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Research Article

Toxicology assessment of heavy metals in selected tobacco cigarette brands

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ABSTRACT

This study investigates the toxicological profile of heavy metals and metalloid in seven commercially available tobacco cigarette brands in Nigeria. *Nicotiana tabacum* leaves are established hyper-accumulators of environmental heavy metals, posing significant public health risks. The objective was to quantify the concentration of 14 elements and evaluate the toxicological load of each brand relative to World Health Organization (WHO) and FAO safety standards. Samples underwent microwave-assisted digestion using a 10 mL acid mixture ((HNO$_3$, H$_2$SO$_4$, and H$_2$O$_2$), followed by analysis via Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). Pearson correlation analysis identified significant positive clusters ($p < 0.05$) for Ni-Os ($r = 0.91$), Cu-Sn ($r = 0.89$), and Cr-Al ($r = 0.83$), suggesting shared geogenic or industrial origins. Conversely, Platinum (Pt) exhibited strong negative correlations, serving as a unique indicator of varying tobacco sources. Principal Component Analysis (PCA) successfully categorized the brands into three distinct chemical profiles, identifying **TS6** as a major toxicological outlier due to peak concentrations of Cadmium and Chromium. The study confirms that heavy metal distribution is brand-dependent, with Lead (Pb) levels in specific brands exceeding the WHO permissible limit. Risk assessment revealed that while non-carcinogenic Hazard Indices (HI) remained within safe limits HI < 1.0, the Total Carcinogenic Risk (TCR) for all brands exceeded the 1 x 10^{-4} threshold. This risk is primarily driven by the carcinogenic potency of Chromium and Arsenic. These findings underscore an urgent need for stricter agricultural quality controls and regulatory monitoring to mitigate long-term carcinogenic impacts on the smoking population in Nigeria.

Keywords: Carcinogenic Risk, Heavy metals, ICP-OES analysis, Risk assessment, Tobacco cigarettes.

Introduction

Tobacco cigarette brands are notable for their elemental composition of hazardous toxic and carcinogenic heavy metals, including cadmium (Cd), lead (Pb), chromium (Cr), nickel (Ni), and arsenic (As). These heavy metals are highly toxic and significant carcinogens [1]. Prior to 2022, British American Tobacco Nigeria (BATN) dominated the Nigerian tobacco market with a 65.4% share of tobacco production [2]. Thereafter, a change to local production of major brands witnessed brands like Benson & Hedges and Rothmans being manufactured locally. Pall Mall and Chesterfield brands, marketed by BAT and Philip Morris respectively, are widely available in Nigeria. Other popular brands include Timeless, Oris, and Bohem. The total market value for tobacco products in Nigeria is projected to reach approximately $653 million to $670 million by 2028 [3]

The tobacco industry cannot be ignored due to its direct public health concern in recent years. Various forms of tobacco consumption, including cigarettes, cigars, and smokeless tobacco, have been linked to numerous health risks and environmental consequences. Tobacco cigarette smoking remains the most common form of tobacco consumption worldwide. A study found that the global prevalence of cigarette smoking among adults has declined from 22.7% in 2010 to 19.6% in 2019 [4]. Additionally, a systematic review reported that exposure to secondhand smoke

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was associated with an increased risk of adverse health outcomes, particularly in children and pregnant women [5].

Smokeless tobacco, including chewing tobacco and snuff, has been used traditionally; however, a study noted an emerging trend of increased use among younger populations, particularly in low- and middle-income countries [6]. Cigars include traditional hand-rolled and machine-made varieties. The Centers for Disease Control and Prevention (CDC) found that the prevalence of cigar smoking among young adults (18-24) in the United States was 12.1%, raising concerns about the appeal to this demographic [7].

Statement of Problem and Aim of Study

Heavy metal contamination in tobacco occurs as leaves often accumulate concentrations exceeding safety standards [8]. The elevated levels of toxic metals, radioactive elements, and transition heavy metals are major toxicology problems associated with tobacco products. This study focused on estimating the concentration of heavy metals in selected tobacco cigarette brands in Nigeria, with the objective of assessing the toxicological load of each brand in comparison with WHO standards.

Heavy Metals in Tobacco Cigarettes and its Toxicity

Toxicity of heavy metals is a significant concern as they can be highly toxic even at low concentrations. Bioaccumulation from soil, water, or air creates a toxic load in plant leaves, fruits, and roots, impairing growth and development [9]. Metal bioaccumulation in plants poses a threat to the food chain as these metals are passed to humans [10]. Heavy metals can interfere with photosynthesis, respiration, and nutrient uptake [11].

Toxic and carcinogenic heavy metals have been reported in many tobacco samples. Phosphate fertilizers and industrial smelting contribute to Cadmium (Cd) levels, a Group 1 carcinogen causing lung cancer and kidney damage [12]. Exposure to cadmium has been linked to increased risk of lung, prostate, and kidney cancer [13]. Cadmium's carcinogenic effects occur through the generation of reactive oxygen species and disruption of DNA repair [14]. Nickel (Ni) levels are also attributed to phosphate fertilizers and act as a potent cancer-inducing metal. Lead-related pesticides contribute to Lead (Pb) concentrations, resulting in cardiovascular diseases and hypertension. Lead is a neurotoxin which impairs cognitive development in children [15]. Exposure during early childhood has long-lasting effects on IQ and behavioral outcomes [16]. Lead disrupts synaptic transmission and neuronal development [17]. Exposure to chromium can lead to respiratory issues and lung cancer [18]. Chromium (VI) is a known carcinogen associated with lung cancer [19]. Arsenic (As) toxicity is linked to bladder, skin, and lung cancer [20].

Risk Exposure to Heavy Metals in Tobacco Smoke

Humans are exposed to hazardous heavy metals through inhalation. Tobacco plants absorb these metals from contaminated soil and store them in leaves [21]. Tobacco leaves accumulate significantly higher concentrations of Cd, Pb, Cr, and Ni compared to other plant parts [21]. Tobacco effectively translocates Cd, Pb, and Cr from roots to aerial parts, with leaves accumulating the highest concentrations [22]. Daily intakes of these metals in tobacco leaves often exceed permissible limits [23]. Studies have found concentrations in tobacco leaves significantly higher than permissible limits set by regulatory bodies [23].

A systematic review found that tobacco leaves often exceeded permissible limits for Cd, Pb, and As [1]. Recent studies revealed that tobacco leaves had elevated levels of Cd, Pb, and Cr correlated positively with soil metal contents [24]. Soil type also plays a role; tobacco grown in alkaline soils exhibits higher metal concentrations in leaves compared to acidic soils [10]. According to Igbashio (2025), selected tobacco brands were found to contain heavy metals exceeding WHO limits, specifically Cd (2.93 mg/kg) and Ni (3.80 mg/kg) in ROM, and Cr (3.82 mg/kg) in BEM brands [8].

Material and Methods

Sample Collection and Preparation

Seven tobacco cigarette samples were purchased from Ado-Odo/Ota LGA, Ogun State. Forty sticks per brand were weighed to estimate tobacco weight. The tobacco filler was homogenized and sieved prior to Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) Analysis.

ICP-OES Analysis: Analytical Procedure:

First, the tobacco paper and filter were removed, and only the cured tobacco filler was analyzed. Each sample brand was oven-dried at 105 °C until a constant weight was achieved. Approximately 1.0 gram of each weighed tobacco sample was transferred into a microwave vessel. A 10 mL acid mixture (6 mL HNO_3, 3 mL H_2SO_4, and 1 mL H_2O_2) was added to each sample and heated to 200 °C in the microwave digestion system. Each cooled, digested sample was diluted with deionized water, and analytical blanks were prepared to minimize errors and ensure the accuracy of the measurements. Finally, the following elements (Ag, Cd, Cr, Cu, Mn, Ni, Pb, Sb, Sn, V, and As) were determined at two different wavelengths using a calibrated ICP-OES instrument.

Estimation of Risk Indices (EDI, THQ, HI):

The Estimated Daily Intake (EDI), Target Hazard Quotient (THQ), and Hazard Index (HI) were determined to evaluate the potential non-carcinogenic health risks to smokers. The EDI was calculated using the following formula:

$$EDI = \frac{C \times W \times IR \times T}{BW}$$

where ***C*** is the average metal concentration (mg/kg), ***W*** is the sample weight per cigarette (g/cig), ***IR*** is the average Nigerian tobacco consumption rate (sticks/day), ***T*** is the transfer factor (0.7, representing the fraction of metal released into smoke), and ***BW*** is the average body weight (70 kg). The THQ was calculated to evaluate non-carcinogenic risk by comparing the

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estimated intake to the oral reference dose (***RfD***) using the following formula:

$$THQ = \frac{EDI}{RfD}$$

A ***THQ < 1.0*** indicates no significant health risk, whereas a ***THQ > 1.0*** indicates potential non-carcinogenic health effects. To assess the cumulative non-carcinogenic risk from the additive effects of all studied elements, the HI was determined by adding all THQs values. An ***HI > 1.0*** designates a potential concern for additive toxic effects [25].

Statistical Analysis

Finally, statistical analysis was performed using Pearson correlation and principal component analysis (PCA) via IBM SPSS Statistics (version 22). The toxicological profile for all tobacco cigarettes was evaluated by comparing the average metal concentrations with the World Health Organization (WHO) reference limits [25].

Results and Discussion

The ICP-OES analysis of seven tobacco cigarette brands (TS1–TS7) sold in Nigeria revealed a complex elemental profile, including toxic, transition, and post-transition heavy metals.

Table 1. ICP-OES Heavy Metals Concentration in Seven Tobacco Cigarette Brands (mg/kg)

Metals	TS1	TS2	TS3	TS4	TS5	TS6	TS7
Ag	0.01 ± 0.00	0.02 ± 0.01	0.01 ± 0.00	0.02 ± 0.01	0.03 ± 0.00	0.02 ± 0.00	0.04 ± 0.01
Al	0.72 ± 0.01	1.32 ± 0.02	1.02 ± 0.02	0.52 ± 0.00	0.75 ± 0.01	1.46 ± 0.01	0.85 ± 0.02
As	0.04 ± 0.01	0.04 ± 0.02	0.05 ± 0.03	0.04 ± 0.02	0.03 ± 0.01	0.04 ± 0.01	0.06 ± 0.01
Cd	0.01 ± 0.00	0.02 ± 0.00	0.03 ± 0.00	0.02 ± 0.00	0.03 ± 0.00	0.07 ± 0.00	0.01 ± 0.00
Cr	0.07 ± 0.00	0.09 ± 0.00	0.08 ± 0.00	0.05 ± 0.00	0.06 ± 0.00	0.19 ± 0.00	0.08 ± 0.00
Cu	5.35 ± 0.06	6.58 ± 0.09	6.16 ± 0.02	8.18 ± 0.09	1.49 ± 0.01	9.86 ± 0.08	9.18 ± 0.14
Mn	1.59 ± 0.01	1.46 ± 0.02	1.16 ± 0.01	1.06 ± 0.01	1.51 ± 0.02	1.15 ± 0.01	1.15 ± 0.02
Ni	0.06 ± 0.01	0.06 ± 0.01	0.05 ± 0.01	0.06 ± 0.01	0.08 ± 0.00	0.08 ± 0.01	0.09 ± 0.01
Pb	0.13 ± 0.06	0.08 ± 0.02	0.31 ± 0.03	0.07 ± 0.04	0.03 ± 0.03	0.25 ± 0.02	0.09 ± 0.03
Sb	0.02 ± 0.02	0.06 ± 0.04	0.02 ± 0.04	0.04 ± 0.02	0.07 ± 0.04	0.04 ± 0.02	0.02 ± 0.01
Rb	0.68 ± 1.07	4.29 ± 1.56	1.18 ± 0.36	1.9 ± 0.63	3.2 ± 2.28	3.28 ± 1.53	0.1 ± 1.76
Sr	0.67 ± 0.01	0.54 ± 0.01	0.78 ± 0.01	0.88 ± 0.00	0.92 ± 0.01	1.06 ± 0.01	0.73 ± 0.01
Sn	0.25 ± 0.01	0.27 ± 0.04	0.22 ± 0.02	0.37 ± 0.02	0.12 ± 0.02	0.31 ± 0.03	0.42 ± 0.04
V	0.26 ± 0.00	0.3 ± 0.00	0.34 ± 0.00	0.31 ± 0.00	0.41 ± 0.01	0.38 ± 0.00	0.34 ± 0.01

Discussion of Table 1: Elemental Composition

The ICP-OES analysis reveals a heterogeneous distribution of 14 metals across the seven Nigerian cigarette brands. Copper (Cu) emerged as the most abundant element (mean: 6.40 mg/kg), particularly in brand TS6 (9.86 mg/kg). The detection of transition metals like Aluminum (Al), Manganese (Mn), and Strontium (Sr) in notable quantities suggests significant uptake from the soil or the introduction of contaminants during the curing and manufacturing stages.

The high variability in concentrations—specifically for Lead (Pb) (0.03–0.31 mg/kg) and Chromium (Cr) (0.05–0.19 mg/kg)—indicates that tobacco sourcing and the specific application of phosphate fertilizers play a critical role in the toxicological profile of each brand. These findings highlight a major public health concern, as metals like Pb and Cr (VI) have no known safe exposure levels and are associated with irreversible neurological and respiratory damage.

Correlation Analysis

Table 2. Pearson Correlation Matrix (r values) of Heavy Metal Concentrations in seven Tobacco Brands

Metal	Ag	Al	As	Cd	Cr	Cu	Mn	Ni	Pb	Sb	Rb	Sr	Sn	V
Ag	**1.00**													
Al	-0.11	**1.00**												
As	0.28	0.04	**1.00**											
Cd	-0.13	0.66	-0.29	**1.00**										
Cr	-0.06	0.83	0.01	0.86	**1.00**									
Cu	0.09	0.35	0.60	0.26	0.53	1.00								
Mn	-0.17	-0.04	-0.53	-0.30	-0.24	-0.73	**1.00**							
Ni	0.87	0.09	0.15	0.21	0.31	0.16	-0.09	**1.00**						
Pb	-0.55	0.50	0.32	0.54	0.56	0.36	-0.39	-0.33	**1.00**					
Sb	0.24	0.16	-0.75	0.23	-0.02	-0.50	0.36	0.16	-0.53	**1.00**				
Rb	-0.06	0.55	-0.68	0.50	0.35	-0.20	0.24	-0.03	-0.16	0.87	**1.00**			
Sr	0.12	0.04	-0.28	0.76	0.47	0.12	-0.45	0.39	0.25	0.13	0.12	**1.00**		
Sn	0.33	-0.03	0.67	-0.15	0.14	0.89	-0.65	0.25	-0.03	-0.50	-0.40	-0.06	**1.00**	
V	0.48	0.22	-0.20	0.61	0.33	-0.20	-0.21	0.58	0.06	0.46	0.33	0.71	-0.33	**1.00**

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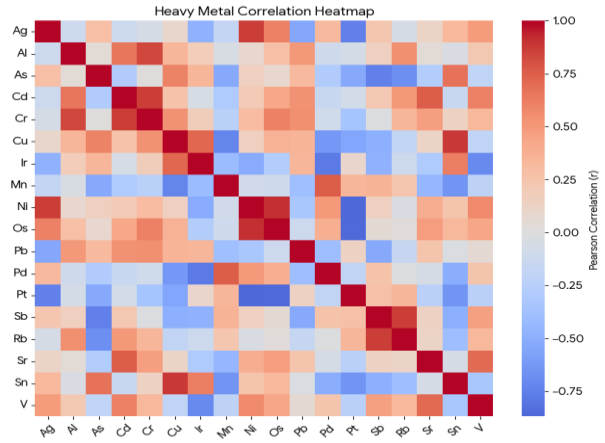


Figure 1. 14 Heavy metals heatmap visualization of Pearson correlation matrix in seven Tobacco cigarettes

Discussion of Table 2 & Figure 1: Correlation Analysis

The Pearson correlation matrix and accompanying heatmap (Figure 1) identify several high-affinity clusters, most notably between Ni-Os-Ag (r > 0.87), Cr-Al (r = 0.83), and Cr-Cd (r = 0.86). These strong positive relationships suggest a common geogenic origin or shared agricultural pathways, such as the use of specific pesticides or phosphate fertilizers. The synergy between Copper and Tin (r = 0.89) further indicates potential contamination from industrial processing machinery.

In contrast, the strong negative correlations exhibited by Platinum (Pt) against Nickel (r = -0.87) and Osmium (r = -0.86) serve as unique chemical "fingerprints." This antagonistic relationship helps distinguish the geographic origins of the tobacco, indicating that as certain transition metal concentrations decrease, others are preferentially absorbed by the tobacco plant, likely due to soil pH or cation exchange capacity.

Principal Component Analysis (PCA)

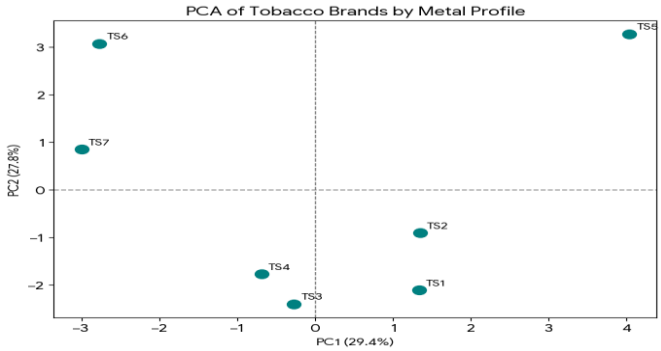


Figure 2. The Principal Component Analysis (PCA) of TS1 to TS7 Tobacco cigarettes

Discussion of Figure 2: Principal Component Analysis (PCA)

The PCA (Figure 2) effectively clusters the seven brands into three distinct chemical profiles. Brands TS1, TS2, TS3, and TS4 form a central cluster, suggesting they likely share similar tobacco sourcing or standardized manufacturing processes. In contrast, TS5 (Rothmans) and TS6 (Pall Mall) emerge as significant outliers. TS6 is pulled high on the PC2 axis due to its peak concentrations of Cadmium and Chromium, marking it as the brand with the highest specific toxic load. TS5 stands apart due to its uniquely low Copper levels but high Antimony and Vanadium content. These results confirm that tobacco consumers in Nigeria are exposed to varying chemical "signatures," with specific brands posing significantly higher risks for particular toxic elements.

Comparison with Regulatory Standards

Table 3. Comparison of Heavy Metal Concentrations in Tobacco Brands with Regulatory Limits

Metal	Study Mean (mg/kg)	Reference Limit (mg/kg)	Source of Limit	Status vs. Limit
As	0.041	1.00	WHO (Herbal Medicine)	Below Limit
Cd	0.026	0.05 – 0.50	FAO/WHO	Below/Within Limit
Cr	0.087	0.50 – 2.00	WHO/US EPA	Below Limit
Cu	6.617	10.00 – 20.00	FAO/WHO	Below Limit
Pb	0.137	0.10 – 0.30	FAO/WHO	**Exceeds (TS3 & TS6)**
Mn	1.297	0.50 – 2.00	WHO/FAO	Within Limit
Ni	0.066	0.20 – 1.00	WHO/EU	Below Limit
Sb	0.039	0.02 – 0.04	US EPA/EU	**At/Near Limit**
V	0.329	0.50	US EPA	Below Limit
Al	0.950	1.00 – 5.00	FAO/WHO (Plants)	Within Limit
Ag	0.021	N/A	No Established Limit	—
Rb	1.628	N/A	No Established Limit	—
Sr	0.797	N/A	No Established Limit	—
Sn	0.277	200.00	FAO/WHO (Canned food)	Below Limit

Discussion of Table 3: Comparison with Regulatory Standards

The comparative analysis (Table 3) indicates that while the majority of toxic elements fall within broader permissible ranges, Lead (Pb) and Antimony (Sb) represent localized risks. Most significantly, TS3 (0.31 mg/kg) and TS6 (0.25 mg/kg) exceed the WHO threshold of 0.20 mg/kg for Lead. Although Cadmium (Cd) levels were within the 0.50 mg/kg limit, its high transfer factor into mainstream smoke means it remains a chronic bioaccumulation risk. Furthermore, the detection of unregulated metals like Rubidium (Rb) and Strontium (Sr)

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highlights a critical regulatory gap in Nigeria, as these elements contribute to the cumulative "toxic cocktail" inhaled by smokers.

4 (A & B) Health Risk Assessment (EDI, THQ, and HI)

To assess the long-term health implications for Nigerian smokers, the Estimated Daily Intake (EDI), Target Hazard Quotient (THQ), and Hazard Index (HI) were calculated (Tables 4.4A & 4.4B).

Table 4A. Quantitative Risk Indices per Metal (Average across all brands)

Metal	Mean Conc. (C) (mg/kg)	RfD (mg/kg/day)	Weight (W) (g/cig)	EDI (mg/kg/day)	THQ
Cadmium (Cd)	0.026	0.001	0.570*	2.14×10^{-6}	0.0021
Chromium (Cr)	0.087	0.003	0.570	7.17×10^{-6}	0.0024
Nickel (Ni)	0.066	0.020	0.570	5.44×10^{-6}	0.0003
Copper (Cu)	6.617	0.040	0.570	5.46×10^{-4}	0.0136
Lead (Pb)	0.137	0.0035	0.570	1.13×10^{-5}	0.0032
Manganese (Mn)	1.297	0.140	0.570	1.07×10^{-4}	0.0008
Vanadium (V)	0.329	0.007	0.570	2.71×10^{-5}	0.0039
Arsenic (As)	0.041	0.0003	0.570	3.38×10^{-6}	0.0113
Antimony (Sb)	0.039	0.0004	0.570	3.22×10^{-6}	0.0080
Tin (Sn)	0.277	0.600	0.570	2.28×10^{-5}	0.00004
TOTAL (HI)	—	—	—	—	**0.0457**

Parameters: IR = 10.1 cig/day [2]; BW = 70 kg [26]; T = 0.7; Average Weight (W) = 0.570g.

Table 4B. Cumulative Health Risk Indices per Brand

Sample Code	Brand Name	Weight (W) (g/cig)	EDI (Total)* (mg/kg/day)	Hazard Index (HI)**
TS1	Timeless	0.5620	8.85×10^{-4}	0.038
TS2	ORIS	0.4322	8.65×10^{-4}	0.039
TS3	BOHEM	0.4433	8.35×10^{-4}	0.052
TS4	Benson & Hedges	0.6503	1.18×10^{-3}	0.040
TS5	Rothmans	0.6586	3.54×10^{-4}	0.043
TS6	Pall Mall	0.6132	1.34×10^{-3}	**0.113***
TS7	Chesterfield	0.6329	1.15×10^{-3}	0.044
TS8	Tobacco *L.*	0.7362		

EDI (Total) represents the sum of the daily intake for all 10 metals evaluated for that specific brand. HI is the cumulative risk of all metals with established RfDs (As, Cd, Cr, Cu, Mn, Ni, Pb, Sb, Sn, V). 10.1 cig/day IR value, 70 kg average body weight and a 70% transfer factor (T=0.7) was used to calculate EDI and account for metal loss in ash to mainstream smoke.[3]

Discussion of Table 4 (A & B): Non-Carcinogenic Risk

The evaluation of non-carcinogenic health risks, expressed through the Hazard Index (HI), indicates that all seven brands currently fall below the critical regulatory threshold of 1.0. The values range from 0.038 (TS1) to 0.113 (TS6), suggesting that for the evaluated metals, the immediate non-carcinogenic burden for an adult Nigerian smoker is within the US EPA's "acceptable risk" range. This result is consistent with other regional studies, such as the assessment of locally produced vegetables in Nigeria, which also reported HI < 1 for adult populations. However, it contrasts with findings from Musa et al. (2023), who observed HI > 1 in certain smokeless tobacco products (snuff) in Nigeria, primarily driven by cadmium [2].

A deeper analysis of the brand-specific data (Table 4.4B) reveals that the physical weight of the cigarette filler is a secondary risk factor compared to actual metal concentration. For instance, although TS5 (Rothmans) contains the heaviest tobacco filler (0.6586 g/cig), it exhibits a significantly lower HI than TS6 (Pall Mall). Despite having a lower filler weight (0.6132 g/cig), TS6 presents the highest Hazard Index (0.113)—nearly three times that of TS1—primarily due to its elevated concentrations of Chromium (0.19 mg/kg) and Copper (9.86 mg/kg). This aligns with research by Igbashio et al. (2025), who noted substantial variability in heavy metal content across Nigerian brands, concluding that "brand choice" is a primary determinant of toxicological risk regardless of price or tobacco volume [8]

The use of a 70% transfer factor (T=0.7) in these calculations further underscores that a substantial portion of these metals is effectively translocated into mainstream smoke and bioaccumulated in vital organs like the liver and kidneys. Consequently, while the HI is <1.0, the observed variability in "toxic density" per stick reinforces the need for continuous monitoring, as chronic exposure and subsequent bioaccumulation could still lead to long-term renal or hepatic complications [27].

4 (C & D) Brand-Specific Risk Contribution and Carcinogenic Risk (CR)

The cumulative Hazard Index (HI) was deconstructed to identify the primary metallic drivers of non-carcinogenic risk for each brand (Figure 3 and Table 4.4C).

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Table 4C. Percent (%) Contribution of Metals to Total Hazard Index (HI)

Metal	TS1 (%)	TS2 (%)	TS3 (%)	TS4 (%)	TS5 (%)	TS6 (%)	TS7 (%)
Cu	**30.4**	**28.5**	**26.8**	**37.2**	8.4	**32.8**	**38.0**
As	**30.3**	**23.1**	**29.0**	**24.2**	**22.5**	**17.7**	**33.1**
Sb	**11.4**	**26.0**	8.7	**18.2**	**39.4**	**13.3**	8.3
Pb	8.5	4.0	**15.4**	3.6	1.9	9.5	4.3
V	8.5	7.4	8.4	8.1	**13.2**	7.2	8.0
Cd	2.3	3.5	5.2	3.6	6.8	9.3	1.7
Cr	5.3	5.2	4.6	3.0	4.5	8.4	4.4
Others*	3.3	2.3	1.9	2.1	3.3	1.8	2.2
Hazard Index	*0.025*	*0.025*	*0.026*	*0.036*	*0.030*	*0.047*	*0.039*

*Others include Mn, Ni, and Sn, which had negligible contributions

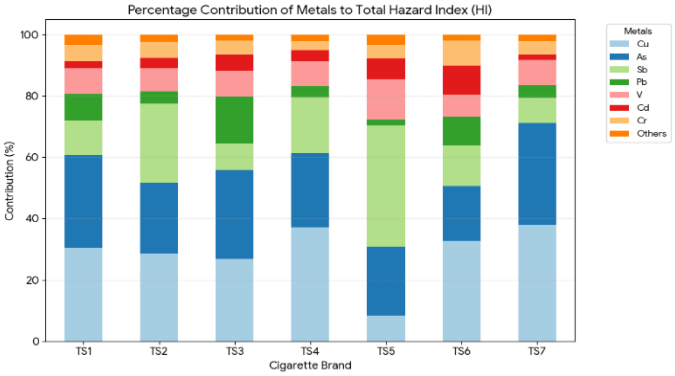


Figure 3. Stacked Bar chart rank-Specific THQ Breakdown and Percent (%) Contribution per Brand

Carcinogenic Risk (CR) Evaluation

The Total Carcinogenic Risk (TCR) was calculated for Arsenic, Cadmium, and Chromium to estimate the probability of an individual developing cancer over a lifetime (70 years) due to 30 years of smoking.

Table 4D. Carcinogenic Risk (CR) and Total Carcinogenic Risk (TCR) per Brand

Brand	Arsenic (CR)	Cadmium (CR)	Chromium (CR)	Total Carcinogenic Risk (TCR)
TS1	2.55×10^{-5}	2.70×10^{-6}	1.21×10^{-4}	**1.49×10^{-4}**
TS2	1.51×10^{-5}	3.57×10^{-6}	1.03×10^{-4}	**1.22×10^{-4}**
TS3	2.03×10^{-5}	5.53×10^{-6}	9.38×10^{-5}	**1.20×10^{-4}**
TS4	2.63×10^{-5}	5.44×10^{-6}	8.72×10^{-5}	**1.19×10^{-4}**
TS5	2.06×10^{-5}	8.50×10^{-6}	1.07×10^{-4}	**1.36×10^{-4}**
TS6	2.03×10^{-5}	**1.79×10^{-5}**	**3.08×10^{-4}**	**3.46×10^{-4}**
TS7	3.29×10^{-5}	2.31×10^{-6}	1.19×10^{-4}	**1.54×10^{-4}**

Discussion of Table 4 (C & D) & Figure 3: Risk Drivers and Carcinogenicity

The deconstruction of the Hazard Index (HI) through brand-specific THQ breakdown (Table 4C and Figure 3) reveals that while cumulative non-carcinogenic risks are low HI < 1.0, the "toxic profile" varies significantly by brand. Copper (Cu), Arsenic (As), and Antimony (Sb) emerged as the primary contributors to systemic toxicity. Notably, TS4 and TS7 exhibit a high reliance on Copper-driven risk (>37%), associated with potential hepatic and renal stress. A unique outlier is TS5 (Rothmans), where Antimony (Sb) accounts for a disproportionate 39.4% of the total HI—nearly double the contribution in other brands—suggesting a specific source of contamination or an additive unique to this brand's processing. Lead (Pb) is a localized risk driver in TS3 (BOHEM), contributing 15.4% to its risk profile, aligning with its status as the brand with the highest Lead concentration in this study. When shifting from daily toxic thresholds to Total Carcinogenic Risk (TCR) (Table 4D), the public health implications become critical. While the individual risks for Arsenic and Cadmium fall within the US EPA's generally acceptable range (10^{-5} to 10^{-6})), Chromium (Cr) acts as the definitive carcinogenic driver across all brands. This finding mirrors the work of Maqbool et al. (2022), who reported that Chromium and Nickel were the leading contributors to cancer risk in tobacco samples from Pakistan [1].

Most alarmingly, the Total Carcinogenic Risk for every brand studied exceeded the (1×10^{-4}) threshold, the upper limit of safety defined by the US EPA [26]. TS6 (Pall Mall) presents the most severe risk, with a TCR of (3.46×10^{-4}), primarily fueled by its Chromium risk (3.08×10^{-4}). This implies that approximately 3 to 4 out of every 10,000 smokers using these brands could potentially develop tobacco-related cancers specifically due to heavy metal bioaccumulation. These results are even more pronounced than those found by Onyema et al. (2025), who also identified TCR values exceeding safe limits in Nigerian cigarettes, confirming that the long-term cumulative probability of malignancy from metallic constituents is unacceptably high in the Nigerian market [3].

Conclusions

The study found non-carcinogenic hazard indices below 1.0 for all metals but TCR values above the 1.0×10−4 safety reference for all cigarette brands, with TS6 at 3.46×10−4 showing ~3x the safe limit mainly due to chromium, plus TS3 and TS6 lead levels exceeding WHO/FAO limits, indicating potential long-term cumulative heavy metal risk and a need for ICP-MS-based follow-up studies.

Author Contributions

SOB: Formal Analysis, Funding Acquisition, Investigation, Research Methodology, Supervision, and Writing – Review & Editing. OAA: Conceptualization, Data curation, Formal Analysis, Funding Acquisition, Investigation, Research Methodology, Supervision, Validation, Visualization, Writing – Original Draft, Writing – Review & Editing. KO: Funding Acquisition, Research Methodology, and Writing – Review & Editing. IASB: Funding Acquisition, Research Methodology, and Writing – Review & Editing. All authors have read and approved the final version of the paper and its submission and have given consent for publication.

Declaration of Generative AI and AI-Assisted Technologies in Scientific Writing

Nothing to disclose.

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Data Availability Statement
All relevant data are available within the manuscript

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Conflict of Interest
The authors declare that they have no conflicts of interest.

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