *et al.*, 2016), Iraq (Dipak *et al.,* 2025), and Yobe State, Nigeria (Usur *et al.,* 2024; Gashua *et al.,* 2025), where higher concentrations of cadmium were also detected in pasteurized cow milk. This study found that chromium (Cr) concentrations also exceeded the permissible limit of 0.05 mg/L, averaging 0.153 mg/L in both pasteurized and unpasteurized samples. Although chromium is an essential trace element in small amounts, excessive intake is toxic and carcinogenic. The relatively high levels may reflect contamination from soil, water, or feed supplements. This finding is consistent with reports from Bangladesh (Islam *et al.,* 2015; Muhib *et al.,* 2016) and Nigeria (Usur *et al.,* 2024; Sunday *et al.,* 2024), where higher concentrations of chromium were also detected in milk samples. Our study showed that lead (Pb) levels in both milk categories were extremely high (0.228 mg/L in pasteurized and 0.220 mg/L in unpasteurized milk), exceeding the WHO safe limit of 0.001 mg/L by more than 200-fold. Lead is a potent neurotoxin, particularly harmful to children, as it can cause impaired cognitive development, anemia, and other systemic health effects. The very high concentrations observed in this study highlight a serious public health concern. Similarly, high levels of lead in milk and meat have been reported in Nigeria (Gashua *et al.,* 2025; Usur *et al.,* 2024; Ali *et al.,* 2011; Sunday *et al.,* 2024; Faleye *et al.,* 2024), Bangladesh (Islam *et al.,* 2015; Rahaman *et al.,* 2020), Palestine (Abdul *et al.,* 2012), Pakistan (Mohammed *et al.,* 2013), and Iraq (Dipak *et al.,* 2025). However, our findings differ from those of Hassan *et al.,* (2022) in Bangladesh, who reported the lowest concentrations of lead in both pasteurized and unpasteurized milk, and also contrast with the report from Kaduna Metropolis, Nigeria, where lower concentrations were detected in various branded and unbranded cow milk samples (Sani *et al.,* 2020). Of the study findings, mercury (Hg) concentrations were within the World Health Organization (WHO) safety limits (0.0026–0.003 mg/L compared to the permissible level of 0.01 mg/L). This suggests a lower risk of mercury toxicity from milk consumption in this region, although continuous monitoring remains important due to the risk of bioaccumulation. These findings differ from reports in Nigeria (Sunday *et al.,* 2024; Usur *et al.,* 2024), where higher concentrations of mercury were detected in some milk samples. The health risk assessment showed that children are more vulnerable than adults, with higher estimated daily intake (EDI) and hazard index (HI) values due to their lower body weight. Although the target hazard quotient (THQ) and HI values were below 1, suggesting no immediate non-carcinogenic risks, the incremental lifetime cancer risk (ILCR) values particularly from chromium (Cr), cadmium (Cd), and lead (Pb) were close to the upper acceptable limit, especially in children.

CONCLUSION

In conclusion, this study found that pasteurized and unpasteurized cow milk in Gashua, Yobe State, Nigeria, contained cadmium (Cd), chromium (Cr), and lead (Pb) above World Health Organization (WHO) permissible limits, while mercury remained within safe levels. Although non-carcinogenic risks were low, carcinogenic risks especially in children approached the upper acceptable limit, with chromium (Cr) as the main contributor. These results point to environmental contamination as the source and highlight the need for to strengthening regulations and monitoring, educating stakeholders on contamination risks, and promoting safe water, feeding, and hygiene practices to ensure milk safety and protect public health.

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