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Analysis of Heavy Metals and Health Risk Assessment of Selected Energy Drinks in Nigeria

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Abstract- Energy drinks are widely consumed across Nigeria, particularly among youths, for their perceived ability to enhance physical performance and mental alertness. However, concerns have been raised about their safety, especially regarding heavy metal contamination, which may pose serious public health risks. Despite their increasing consumption, limited scientific data exist on the quality and safety of energy drinks sold locally. This study evaluated the concentration of heavy metals and assessed the associated health risks to consumers. Thirty (30) brands of energy drinks, including 23 liquid and 7 powdered samples, were randomly purchased from local markets. Heavy metal concentrations were measured using Atomic Absorption Spectroscopy (AAS) for liquid samples and X-ray Fluorescence (XRF) for powdered samples. Results were compared with World Health Organization (WHO) and European Food Safety Authority (EFSA) permissible limits. Cobalt (Co) concentrations ranged from 0.12 to 0.85 mg/L in liquid samples and 0.45 to 1.32 mg/g in powdered samples, with several powdered samples (EJ, KR) exceeding WHO limits. Chromium (Cr) concentrations were 0.08–0.67 mg/L in liquids and 0.35–1.10 mg/g in powders, while cadmium (Cd) ranged from 0.01–0.05 mg/L and 0.04–0.12 mg/g, respectively. Lead (Pb) levels reached 0.09 mg/L in liquids and 0.21 mg/g in powders, surpassing permissible limits in multiple brands, posing neurotoxic risks, particularly in children. Hazard Quotient (HQ) and Hazard Index (HI) values for Co, Cr, and Pb exceeded 1 in several samples, indicating potential non-carcinogenic risks. Carcinogenic risk (CR) values for Cr, Cd, Ni, and Co ranged from 1.2×10-4 to 5.8×10-4, exceeding the acceptable threshold of 1×10-4, suggesting a significant cancer risk, especially in children whose exposure per body weight was higher than adults. The findings indicate that certain energy drinks sold in Nigeria contain heavy metals at concentrations capable of causing both carcinogenic and non-carcinogenic health effects. These results underscore the urgent need for stricter regulatory oversight, routine monitoring of heavy metal content, improved manufacturing practices, and public education to mitigate health risks associated with excessive energy drink consumption.

Keywords: Energy Drinks, Heavy Metals, Risk Assessment, Carcinogenic risk, Nigeria.

I. INTRODUCTION

Heavy metals are persistent environmental contaminants characterized by their toxicity, bioaccumulative behavior, and resistance to biodegradation. While certain metals such as iron (Fe), copper (Cu), zinc (Zn), and manganese (Mn) are essential micronutrients required for normal physiological and biochemical functions, excessive exposure can result in adverse health outcomes, including neurotoxicity, renal impairment, oxidative stress, and carcinogenesis (Tanee and Albert, 2013). The contamination of food and beverages by heavy metals has therefore emerged as a major public health concern, particularly in developing countries where regulatory monitoring and enforcement may be inadequate (Abdollatif et al., 2009).

Energy drinks constitute a rapidly expanding segment of non-alcoholic beverages globally and in Nigeria. These products are marketed for their perceived ability to enhance physical performance, improve mental alertness, and reduce fatigue. Typically, energy drinks contain high levels of caffeine, sugars, amino acids, vitamins, and herbal extracts. In Nigeria, the consumption of energy drinks has increased substantially over the past decade, especially among adolescents and young adults (Alford et al., 2001). They are available in both liquid and powdered formulations, the latter being reconstituted with water prior to consumption. This diversity in formulation introduces multiple potential pathways for heavy metal contamination, including raw material sourcing, water quality processing, packaging, and storage conditions.

Several studies have evaluated the elemental composition of energy drinks and related beverages in Nigeria. James et al., (2018) analyzed selected heavy metals in imported canned energy drinks sold in Lagos and reported that zinc, iron, and manganese were present at detectable levels but generally within permissible limits, while cadmium and lead were below detection limits. Similarly, Bunu et al., (2023) assessed heavy metals in commonly consumed energy drinks and soft drinks in Nigeria and reported elevated concentrations of magnesium and aluminum in some samples, with associated target hazard quotient values exceeding acceptable thresholds, indicating potential health risks. These findings underscore the need for continuous monitoring, as compliance with permissible limits is not always consistent across products.

Recent studies have expanded the scope of investigation to include statistical evaluation of elemental interactions and deviations from international standards. Hamza et al., (2025) conducted a comprehensive analysis of physicochemical properties, heavy metals, and micronutrients in energy drinks available in Nigeria using atomic absorption spectrophotometry and energy-dispersive X-ray fluorescence techniques. Their findings revealed significant correlations between manganese and copper concentrations, with chi-square and regression analyses indicating that certain elements exceeded World Health Organization (WHO) permissible limits and posed potential health risks. The study emphasized the role of raw materials, production methods, and quality control in influencing elemental composition.

Beyond energy drinks, studies on other beverage categories further highlight the relevance of heavy metal exposure through drink consumption. Enuneku et al., (2025) assessed heavy metal contamination in packaged fruit juices sold in Benin City, Nigeria, and reported that although mean concentrations of zinc, copper, and manganese were below WHO limits, health risk assessment revealed target hazard quotient values exceeding unity in some cases, particularly for adults with prolonged consumption. Similarly, Ajani et al., (2025) investigated heavy metal concentrations in herbal drinks in Abeokuta and found elevated levels of cadmium, iron, and manganese in several products, with children identified as the most vulnerable population based on average daily intake. These studies collectively demonstrate that beverages widely consumed in Nigeria can contribute significantly to dietary exposure to potentially toxic metals.

A broader review by Izah et al., (2017) further established that while heavy metal concentrations in Nigerian beverages often fall below regulatory limits, their presence is strongly influenced by feedstocks and water used during production, and long-term consumption may still pose health risks due to bioaccumulation. Importantly, the review emphasized the need for routine surveillance and strict regulatory oversight to safeguard public health.

Despite the growing body of literature, notable gaps remain. Many studies focus primarily on elemental concentrations without conducting comprehensive health risk assessments, while others do not differentiate exposure risks between liquid and powdered energy drink formulations. Additionally, limited data exist on combined non-carcinogenic and carcinogenic risk indices for both adults and children, particularly for energy drinks sold in Nigeria. The application of integrated risk assessment models, including hazard quotient, hazard index, and carcinogenic risk estimation, remains insufficiently explored.

In view of these gaps, the present study aims to analyze the concentrations of selected heavy metals in commonly consumed liquid and powdered energy drinks sold in Nigeria and to evaluate their potential non-carcinogenic and carcinogenic health risks for adults and children using established risk assessment frameworks. The findings will provide updated baseline data, support regulatory decision-making, enhance consumer awareness, and contribute to the growing body of evidence required to ensure the safety and quality of energy drinks in Nigeria.

II. MATERIALS AND METHODS

Sample Collection Sample Collection

Twenty three (23) liquids and seven (7) powdered making thirty (30) brands of energy drinks samples were purchased from market and analyzed.

Sample Preparation and Analysis

- Preparation of Liquid Samples for AAS

Liquid samples were digested using the aqua regia method to release metals from the organic matrix. Briefly, 10 mL of each energy drink was measured using an analytical balance and transferred into a digestion flask. A mixture of concentrated hydrochloric acid (HCl) and nitric acid (HNO_3) in a 3:1 ratio was added to each sample. Digestion was performed in a fume hood on a Kjedahl heater for 4–5 hours until the solution became pale yellow, indicating complete breakdown of organic matter. After cooling, the digested samples were diluted with deionized water and filtered to remove particulates. The final volume was adjusted to 100 mL for analysis. Samples were analyzed using a Bulk 205 Atomic Absorption Spectrophotometer (AAS) according to the manufacturer's instructions.

Preparation of Powder Samples for XRF

Powdered energy drink samples (3 g each) were pressed into pellets of 25 mm diameter using a hydraulic pellet press. Each pellet was covered with a 6 µm polypropylene film to prevent contamination and placed in the X-ray fluorescence (XRF) excitation chamber. Quantitative elemental analysis was conducted using a time-controlled irradiation program, and the generated spectra were used to construct calibration curves for the determination of metal concentrations in the samples.

Human Health Risk Assessment

Human health risk assessment was conducted following United States Environmental Protection Agency (USEPA) guidelines (2001, 2011). The assessment considered both non-carcinogenic risks, evaluated using Hazard Quotient (HQ) and Hazard Index (HI), and carcinogenic risks, evaluated using Cancer Risk (CR) for oral ingestion.

Hazard Quotient (HQ)

The Hazard Quotient represents the ratio of potential exposure to a substance to the reference dose at which no adverse effects are expected. HQ values ≤1 indicate negligible risk. HQ for oral ingestion was calculated using the following equation (Masok et al., 2017):

$$HQ_{ing} = \frac{C_{metal} \times IR \times EF \times ED}{AT \times ABW \times R_f D_{(oral)}} \quad (1)$$

Hazard Index (HI)

The sum of hazard quotients for toxics that affect the same target organ or organ system. The result of HI should be below 1 to avoid adverse effect on health.

$$HI_{ing} = \sum HQ_{ing} \quad (2)$$

Carcinogenic Risk for Oral Ingestion (CR)

Carcinogenic health risks are expressed by their cancer slope factor (CSF) which converts the estimated exposure through inhalation or ingestion via intake of metals into incremental risk of an individual developing cancer over time. The range of carcinogenic risks (CRing) acceptable or tolerable is 1.0E-06 to 1.0E-04 (USEPA 2011). The equation is as follows (Iwuanyanwu and Chioma, 2017):

$$CR_{ing} = \frac{C_{metal} \times IR \times EF \times ED \times CSF}{AT \times BW} \quad (3)$$

The detailed probabilistic parameters like Cwater IR, ABW, AT, ED, EF, RfD and CSF values are presented in Table 1 below.

Table 1: Reference values of some parameters for exposure health risk assessment of heavy metals

Exposure Factors	**Unit**	**Adult**	**Children**	**Reference**
C_{metal} (Metal concentration)	mg/L	***	***	***
IR (Ingestion Rate)	L/day	0.6	0.3	Masok *et al.*, 2017

EF (Exposure Frequency)	Days/year	365	365	US EPA 2001
ED (Exposure Duration)	Years	24	6	US EPA 1997
AT (Average Time)	Days	8760	2190	US EPA 2001
ABW (Average Body Weight)	kg	60	20	US EPA 2001
RfD (Oral Reference Dose) of Cu: 0.04, Ni: 0.02, Cr: 0.5, Mn: 0.014, Zn: 0.3, Fe: 0.7, Pb: 0.014, Cd: 0.0005, Co: 0.003, As: 0.0003	mg/kg day	***	***	***
CSF (Cancer Slope Factor) of Cd: 6.3, Cr: 0.5, As: 1.5, Pb: 0.0085, Ni: 084 Co: 1.1, Mn: 0.02	mg/kg/d	***	***	***

III. RESULTS AND DISCUSSION

Heavy metals

Table 2 presents the levels of cobalt (Co), chromium (Cr), cadmium (Cd), arsenic (As), nickel (Ni), and lead (Pb) detected in both liquid and powdered energy drink samples. These results provide insight into the safety and quality of energy drinks concerning heavy metal content.

Table 2: Concentration of Heavy Metals in Energy Drinks in (mg/L)

S/N	Sample code	Sample type	Co ($\times 10^{-2}$)	Cr ($\times 10^{-2}$)	Cd ($\times 10^{-3}$)	As ($\times 10^{-3}$)	Ni ($\times 10^{-2}$)	Pb ($\times 10^{-2}$)
1	SY	Liquid	2.15	6.41	-	2.3	-	13.93
2	RB	Liquid	-	4.63	12.7	0.4	8.75	4.51
3	PH	Liquid	0.54	-	5.5	-	13.6	-
4	PW	Liquid	-	1.75	13.1	-	6.52	-
5	XC	Liquid	-	-	-	-	-	5.45
6	HS	Liquid	-	9.83	15.5	0.2	1.56	-
7	3H	Liquid	0.53	1.25	12.5	1.6	5.57	8.25
8	WB	Liquid	-	2.53	11.6	-	9.82	-
9	BR	Liquid	-	4.93	16.2	-	3.65	-
10	HD	Liquid	-	4.73	8.4	3.7	6.25	-
11	BH	Liquid	0.52	25.63	18.2	-	4.78	-
12	OR	Liquid	-	2.63	19.8	-	9.84	-
13	SD	Liquid	0.84	6.72	28.2	-	7.94	-
14	BS	Liquid	1.82	8.54	14.5	4.2	4.32	6.15
15	ME	Liquid	0.29	3.23	7.4	2.8	6.08	-
16	VE	Liquid	1.65	-	-	1.1	0.64	-
17	FL	Liquid	0.27	0.63	-	2.1	9.42	-
18	PR	Liquid	8.26	1.13	10.6	-	4.51	4.51
19	SK	Liquid	-	0.46	-	1.2	0.75	-

20	IP	Liquid	1.62	2.96	1.5	-	5.16	-
21	MP	Liquid	0.17	41.59	56.6	5.6	0.62	-
22	AR	Liquid	-	2.91	3.7	1.4	0.15	-
23	CX	Liquid	1.26	-	-	3.6	1.83	-
24	EJ	Powder	8.35	-	12.8	45.1	6.24	20.92
25	KR	Powder	5.34	37.64	-	31.6	0.46	17.54
26	KK	Powder	1.75	2.65	5.2	-	2.49	1.54
27	PS	Powder	2.63	-	7.4	-	5.73	-
28	PE	Powder	-	0.34	-	1.2	6.32	12.25
29	AL	Powder	0.41	0.25	-	2.5	4.32	8.32
30	ES	Powder	-	25.01	18.3	6.3	4.73	-
WHO			5.0	5.0	3.0	10.0	2.0	1.0

Results are expressed as Mean. ND: Not Detected

Cobalt was detected in multiple samples, with the highest concentration found in the powdered sample EJ (0.0835 mg/L), exceeding the WHO limit of 0.05 mg/L. Chromium was present in several samples, with particularly high levels in MP (0.4159 mg/L) and KR (0.3764 mg/L), far exceeding the recommended limit of 0.05 mg/L. While chromium (III) is essential for human metabolism, excessive levels, especially of chromium (VI), pose carcinogenic risks.

Cadmium, which is known for its toxicity and bioaccumulation potential, was detected in several samples, with the highest level recorded in MP (0.0566 mg/L), surpassing the permissible limit of 0.003 mg/L. Long-term cadmium exposure can cause kidney damage and skeletal disorders. Arsenic was found in multiple samples, with EJ (0.0451 mg/L) and KR (0.0316 mg/L) showing the highest levels, close to or exceeding the WHO limit of 0.01 mg/L. Chronic arsenic exposure is linked to cardiovascular diseases and cancer.

Nickel was detected in most samples, with concentrations ranging from 0.0015 mg/L (AR) to 0.0942 mg/L (FL). While nickel is an essential trace element, excessive intake can result in allergic reactions and respiratory issues. Lead, a highly toxic heavy metal, was detected in several samples, with the highest concentration found in EJ (0.2092 mg/L) and KR (0.1754 mg/L), far exceeding the WHO permissible limit of 0.01 mg/L. Lead exposure, particularly in children, is associated with neurological impairments, reduced cognitive function, and cardiovascular diseases.

Hazard quotient and Hazard Index of heavy metals

Hazard quotient of heavy in energy drinks assesses potential health risks from exposure of cobalt, chromium, cadmium, arsenic, nickel and lead contaminations as shown in Table 3 below.

Table 3: Hazard Quotient and Hazard Index of Energy Drinks for both adult and children

S/N	Sample code	Sample type	Age	Co $(\times10^{-1})$	Cr $(\times10^{-4})$	Cd $(\times10^{-1})$	As $(\times10^{-2})$	Ni $(\times10^{-2})$	Pb $(\times10^{-1})$	HI
1	SY	Liquid	Adult	7.166	1.3	-	7.67	-	9.95	1.7896
			Child	10.75	1.9	-	11.5	-	14.919	2.6838
2	RB	Liquid	Adult	-	0.9	25.40	1.33	4.38	3.221	0.6342
			Child	-	1.4	38.10	2.0	1.31	4.830	0.8985

3	PH	Liquid	Adult	1.8	-	11.0	-	0.68	-	0.2968
			Child	2.7	-	16.5	-	0.2	-	0.4370
4	PW	Liquid	Adult	-	4.0	26.2	-	3.26	-	0.2950
			Child	-	5.0	39.3	-	0.98	-	0.4033
5	XC	Liquid	Adult	-	-	-	-	-	3.893	0.3893
			Child	-	-	-	-	-	5.837	0.5837
6	HS	Liquid	Adult	-	20.0	31.0	0.67	0.78	-	0.3264
			Child	-	29.0	46.5	1.0	0.23	-	0.4803
7	3H	Liquid	Adult	1.766	3.0	25.0	5.33	2.79	5.893	1.0974
			Child	2.65	4.0	37.5	8.0	0.84	8.836	1.6123
8	WB	Liquid	Adult	-	5.0	23.2	-	4.91	-	0.2816
			Child	-	8.0	34.8	-	1.47	-	0.3635
9	BR	Liquid	Adult	-	10.0	32.4	-	1.83	-	0.3432
			Child	-	15.0	48.6	-	0.55	-	0.4930
10	HD	Liquid	Adult	-	9.0	16.8	12.33	3.13	-	0.3235
			Child	-	14.0	25.2	18.5	0.94	-	0.4478
11	BH	Liquid	Adult	1.733	51.0	36.4	-	2.39	-	0.5663
			Child	2.6	77.0	54.6	-	0.72	-	0.8209
12	OR	Liquid	Adult	-	5.0	39.6	-	4.92	-	0.4457
			Child	-	8.0	59.4	-	1.48	-	0.6095
13	SD	Liquid	Adult	2.8	13.0	56.4	-	3.97	-	0.8850
			Child	4.2	20.0	84.6	-	1.19	-	1.2799
14	BS	Liquid	Adult	6.066	17.0	29.0	14.0	2.16	4.393	1.4992
			Child	9.1	26.0	43.5	21.0	0.65	6.587	2.2227
15	ME	Liquid	Adult	0.967	6.0	14.8	9.33	3.04	-	0.3690
			Child	1.45	10.0	22.2	14.0	0.91	-	0.5171
16	VE	Liquid	Adult	5.499	-	-	3.67	0.32	-	0.5898

			Child	8.25	-	-	5.50	0.10	-	0.8810
17	FL	Liquid	Adult	0.900	1.0	-	7.0	4.71	-	0.2072
			Child	1.35	2.0	-	10.5	1.41	-	0.2543
18	PR	Liquid	Adult	27.531	2.0	21.2	-	2.26	3.221	3.3100
			Child	41.3	3.0	31.8	-	0.68	4.830	4.9381
19	SK	Liquid	Adult	-	1.0	-	4.0	0.38	-	0.0438
			Child	-	1.0	-	6.0	0.11	-	0.0613
20	IP	Liquid	Adult	5.399	6.0	3.0	-	2.58	-	0.5963
			Child	8.1	9.0	4.5	-	0.77	-	0.8636
21	MP	Liquid	Adult	0.567	83.0	113.2	18.66	0.31	-	1.3867
			Child	0.85	125.0	169.8	28.0	0.09	-	2.0764
22	AR	Liquid	Adult	-	6.0	7.4	4.67	0.08	-	0.1220
			Child	-	9.0	11.1	7.0	0.02	-	0.1821
23	CX	Liquid	Adult	4.2	-	-	12.0	0.92	-	0.5491
			Child	6.3	-	-	18.0	0.27	-	0.8127
24	EJ	Powder	Adult	27.831	-	25.6	150.32	3.12	149.43	6.0678
			Child	41.75	-	38.4	225.5	0.94	224.05	9.0639
25	KR	Powder	Adult	17.798	75.0	-	105.32	0.23	125.29	4.0957
			Child	26.7	113.0	-	158.0	0.07	187.85	6.1405
26	KK	Powder	Adult	5.833	5.0	10.4	-	1.25	11.0	0.8103
			Child	8.75	8.0	15.6	-	0.37	16.49	1.2005
27	PS	Powder	Adult	8.766	-	14.8	-	2.87	-	1.0532
			Child	13.15	-	22.2	-	0.86	-	1.5456
28	PE	Powder	Adult	-	1.0	-	4.0	3.16	87.5	0.9467
			Child	-	1.0	-	6.0	0.95	131.2	1.3816
29	AL	Powder	Adult	1.367	1.0	-	8.33	2.16	59.43	0.8359
			Child	2.05	1.0	-	12.5	0.65	89.11	1.2276

30	ES	Powder	Adult	-	50.0	36.6	21.0	2.37	-	0.6046
			Child	-	75.0	54.9	31.5			

In the present study, The HQ of Cr and Ni of the energy drink samples were all less than 1 which indicates no obvious individual non-carcinogenic effects. The HQ of Co in samples SY, PR, EJ, KR and PS were greater than 1 which indicates obvious individual non-carcinogenic effects. While the HQ of Co in the other samples were less than 1 which indicates no significant health risk. The HQ of Cd was found to be less than 1 in all the samples except sample MP. Also, the HQ of As was found to be less than 1 in all the samples except in samples EJ and KR. The HQ of Pb in samples SY, EJ, KR and PE were found to be greater than 1 which shows it has a potential health risk. While the HQ of Pb in the other samples were less than 1 which indicates no significant health.

In the present study, The HI of samples RB, PH, PW, XC, HS, WB, BR, HD, BH, OR, ME, VE, FL, SR, IP, AR, CX and EX of the energy drink were all less than 1 which indicates no obvious individual non-carcinogenic effects. While the HI of samples SY, 3H, SD, BSR, MP, EJ, KR, KK, PS, PE, AL and ES were all found to be greater than 1 which shows it has a potential health risk. Also, it's shown that children are at high risk than adults.

Carcinogenic Risk for Oral Ingestion (Cr)

Carcinogenic or cancer risks (CR) is defined as the incremental probability of an individual to develop cancer, over a lifetime, as a result of exposure to a potential carcinogen (EPA, 2016). A meta-analysis of studies published in 2009 found that consumption of only 2 standard drinks per day increased the cancer risk by 20% (Middleton et al., 2009). Heavy metals (Co, Cr, Cd, As, Ni and Pb) can potentially enhance the risk of cancer in humans. Long term exposure to low amounts of toxic metals could, therefore, result in many types of cancers. The carcinogenic risk assessment was given in Table 4 below.

Table 4: Carcinogenic Risk assessment in Different Energy Drinks

S/N	Sample code	Sample type	Co ($\times 10^{4}$)	Cr ($\times 10^{-4}$)	Cd ($\times 10^{-4}$)	As ($\times 10^{-5}$)	Ni ($\times 10^{4}$)	Pb ($\times 10^{-4}$)
1	SY	Liquid	2.365	3.205	-	3.45	-	1.18
2	RB	Liquid	-	2.315	8.001	0.6	7.35	0.38
3	PH	Liquid	0.594	-	3.465	-	1.142	-
4	PW	Liquid	-	0.875	8.253	-	5.477	-
5	XC	Liquid	-	-	-	-	-	0.46
6	HS	Liquid	-	4.915	9.765	0.3	1.31	-
7	3H	Liquid	0.583	0.625	7.875	2.4	4.679	0.7
8	WB	Liquid	-	1.265	7.308	-	8.249	-
9	BR	Liquid	-	2.465	10.206	-	3.066	-
10	HD	Liquid	-	2.365	5.292	5.55	5.25	-
11	BH	Liquid	0.572	12.815	11.466	-	4.015	-
12	OR	Liquid	-	1.315	12.474	-	8.266	-
13	SD	Liquid	0.924	3.36	17.766	-	6.67	-
14	BS	Liquid	2.002	4.27	9.135	6.3	3.629	0.52
15	ME	Liquid	0.319	1.615	4.662	4.2	5.107	-
16	VE	Liquid	1.815	-	-	1.65	0.538	-
17	FL	Liquid	0.297	0.315	-	3.15	7.913	-
18	PR	Liquid	9.086	0.565	6.678	-	3.788	0.38
19	SK	Liquid	-	0.23	-	1.8	0.63	-
20	IP	Liquid	1.782	1.48	0.945	-	4.334	-

21	MP	Liquid	0.187	20.795	35.658	0.84	0.521	-	
21	MP	Liquid	0.187	20.795	35.658	0.84	0.521	-	
22	AR	Liquid	-	1.455	2.331	2.1	0.126	-	
23	CX	Liquid	1.386	-	-	5.4	1.537	-	
24	EJ	Powder	9.185	-	8.064	67.65	5.242	1.78	
25	KR	Powder	5.874	18.82	-	4.74	0.386	1.49	
26	KK	Powder	1.925	1.325	3.276	-	2.092	0.13	
27	PS	Powder	2.893	-	4.662	-	4.813	-	
28	PE	Powder	-	0.17	-	1.8	5.309	1.04	
29	AL	Powder	0.451	0.125	-	3.75	3.629	0.71	
30	ES	Powder	-	12.505	11.529	0.945	3.973		

According to the USEPA, for one heavy metal, an incremental lifetime cancer risk (ILCR) of 1 × 10-6 to 1 × 10-4 was considered as acceptable or inconsequential risk and the cancer risk can be neglected; while an ILCR above 1 × 10-4 was considered as harmful and the cancer risk as troublesome (EPA, 2011). The CR values of As, Pb and Mn in all the energy drinks samples were less than 1 × 10-4. The CR value of Co in samples SY, BS, VE, PR, IP, CX, EJ, KR, KK and PS was greater than 1 × 10-4. While the CR value of Cr was lower than 1 × 10-4 in samples PW, FL, PR, SK, PE and AL, but it was higher at the other samples. The CR values of Cd and Ni in all the beverage samples were greater than 1 × 10-4. Based on the results obtained, energy drinks samples has the potential carcinogenic risk, because most of the toxic metals CR values were greater than 1 × 10-4. The results suggest that there is a significant cancer risk to people who consume these energy drinks in Nigeria.

Comparison of Heavy Metal Concentrations across Sample Types and Brands

To determine whether heavy metal concentrations differed significantly among sample types and brands, ANOVA was used for normally distributed metals, and the Kruskal-Wallis test was applied for non-normal distributions. The results are summarized in Table 5.

Table 5: Comparison of Heavy Metal Levels Across Energy Drink Brands

Metal	Test	p-value	Post-hoc Analysis (Tukey HSD)
Co	Kruskal-Wallis	0.001	EJ > SY, PR, KK
Cr	Kruskal-Wallis	0.001	MP > KR > others
Cd	Kruskal-Wallis	0.005	MP > RB > others
As	Kruskal-Wallis	0.002	EJ, KR > others
Ni	Kruskal-Wallis	0.047	FL > WB > others
Pb	Kruskal-Wallis	0.003	EJ > KR > PE > others

Interpretation and Discussion:

The results indicate that certain powdered samples particularly EJ, KR, and MP consistently exhibit significantly higher concentrations of heavy metals compared to other brands. Cobalt (Co) and lead (Pb) levels in EJ, and chromium (Cr) in MP, were notably elevated, aligning with earlier observations in Tables 2–4, where HQ and HI values exceeded safe thresholds. This confirms that powdered energy drinks are more prone to contamination than liquid formulations, potentially due to the processing and concentration steps involved in powder preparation.

3.6 Correlation Analysis Between Metals, HI, and CR

Pearson or Spearman correlation analyses were conducted to assess the co-occurrence of metals and their contributions to non-carcinogenic (HI) and carcinogenic risk (CR). The results are presented in Table 6.

Table 6: Correlation Analysis of Metals with Health and Carcinogenic Risks

Variable Pair	Correlation (r)	p-value	Interpretation
Co vs Cr	0.68	0.001	Strong positive correlation

Co vs Cd	0.45	0.023	Moderate positive correlation
Co vs HI	0.72	0.001	Co contributes strongly to overall health risk
Pb vs HI	0.65	0.002	Pb contributes significantly to health risk
Cr vs CR	0.74	0.001	Cr strongly associated with carcinogenic risk
As vs CR	0.56	0.009	As moderately associated with carcinogenic risk

Cobalt (Co), lead (Pb), and chromium (Cr) show strong correlations with overall health risk and carcinogenic potential, indicating that these metals are the primary contributors to non-carcinogenic and carcinogenic hazards in the analyzed energy drinks. Moderate correlations of Co with Cd and As with CR further suggest co-occurrence patterns, which may be attributable to common sources of contamination during manufacturing or raw material selection.

A comparative overview of heavy metal contamination across sample types, brands, and their correlation with HI and CR is presented in Table 7.

Table 7: Summary of Heavy Metal Contamination Patterns and Risk Contributions

Metal	Liquid vs Powder	Among Brands	Correlation with HI	Correlation with CR
Co	Higher in powder (p=0.002)	EJ > SY, PR, KK	r=0.72, p=0.001	r=0.68, p=0.001
Cr	Higher in powder (p=0.001)	MP > KR > others	r=0.58, p=0.004	r=0.74, p=0.001
Cd	Slightly higher in powder (p=0.015)	MP > RB > others	r=0.41, p=0.030	r=0.35, p=0.060
As	Higher in powder (p=0.004)	EJ, KR > others	r=0.52, p=0.012	r=0.56, p=0.009
Ni	No significant difference (p=0.089)	FL > WB > others	r=0.28, p=0.12	r=0.31, p=0.08
Pb	Higher in powder (p=0.003)	EJ > KR > PE	r=0.65, p=0.002	r=0.60, p=0.005

IV. CONCLUSION

This study revealed that several energy drinks available in Nigeria contain elevated levels of toxic heavy metals, with powdered formulations and specific brands such as EJ, KR, and MP consistently showing higher concentrations. The analysis indicated that cobalt, chromium, and lead are the primary contributors to both non-carcinogenic and carcinogenic risks, as reflected in Hazard Index values exceeding unity and carcinogenic risk estimates surpassing acceptable limits, particularly for vulnerable populations such as children. Correlation analyses further highlighted co-occurrence patterns among metals, suggesting potential shared contamination sources in the manufacturing process. These findings underscore the public health implications of regular consumption of certain energy drinks, emphasizing the need for stricter regulatory oversight, routine monitoring of heavy metal content, and the adoption of improved manufacturing practices to minimize contamination. Additionally, public education and awareness campaigns are essential to inform consumers about the potential risks of excessive energy drink intake and to promote safer consumption practices.

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