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Research paper

Assessment of Potentially Toxic Elements in Tea Beverages Prepared by Vendors Within Bayero University kano Old Campus: Implications for Public Health

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Abstract

Tea is one of the most widely consumed beverages worldwide, making contamination by potentially toxic metals a public health concern. This study determined the concentrations of arsenic (As), cadmium (CD), chromium (Cr), nickel (Ni), and lead (Pb) in five commercially available tea brands sold around Bayero University Kano (BUK) Old Campus, Nigeria, and assessed their transfer into tea infusions and associated health risks. Maximum concentrations in dry tea were 0.72 mg/kg (As), 0.21 mg/kg (Cd), 3.88 mg/kg (Cr), 3.84 mg/kg (Ni), and 3.85 mg/kg (Pb), while maximum concentrations in tea infusions were 0.024, 0.00080, 0.044, 0.05180, and 0.01060 mg/L, respectively. Transfer rates ranged from 14.0–27.8% (As), 14.0–19.0% (Cd), 35.2–64.2% (Cr), 28.1–67.5% (Ni), and 11.9–13.8% (Pb). Significant differences in mean metal concentrations were observed ($p < 0.05$), and Pearson correlation analysis revealed strong positive associations among Cr, Ni, and Cd, indicating possible common sources or similar accumulation behavior. Estimated daily intakes were below their respective oral reference doses, while hazard quotients and hazard indices (4.56×10^{-2}–2.68×10^{-1}) remained below 1, indicating negligible non-carcinogenic risk. However, total cancer risks (3.39×10^{-5}–7.45×10^{-4}) exceeded acceptable lifetime limits for some tea brands, suggesting a potential carcinogenic risk from long-term consumption.

Keywords: *Arsenic; Cadmium; Cancer Risk; Chromium; Health Risk Assessment; Lead; Nickel; Potentially Toxic Elements; Tea Beverage; Transfer Rate.*

1. Introduction

Tea is one of the most widely consumed beverages globally and is valued not only for its refreshing properties but also for its potential health benefits. Regular tea consumption has been associated with a reduced risk of several chronic diseases, including cardiovascular disorders, diabetes, certain cancers, and neurodegenerative diseases[1]. The worldwide consumption of tea, estimated at billions of cups daily, highlights its considerable social, cultural, and economic significance [2]. As one of the most traded agricultural commodities, tea is cultivated and consumed across Asia, Africa, Europe, and the Americas, making its quality and safety an issue of global public health concern.

Despite its benefits, tea may serve as a pathway for human exposure to heavy metals. Tea plants can absorb metals from contaminated soils, irrigation water, fertilizers, pesticides, and atmospheric deposition during cultivation [3]. In addition, processing, packaging, transportation, storage, and preparation practices may further contribute to metal contamination. Consequently, the consumption of contaminated tea may increase the accumulation of toxic elements in the human body. However, not all the metals present in tea leaves are leached into the infusion, as the transfer of metals depends on their chemical characteristics, tea type, and brewing conditions. Studies conducted in major tea-producing countries such as China, India, Sri Lanka, Kenya, and South Africa have reported varying concentrations of heavy metals in tea products, emphasizing the need for routine quality assessment worldwide.

The widespread use of agrochemicals in tea plantations has raised concerns regarding the transfer of contaminants from the environment to tea leaves. Studies have shown that pesticide residues and heavy metals present in agricultural soils can be taken up by tea plants and subsequently enter the food chain [4]. Variations in environmental pollution, agricultural practices, industrial activities, and climatic conditions across different regions may influence the extent of contamination. Given the increasing popularity of tea consumption, continuous monitoring of its quality and safety is essential to protect public health.

Heavy metals are naturally present in the environment; however, anthropogenic activities such as industrialization, mining, waste disposal, urbanization, fossil fuel combustion, and intensive agriculture can significantly elevate their concentrations in soils and water bodies [5]. These metals are characterized by their persistence, non-biodegradable nature, and potential to bioaccumulate in living organisms. Human exposure occurs primarily through ingestion, inhalation, and dermal contact, with the severity of toxic effects depending on the level of exposure, duration, and chemical form of the metal [6]. Numerous studies conducted worldwide have demonstrated that heavy metals can

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accumulate in agricultural products and beverages, making food safety monitoring an important component of environmental and public health protection.

Certain metals, including iron (Fe), zinc (Zn), copper (Cu), cobalt (Co), and manganese (Mn), are essential micronutrients required for various physiological and biochemical processes. They serve important functions in enzyme activation, metabolism, growth, and immune responses [5]. However, excessive exposure to these metals may result in adverse health effects. However, toxic metals such as lead (Pb) and cadmium (Cd) have no known beneficial biological role and can cause severe health problems even at relatively low concentrations.

Lead exposure has been linked to hematological, neurological, developmental, and renal disorders. One of its toxic mechanisms involves the inhibition of δ-aminolevulinic acid dehydratase, an important enzyme in heme biosynthesis, thereby disrupting normal physiological functions [7]. Cadmium, on the other hand, is recognized for its carcinogenic potential and has been associated with kidney damage, oxidative stress, osteoporosis, and several chronic diseases[8]. Consequently, the assessment of heavy metal concentrations in tea and other beverages is crucial for evaluating potential health risks and ensuring consumer safety.

Heavy metals are capable of moving between environmental compartments, including soil, water, air, plants, animals, and humans, where they undergo physical, chemical, and biological transformations that influence their mobility, bioavailability, and toxicity. This environmental cycling facilitates their transfer into agricultural products, including tea. Tea is one of the most widely consumed beverages worldwide and is prepared from the processed leaves of the tea plant, Camellia sinensis. Depending on the degree of processing and oxidation, tea is classified into black, green, oolong, and white tea. In addition to its popularity as a beverage, tea consumption has attracted considerable scientific interest because of its potential health benefits, particularly its protective effects against cardiovascular diseases and stroke [9].

Although numerous studies have investigated heavy metal contamination in tea from major tea-producing and consuming countries, information on tea beverages prepared and sold by local vendors in many developing countries, including Nigeria, remains limited. This is particularly important because contamination may occur not only during cultivation but also during processing, packaging, storage, preparation, and handling before consumption.

This study was undertaken in response to the widespread consumption of tea beverages by students within the Old Campus of Bayero University, Kano. Tea is commonly consumed throughout the day, from the early morning until late at night, and serves as a convenient meal substitute for many students due to busy academic schedules, limited time for food preparation, and, in some cases, habitual consumption.

Despite its popularity, there is limited information on the levels of potentially toxic elements that may be present in tea beverages sold by vendors on campus, as well as the health risk associated with their consumption. Therefore, this study aims to determine the concentrations of selected heavy metals in tea beverages sold within Bayero University Old Campus and assess whether their levels pose any potential health risk to the student population.

2. Materials and Methods

All chemicals and reagents used were of analytical-reagent (AR) grade, and deionized water was used throughout for the preparation of standards, blanks, and sample dilutions. To minimize trace-element contamination, all glassware and sample-contact materials were washed with laboratory detergent, rinsed with tap water, treated with 10% (v/v) HNO_3, and thoroughly rinsed with deionized water before use. This procedure was consistent with the laboratory-cleaning recommendations of[10].For trace-element determination, which recognizes reagent purity and glassware cleanliness as important factors affecting blank levels and analytical quantification.

2.1. Samples collection

Five commercially available tea brands commonly consumed by students were selected for analysis from vendors operating within the Old Campus of Bayero University Kano (BUK), Kano State, Nigeria. The selected brands were identified by their local trade names and coded as BUZ (Buz), AHM (Ahmar), AGG (Argagai), LPN (Local Lipton), and HLD (High Land). For each brand, three retail samples were purchased from three different vendors operating within the Old Campus, giving a total of 15 primary samples (five brands × three vendors). The samples were obtained from different production batches where available to minimise the likelihood of repeatedly sampling material from the same batch; however, batch or lot identification numbers were not recorded.

For each brand, the three samples obtained from the different vendors were combined in equal proportions by mass to form a composite sample. Each composite was thoroughly mixed and homogenised to promote uniform distribution of the constituents. Approximately 100 g of each homogenised composite sample was transferred into a clean, labelled polyethylene bag and securely sealed to minimise contamination and moisture uptake. The samples were transported to the laboratory and stored in a cool, dry environment at room temperature, away from direct sunlight, until sample preparation and analysis.

2.2 Sample Preparation and Digestion of Dry Tea Samples

A 20.00 g portion of each homogenized tea sample was accurately weighed into a clean porcelain crucible and ashed at 500 °C in a muffle furnace until a uniform light-gray ash was obtained. After cooling, the ash was quantitatively transferred to a digestion vessel and treated with 12 mL of a 3:1 (v/v) mixture of concentrated nitric acid (HNO_3, 65% w/w, specific gravity 1.40 g/mL) and perchloric acid ($HClO_4$, 70% w/w, specific gravity 1.67 g/mL), both of analytical-reagent grade. The samples were subjected to microwave-assisted digestion until complete dissolution was achieved. The cooled digests were filtered through Whatman No. 42 filter paper into 100 mL volumetric flasks and diluted to volume with deionized water. The resulting solutions were transferred into clean polyethylene bottles and stored until elemental analysis[11].

2.3. Preparation and digestion of tea infusions

For each sample, 2.00 g of dry tea was accurately weighed into a clean porcelain vessel and infused with 100 mL of deionized water. The mixture was boiled for 10 min, stirred periodically with a clean plastic rod, covered, and allowed to stand for 3–8 min to simulate typical tea preparation. No additives were used. The infusion was filtered, evaporated to near dryness, and the residue digested with 12 mL of a 3:1 (v/v) mixture of concentrated HNO_3 (65% w/w; specific gravity 1.40 g/mL) and $HClO_4$ (70% w/w; specific gravity 1.67 g/mL).

Microwave-assisted digestion was continued until a clear solution was obtained. After cooling, the digest was filtered and made up to 100 mL with deionized water before storage in clean polyethylene bottles[12].
The digestion procedure was validated using an appropriate certified reference material (CRM), and the prepared dry-tea and infusion digests were analyzed for selected potentially toxic metals by Microwave Plasma–Atomic Emission Spectrometry (MP-AES) at the Centre for Dryland Agriculture, Bayero University Kano.

2.4. Instrumentation

The digested dry-tea and infusion samples were transferred into clean, acid-washed MP-AES tubes and analyzed using an Agilent 4200 MP-AES (Agilent Technologies) after instrument stabilization under the manufacturer's recommended conditions. Calibration was performed with freshly prepared external multi-element standards covering the expected concentration ranges of As, Cd, Cr, Ni, and Pb. Reagent blanks, calibration verification standards, duplicates, and quality-control samples were included throughout the analytical sequence to monitor contamination, calibration stability, accuracy, and precision.
The samples were introduced into the nitrogen microwave plasma, where the analytes were atomized and excited, and their characteristic emission intensities were measured at the selected analytical wavelengths. Elemental concentrations were calculated from the respective calibration curves after appropriate blank correction. Each sample was analyzed in triplicate, and the mean concentration was used for subsequent statistical analysis. Method accuracy was verified using an appropriate certified reference material (CRM)[13].

2.5. Human health risk assessment

Non-Carcinogenic Risk Assessment
The potential non-carcinogenic health risk associated with the consumption of tea infusions was evaluated by estimating the Estimated Daily Intake (EDI) of the selected potentially toxic elements using Equation (1):

$$\text{EDI (mg/kg body weight/day)} = (C \times IR \times TR) / (BW \times 1{,}000[14] \quad (1)$$

Where C is the concentration of the metal in the tea infusion (mg/kg), IR is the average daily tea ingestion rate (11.4 g person^{-1} day^{-1}) [11]. TR is the transfer rate of the metal from the dry tea leaves to the prepared infusion, expressed as the ratio of the metal concentration in the infusion to that in the tea leaves, and BW is the average body weight (kg). The factor 1,000 was used to convert the ingestion rate from grams to kilograms. As the study population consisted exclusively of university students, only adult exposure was considered. Accordingly, an average adult body weight of 70 kg was adopted for the EDI calculation [15].
The non-carcinogenic health risk was further assessed using the Target Hazard Quotient (THQ), which compares the estimated exposure level with the corresponding oral reference dose (RfD). The THQ was determined using Equation (2):

$$\text{THQ} = \text{Exposure dose/Oral reference dose (RfD)[16]. (mg/kg/day)} \quad (2)$$

Where RfD represents the oral reference dose (mg/kg/day) established by regulatory agencies. An individual metal is considered unlikely to pose adverse non-carcinogenic effects when THQ < 1, whereas THQ ≥ 1 indicates a potential health concern due to long-term exposure. The oral reference dose values used in this study were 0.001 mg/kg/day for Cd, 0.003 mg/kg/day for Cr, 0.020 mg/kg/day for Ni, 0.0003 mg/kg/day for As, and 0.0035 mg/kg/day for Pb, as recommended by the United States Environmental Protection Agency and previous studies[17].
To estimate the cumulative non-carcinogenic effects arising from simultaneous exposure to multiple metals, the Hazard Index (HI) was calculated as the sum of the individual THQ values.

$$THQ_i = THQ_1 + THQ_2 + THQ_3 \text{----------} THQ_n \text{-[18]} \quad (3)$$

Where THQ_i is the Target Hazard Quotient for the ith metal. An HI value below 1 indicates that combined exposure is unlikely to result in adverse health effects, whereas an HI value equal to or greater than 1 suggests the possibility of cumulative non-carcinogenic health risks.

2.6. Carcinogenic risk assessment

The lifetime carcinogenic risk associated with the ingestion of carcinogenic metals through tea consumption was estimated using the Estimated Cancer Risk (ECR), calculated according to Equation (4):

$$ECRi = EDI \times CSFo \text{ [19].} \quad (4)$$

Where EDI is the estimated daily intake (mg/kg/day), and CSF_o is the oral cancer slope factor (mg/kg/day)$^{-1}$.
The oral cancer slope factors adopted in this study were 6.3 for Cd, 0.5 for Cr, 1.7 for Ni, 1.5 for As, and 0.0085 for Pb, based on values reported by the United States Environmental Protection Agency. The calculated ECR values were interpreted according to USEPA guidelines to determine the potential lifetime cancer risk associated with long-term consumption of tea infusions contaminated with these potentially toxic elements.

2.7. Statistical analysis

Statistical analysis was performed using Analysis of Variance (ANOVA) in IBM SPSS Statistics version 26, a widely recognized statistical software package. The analysis was conducted to determine whether the concentrations of the analyzed metals differed significantly among the various tea brands. The ANOVA results indicated significant differences, as the p-value was less than the significance level of 0.05. This suggests that the observed variations in metal concentrations among the tea brands were statistically significant.

3. Results and Discussion

Table1: The Mean Concentrations of Some Heavy Metals in Dry Tea Samples

	As	Cd	Cr	Ni	Pb
BUZ	BDL	0.12±0.01	2.85±0.28	3.72±0.41	BDL
AHM	BDL	0.16±0.01	1.73±0.34	3.84±0.52	3.12±0.22
AGG	0.39±0.02	0.10±0.01	BDL	2.96±0.36	2.18±0.15
LPN	0.72±0.05	0.21±0.02	3.88±0.00	BDL	3.85±0.28
HLD	0.51±0.03	0.14±0.01	2.32±0.31	2.21±0.46	BDL

Table 2: The Mean Concentrations of Some Metals in Tea Infusion(Mg/L)

	As	Cd	Cr	Ni	Pb
BUZ	BDL	0.00038±0.002	0.02008±0.09	0.04040±0.14	BDL
AHM	BDL	0.00054±0.002	0.01419±0.12	0.05180±0.18	0.00740±0.03
AGG	0.0160±0.01	0.00028±0.01	BDL	BDL	BDL
LPN	0.00400±0.02	0.0008±0.003	0.044±0.15	BDL	0.01060±0.04
HLD	0.024±0.002.	0.00048±0.10	0.02980±0.14	0.01242±0.04	BDL

Table 3: Transfer Rates of Heavy Metals from Dry Tea to Infusion (%)

	As.	Cd.	Cr	Ni	Pb
BUZ	BDL	15.8	35.22	54.30	BDL
AH	BDL	16.9	41	67.45	11.86
AGG	20.51	14.0	BDL	BDL	BDL
LPN	27.78	19.0	56.70	BDL	13.77
HLD	23.53	17.1	64.22	28.1	BDL

Table 4: Estimated Daily Intakes of Some Metals in Selected Brands of Tea from BUK Old Campus

	As	Cd	Cr	Ni	Pb
BUZ	0.00	3.09×10^{-6}	2.13×10^{-4}	3.28×10^{-4}	4.46×10^{-5}
AHM	0.00	4.40×10^{-6}	1.16×10^{-4}	4.22×10^{-4}	6.03×10^{-5}
AGG	1.30×10^{-5}	2.29×10^{-6}	0.00	0.00	0.00
LPN	3.26×10^{-5}	6.50×10^{-6}	3.58×10^{-4}	1.66×10^{-4}	8.63×10^{-5}
HLD	1.95×10^{-5}	3.90×10^{-6}	2.43×10^{-4}	1.01×10^{-4}	0.00

Table 5: Hazard Quotients (HQ) and Hazard Indices(HI) of the Metals in the Tea Infusion

	As.	Cd.	Cr	Ni.	Pb.	HI
BUZ.	0.00	3.09×10^{-3}	7.10×10^{-2}	1.65×10^{-2}	1.2×10^{-2}	1.03×10^{-1}
AHM.	0.00	4.40×10^{-3}	3.89×10^{-2}	2.11×10^{-2}	1.7×10^{-2}	8.14×10^{-2}
AGG.	4.33×10^{-2}	2.28×10^{-3}	0.00	0.00	0.00	4.56×10^{-2}
LPN	1.09×10^{-1}	6.51×10^{-3}	1.19×19^{-1}	8.30×10^{-2}	2.47×10^{-2}	2.68×10^{-1}
HLD	1.55×10^{-1}	6.50×10^{-2}	3.91×10^{-3}	8.10×10^{-2}	0.00	3.05×10^{-1}

Table 6: Cancer Risk CR) and Total Cancer Risk (TCR) for All Metals in the Tea Infusions

	As.	Cd.	Ni.	Pb.	TCR
BUZ.	0.00	1.95×10^{-5}	5.58×10^{-4}	3.73×10^{-4}	5.79×10^{-4}
AHM	0.00	2.80×10^{-5}	7.16×10^{-4}	5.14×10^{-4}	7.45×10^{-4}
AGG	1.95×10^{-5}	1.39×10^{-5}	0.00	0.00.	3.39×10^{-5}
LPN	4.89×10^{-5}	4.09×10^{-5}	2.82×10^{-4}	7.34×10^{-7}	3.73×10^{-4}
HLD	2.93×10^{-5}	2.48×10^{-5}	1.72×10^{-4}	0.00	2.26×10^{-4}

Table 7: ANOVA

Groups	Count	Sum	Average	Variance		
BUZ	5	3557.89	508.27	29092.694		
AHM	5	5263	751.85714	78916.196		
ACG	5	565.72	80.817143	214.58326		
LPN	5	14.31	2.0442857	0.7725539		
HLD	5	27.118	3.874	1.9795307		
Source of Variation	SS	Df	MS	F	P-value	F crit
Between Groups	3271592.775	4	817898.19	37.786506	2.61354E-11	2.6896276
Within Groups	649357.355	20	21645.245			
Total	3920950.13	24				

Table 8: Correlation Results

	BUZ	AHM	AGG	LPN	HLD
BUZ	1				
AHM	0.999574092	1			
AGG	0.996149413	0.99801863	1		
LPN	0.998867291	0.99892794	0.99806206	1	
HLD	0.999684512	0.99901741	0.99609959	0.99946341	1

	As	Cd	Cr	Ni	Pb
As	1				
Cd	0.514794949	1			
Cr	0.528417307	0.75375923	1		

Ni	0.705182567	0.64401967	0.9454523	1	
Pb	-0.433899116	-0.12541213	0.26524471	0.1997731	1

Arsenic (As)

Tables 1 and 2 show that arsenic (As) was not detected (BDL) in the dry tea samples of BUZ and AHM, whereas AGG, LPN, and HLD contained 0.39 ± 0.02, 0.72 ± 0.05, and 0.51 ± 0.03 mg/kg, respectively. Following infusion, As remained undetectable in BUZ and AHM but was detected at 0.016 ± 0.01, 0.004 ± 0.02, and 0.024 ± 0.002 mg/L in AGG, LPN, and HLD, respectively. The concentrations in AGG, LPN, and HLD exceeded the recommended maximum limit of 0.30 mg/kg, suggesting potential environmental or agricultural contamination. Possible sources include contaminated soil and irrigation water, atmospheric deposition, and agrochemical inputs.

The considerably lower concentrations in the infusions indicate limited transfer of As from the tea leaves into the beverage. The maximum infusion concentration was 0.024 mg/L in HLD, compared with 0.72 mg/kg in the corresponding dry tea. This substantial reduction suggests that a relatively small fraction of the As present in the leaves was released during brewing, possibly because of its association with less soluble components of the plant matrix.

The maximum infusion concentration in the present study (0.024 mg/L) was lower than the 0.20 mg/L reported by [20] for teas marketed in Ghana, 0.21 mg/L reported by [21] for Chinese teas, and 0.325 mg/L reported by [22]. However, it was slightly higher than the 0.021 mg/L reported by [23] for Brazilian teas and fell within the range of 0.008–0.445 mg/L reported for teas marketed in Riyadh, Saudi Arabia [24]. The differences among studies may reflect variations in geographical origin, soil geochemistry, environmental contamination, agricultural practices, tea cultivar, processing, and brewing conditions.

Cadmium (Cd)

As presented in Tables 1 and 2, cadmium (Cd) concentrations in the dry tea samples ranged from 0.10 ± 0.01 mg/kg in AGG to 0.21 ± 0.02 mg/kg in LPN, while the corresponding infusions contained 0.00028 ± 0.01–0.00080 ± 0.003 mg/L. All dry tea samples were below the FAO/WHO maximum permissible limit of 0.50 mg/kg. The low infusion concentrations, with a maximum of 0.00080 mg/L in LPN, indicate limited transfer of Cd from the leaves into the beverage during brewing.

The maximum Cd concentration in the present infusions was substantially lower than the 0.05 mg/L reported by [13], 0.37 ± 0.01 mg/L reported for Nigerian teas by [25], and 0.248 ± 0.027 mg/L reported for green tea from the Palestinian market [26]. It was also considerably lower than the 0.92–3.98 mg/L reported for teas marketed in Jazan, Saudi Arabia [27] Chromium (Cr)

As shown in Tables 1 and 2, chromium (Cr) was not detected in AGG but was present in AHM, HLD, BUZ, and LPN at 1.73 ± 0.34, 2.32 ± 0.31, 2.85 ± 0.28, and 3.88 ± 0.48 mg/kg, respectively. In the corresponding infusions, concentrations were 0.02008 ± 0.09, 0.01419 ± 0.12, 0.02980 ± 0.14, and 0.044 ± 0.15 mg/L in BUZ, AHM, HLD, and LPN, respectively, while AGG showed no detectable Cr. The dry tea concentrations in BUZ, HLD, and LPN exceeded the commonly accepted limit of 2.0 mg/kg, indicating elevated Cr levels in these brands.

Despite the relatively high concentrations in dry tea, only low concentrations were detected in the infusions, with a maximum of 0.044 mg/L. This indicates limited transfer of Cr during brewing. The maximum concentration was lower than the 0.39 ± 0.03 mg/L reported for teas from Lagos, Nigeria by [28], 0.721 mg/L reported for green tea from Hangzhou, China by [18], and 0.16 ± 0.11 mg/L reported for Japanese green herbal tea by [29]. It was, however, higher than the 0.0023 mg/kg reported for imported herbal dry teas consumed in Dutsin-Ma, Katsina State, Nigeria by [30]. Since total Cr was determined in the present study, its oxidation state could not be established.

Nickel (Ni)

Tables 1 and 2 show that nickel (Ni) was not detected in LPN dry tea but was present in HLD, AGG, BUZ, and AHM at concentrations of 2.21 ± 0.46, 2.78 ± 0.38, 3.72 ± 0.41, and 3.84 ± 0.52 mg/kg, respectively. These concentrations exceeded the permissible limit of 1.63 mg/kg. In the corresponding infusions, Ni was not detected in AGG but was measured at 0.01242 ± 0.04, 0.05180 ± 0.18, and 0.04040 ± 0.14 mg/L in HLD, AHM, and BUZ, respectively. Thus, the maximum Ni concentration in the infusion was 0.05180 mg/L in AHM, considerably lower than the concentration in the corresponding dry tea.

Compared with previous studies, the maximum concentration observed in the present study was lower than the 0.19 ± 0.71 mg/L reported for tea from Neyshabur City, Iran [30], 10.70 ± 4.37 mg/L reported for green tea from Hangzhou, China [17] and 65.5 ± 14.2 mg/L reported for brewed black tea from Türkiye [32]

Lead (Pb)

As presented in Tables 1 and 2, lead (Pb) was not detected in BUZ and HLD, while AGG, AHM, and LPN contained 2.18 ± 0.15, 3.12 ± 0.22, and 3.85 ± 0.28 mg/kg, respectively. Following infusion, Pb remained undetectable in BUZ, AGG, and HLD but was detected at 0.00740 ± 0.03 and 0.01060 ± 0.04 mg/L in AHM and LPN, respectively. Thus, the maximum Pb concentration in the infusion was only 0.01060 mg/L, demonstrating limited transfer from the dry tea into the beverage.

All dry tea samples were below the stated WHO/FAO permissible limit of 10.0 mg/kg. Nevertheless, the presence of Pb warrants attention because prolonged exposure may result in adverse neurological, renal, cardiovascular, and developmental effects. The maximum infusion concentration observed in this study was considerably lower than the 0.097 ± 0.10 mg/L reported for tea brands marketed in Zaria by [33] 0.052 ± 0.00 mg/L reported for tea infusions by [34], 0.16 ± 0.00 mg/L reported for tea by [35], 1.19 ± 0.00 mg/L reported by [36] and 35.13 mg/L reported for herbal teas from Abuja by [37].

Nickel (Ni)

From table3,above Nickel (Ni) showed considerable variation in transfer among the tea brands. No transfer was observed in AGG and LPN, while HLD, BUZ and AHM recorded 28.1%, 54.3% and 67.45%, respectively. The higher values indicate appreciable Ni mobility during brewing. The results are broadly comparable with the high Ni extraction reported by [38] and the substantial elemental transfer reported by [39] and [40], respectively.

Chromium (Cr)

Chromium (Cr) exhibited relatively high transfer, ranging from 35.22% in BUZ to 64.22% in HLD, while transfer could not be determined for AGG because Cr was not detected. The present values are generally comparable with the 42.3% mean Cr transfer reported by [38] and the substantial extraction reported by [41] and [39]. In contrast, [42], which investigated 497 black-tea samples, reported a maximum Cr transfer of only 5.96%.

Arsenic (As)

Arsenic (As) showed comparatively low-to-moderate transfer, with values of 20.51%, 23.53% and 27.78% for AGG, HLD and LPN, respectively, while transfer could not be determined for BUZ and AHM because As was not detected. The present values are considerably higher than the maximum As transfer of 8.53% reported by Barman et al. (2020)[42] for black tea. into the infusion.

Cadmium (Cd)

Cadmium (Cd) showed relatively low transfer, ranging from 14.0% in AGG to 19.0% in LPN, indicating that most Cd remained in the dry tea leaves. The results are close to the 14.3% Cd migration reported for green tea by [43] and are higher than the approximately 6.6% reported by [44] but significantly lower than the 53.6% mean transfer reported by [38]. Such differences among studies indicate that Cd extraction is strongly influenced by tea type, matrix characteristics, metal speciation, and brewing conditions.

Lead (Pb)

Lead (Pb) exhibited the lowest mobility among the investigated metals. Transfer rates of 11.86% and 13.77% were obtained for AHM and LPN, respectively, whereas no transfer was detected in BUZ, AGG, and HLD. These values are lower than the 31.5% mean Pb transfer reported by [38] and the higher migration rates reported by [43] for black (50.2%) and green tea (21.3%). However, the present values are within the broad range of Pb transfer reported in tea studies. The relatively low Pb mobility may be associated with stronger binding of Pb to tea constituents and the occurrence of less soluble Pb forms.

The variations in metal concentrations observed in this study and those reported in previous studies may be attributed to differences in environmental exposure, metal bioavailability, tea cultivar, geographical origin, soil characteristics, agricultural practices, and processing conditions. Variations in the extent to which individual metals are absorbed and retained by tea plants, together with differences in manufacturing, storage, analytical methods, and brewing procedures, may also contribute to the observed differences in metal concentrations among studies.

Table 4 presents the estimated daily intake (EDI) of the investigated metals through consumption of the selected tea brands. The EDI was estimated using an average adult body weight of 70 kg, a daily tea consumption rate of 11.4 g/person/day, and the experimentally determined transfer of metals into the brewed infusions. The EDI varied among the tea brands, reflecting differences in metal concentrations and their transfer from the tea leaves into the prepared beverage.

LPN recorded the highest EDI values for As (3.26×10^{-5} mg/kg bw/day), Cd (6.50×10^{-6} mg/kg bw/day), Cr (3.58×10^{-4} mg/kg bw/day), and Pb (8.63×10^{-5} mg/kg bw/day), whereas AHM had the highest Ni intake (4.22×10^{-4} mg/kg bw/day). The relatively high EDI values observed for these brands correspond with their comparatively elevated metal concentrations in the dry tea samples. AGG recorded lower detectable EDIs for As (1.30×10^{-5} mg/kg bw/day) and Cd (2.29×10^{-6} mg/kg bw/day), while Cr, Ni, and Pb were not detected in its infusion and therefore contributed no measurable EDI. As was also below the detection limit in the BUZ and AHM infusions, whereas Pb was not detected in BUZ and HLD. These variations indicate that the transfer of individual metals from tea leaves into the infusion differed among the brands.

Although Pb showed relatively limited transfer during brewing, its EDI exceeded those of As and Cd in several brands because of its comparatively high concentration in the dry tea samples. All EDI values were below their respective oral reference doses (RfDs), indicating that the estimated exposure to the investigated metals through consumption of the tea infusions was below the levels associated with appreciable non-carcinogenic risk under the exposure conditions considered.

The present findings are consistent with those reported by [19], [45 - 47], who similarly observed metal EDIs below their respective RfDs in tea and related beverages. These findings suggest that, based on the estimated daily consumption considered in the present study, exposure to the investigated metals through tea consumption remains within the corresponding non-carcinogenic reference levels.

3.1. Hazard quotient (HQ) and hazard index (HI)

Table 5 presents the hazard quotients (HQs) and hazard indices (HIs) calculated for the investigated metals. All individual HQ values were below 1.0, indicating that exposure to each metal individually was unlikely to produce appreciable non-carcinogenic effects at the estimated intake levels.

LPN recorded the highest HQs for As (1.09×10^{-1}), Cd (6.51×10^{-3}), Cr (1.19×10^{-1}), and Ni (8.30×10^{-2}), while AHM recorded the highest Pb HQ (1.70×10^{-2}). The relatively high HQs observed in LPN are connected with its relatively high EDIs for several metals. HLD also recorded a comparatively high As HQ of 1.55×10^{-1}.

The HI, representing the combined non-carcinogenic hazard of the investigated metals, ranged from 4.56×10^{-2} in AGG to 3.42×10^{-1} in LPN. HLD, BUZ, and AHM recorded HIs of 3.05×10^{-1}, 1.03×10^{-1}, and 8.14×10^{-2}, respectively. Since all HI values were below 1.0, the combined exposure to the investigated metals through consumption of the tea infusions is unlikely to pose a significant non-carcinogenic health risk under the assumed exposure conditions.

Chromium was included in the HI assessment because total Cr was determined and its non-carcinogenic contribution was evaluated. However, Cr was excluded from the carcinogenic risk assessment because the analytical procedure did not differentiate between Cr(III) and Cr(VI).

The findings agree with [47], who reported HQ and HI values below 1 for heavy metals in green tea consumed in Awka, Anambra State, Nigeria. Similar results were reported by [48] for Asphalatus linearis tea consumed in South Africa, [49] for tea infusions from Jiangsu Province, China, [50] for imported black tea in Iran, and [27] for tea samples from Jazan, Saudi Arabia. These studies, together with the present findings, indicate that although tea may contain measurable concentrations of potentially toxic metals, the resulting combined non-carcinogenic exposure can remain below the level of concern under normal consumption conditions.

3.2. Cancer risk (CR) and total cancer risk (TCR)

Table 6 presents the estimated cancer risks (CRs) and total cancer risks (TCRs) associated with consumption of the investigated tea infusions. Chromium was excluded from the carcinogenic assessment because only total Cr was determined, and the analytical procedure did not distinguish between Cr(III) and Cr(VI).

The CR values varied among the tea brands and metals. Detectable As-related cancer risks ranged from 1.95×10^{-5} in AGG to 4.89×10^{-5} in LPN, while Cd-related risks ranged from 1.39×10^{-5} in AGG to 4.09×10^{-5} in LPN. No As-related cancer risk was estimated for BUZ and AHM because As was not detected in their infusions. Ni represented the major contributor to carcinogenic risk in most brands, with CR values ranging from 1.72×10^{-4} in HLD to 7.16×10^{-4} in AHM. Pb contributed CR values ranging from 7.34×10^{-7} in LPN to 5.14×10^{-4} in AHM, while no Pb-related cancer risk was estimated for AGG and HLD because Pb was not detected in their infusions.

The TCR ranged from 3.34×10^{-5} in AGG to 1.26×10^{-3} in AHM. BUZ, LPN, and HLD recorded TCR values of 9.51×10^{-4}, 3.73×10^{-4}, and 2.26×10^{-4}, respectively. Using the commonly applied USEPA lifetime cancer-risk range of 1×10^{-6} to 1×10^{-4} as a screening benchmark, AGG was the only tea brand with a TCR below the upper benchmark of 1×10^{-4}. The TCR values for BUZ, AHM, LPN, and HLD exceeded this upper value, indicating potential carcinogenic concern under prolonged lifetime exposure at the assumed consumption rate.

AHM had the highest TCR (1.26×10^{-3}), primarily because of its relatively high Ni (7.16×10^{-4}) and Pb (5.14×10^{-4}) contributions. BUZ also recorded a relatively high TCR (9.51×10^{-4}), largely attributable to Ni and Pb. In LPN and HLD, Ni was the principal contributor to the total cancer risk. Thus, Ni represented the most important contributor to the estimated carcinogenic risk across the tea brands, although Pb also made a substantial contribution in AHM and BUZ.

The present findings are partly consistent with [11] who reported cancer-risk values within the USEPA acceptable range of 1×10^{-6} to 1×10^{-4}. Similarly, [51] found that the investigated tea samples had cancer-risk values within the recommended threshold, while [52] reported that heavy-metal-associated cancer risks in herbal teas consumed in Iran were below the acceptable limit. In contrast, [18] reported cancer-risk values exceeding 1×10^{-4} in several commercially available tea samples, which agrees with the elevated TCR values observed for four of the five tea brands in the present study.

The differences between the present findings and those of previous studies may be associated with variations in metal concentrations, geographical origin, environmental contamination, tea cultivar, agricultural practices, processing conditions, consumption rates, body-weight assumptions, and toxicity parameters used in the risk assessment. Such differences can substantially influence both estimated exposure and the resulting health-risk indices.

Collectively,the non-carcinogenic assessment indicated that none of the individual metals or their combined exposure exceeded the threshold of concern, as all HQ and HI values were below 1. However, the carcinogenic assessment produced a different pattern, with TCR values exceeding the upper screening benchmark for four of the five tea brands. These findings suggest that while the investigated teas may not present appreciable non-carcinogenic risks under the assumed exposure conditions, potential long-term carcinogenic risks associated particularly with Ni and Pb warrant attention.

3.3 As presented in Table 7, one-way ANOVA revealed a statistically significant difference in the mean concentrations of the analyzed metals ($F(4,30) = 37.79$, $p < 0.05$). The calculated F-value (37.79) exceeded the critical F-value (2.69), indicating significant variation in the concentrations of As, Cd, Cr, Ni, and Pb. Among the analyzed metals, cadmium and arsenic exhibited the highest mean concentrations, whereas chromium, lead, and nickel occurred at comparatively lower levels.

As shown in Table 8, Pearson correlation analysis revealed strong positive associations among chromium, nickel, and cadmium, with the strongest correlation observed between Cr and Ni ($r = 0.945$), suggesting a common source or similar accumulation behavior. Arsenic showed moderate positive correlations with Cd, Cr, and Ni ($r = 0.515–0.705$). On the other hand, lead displayed weak correlations with Cd, Cr, and Ni and a moderate negative correlation with As ($r = −0.434$), indicating a different source or accumulation pattern.

4. Conclusion

This study evaluated the concentrations of arsenic (As), cadmium (Cd), chromium (Cr), nickel (Ni), and lead (Pb) in commercially available tea products and their infusions, together with the associated health risks. Brewing reduced the concentrations of all investigated metals, although varying proportions were transferred into the infusions. Chromium and nickel showed the highest transfer rates, while lead exhibited the lowest.

The concentrations of As, Cd, and Pb in both dry tea and the prepared infusions were within the recommended permissible limits. However, Cr and Ni exceeded the guideline values in several samples, suggesting possible contamination during cultivation, processing, handling, or storage.

Health risk assessment showed that the Estimated Daily Intake (EDI), Hazard Quotient (HQ), and Hazard Index (HI) for all metals were below their respective safety thresholds, indicating no significant non-carcinogenic risk from normal tea consumption. However, the individual Cancer Risk (CR) values for As, Cd, Cr, and Ni, as well as the Total Cancer Risk (TCR), exceeded the acceptable limits recommended by the USEPA, indicating a potential lifetime carcinogenic risk associated with prolonged consumption of the teas.

4.1. Recommendations

Students who consume tea regularly should practice moderate consumption and maintain a varied diet to minimize long-term exposure to potentially toxic heavy metals.

Routine surveillance of heavy metals in tea products should be strengthened to ensure compliance with established food safety standards.

Tea producers should implement good agricultural and manufacturing practices to minimize heavy metal contamination during cultivation, processing, and packaging.

Regulatory agencies should prioritize measures to reduce chromium and nickel contamination, as their concentrations exceeded the recommended permissible limits in this study.

Periodic health risk assessments should be conducted to evaluate long-term exposure associated with tea consumption, while further research should identify the major sources of heavy metal contamination and assess potential health risks among vulnerable population groups.

Other toxic metals not included in this study and essential mineral elements should be investigated in the future.

4.2. Conflict of interest

The authors hereby declare that no conflicts of interest exist between them.

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