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Assessment of Heavy Metal and Trace Element Contamination in Sachet Water and Regulatory Gaps in Lagos Nigeria

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Abstract

Background: A large portion of the Nigerian population lack access to safe drinking water, leading many to depend on sachet water because it is affordable and widely available. This study evaluated heavy metals and trace elements concentrations in sachet water samples from various locations across Lagos State, Nigeria.

Methods: A cross-sectional study was conducted on 29 sachet water samples from the 20 Local Government Areas of Lagos State. The concentrations of heavy metals and trace elements were measured using the Agilent 5800 Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) system.

Results: The samples were clear and debris-free on physical examination, NAFDAC registration numbers, product names, and manufacturing addresses were seen on their labels, however relevant information including batch number, expiry and production dates were not found among the information on the sachet water labels. Chemical analysis of the sachet water showed that the concentrations of lead, arsenic, uranium, and mercury exceeded WHO safety limits in 65.5%, 51.7%, 17.2%, and 3.5% of the samples, respectively. Other heavy metals and trace elements analyzed were within permissible limits. Most of the metals had hazard quotient values below 1, suggesting minimal health risks from these elements for both adult and children's consumers.

Conclusions: Sachet water samples in the study area generally meet safety limits for heavy metal and trace element exposure, however, the presence of elevated levels of heavy metals in some samples and poor compliance with the laid down regulations for the sachet water labels calls for strengthened regulatory monitoring.

Keywords: Lagos, heavy metals, trace elements, sachet water.

Introduction

Access to safe drinking water has been a public health challenge, particularly in low- and middle-income countries like Nigeria. Globally, approximately 2.2 billion people do not have access to potable water [1]. In Nigeria, pipe borne water is not widely available to the populace in many states including Lagos State. Sachet water is the primary source of drinking water for a large segment of the population due to its affordability and ease of access, however, this growing dependence raises significant public health and environmental concerns. The suitability of water for various human uses is determined by its chemical, physical, biological, and radiological properties [2]. Safe drinking water is water that does not pose a significant risk to health when consumed over a lifetime, taking into account variations in sensitivity at different stages of life [3]. The World Health Organization (WHO) and Nigeria Standard for Drinking Water Quality (NSDWQ) established quality standards for safe and potable drinking water [4] [5], however, the required quality of water may vary depending on its intended use.

In response to inadequate public water supply systems in most parts of Lagos State, residents have resorted to drilling boreholes to access groundwater, while many private companies have initiated the commercial production of packaged water. Packaged water is typically distributed either in plastic bottles, referred to as bottled water, or in heat-sealed plastic sleeves of approximately 500 milliliters in volume, known as sachet water or pure water. About 18% of urban households in Nigeria rely on sachet water for drinking, cooking, and other domestic purposes [6]. Over the years, the consumption of sachet water has steadily increased, driven by increased consumer demand resulting from government's inability to provide safe and sustainable water sources for the population [7] [8].

Chemical contamination of drinking water can be toxic and may result in both acute and chronic health effects. A significant number of serious health concerns are linked to chemical contamination caused by environmental pollutants, including trace elements and heavy

metals. This is in addition to microbial contamination, which may arise from poor hygiene during the production process or unsafe vendor practices.

Trace elements, also referred to as trace metals, are nutritionally essential minerals required for normal biological functions. They serve as critical components of various enzymes and include calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), etc. [9]. While heavy metals are non-biodegradable naturally occurring metallic elements with high density and atomic mass, typically 5 times greater than that of water, there are toxic and essential heavy metals. [9]. Toxic heavy metals such as (lead (Pb), mercury (Hg), cadmium (Cd), arsenic (As) contamination has been linked to pathological conditions affecting the blood, kidneys, liver, heart, spleen, and other organs [10] [11]. In contrast, essential heavy metals; cobalt (Co), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), and zinc (Zn) are vital at low concentrations, serving as catalysts for enzymatic activities [12]. However, excessive exposure to these elements can lead to toxicity, adversely impacting growth, reproduction, and various biological functions.

Studies on the contamination of commercially available drinking water in Nigeria have shown the presence of various heavy metals. A study by [13], conducted in the eastern region of Nigeria reported appreciably high concentration of lead, cadmium, and copper in the sachet water samples. Similarly, [14] documented significantly high levels of lead, cadmium, and arsenic exceeding the WHO permissible limit in sachet water sold in Gashua, Bade L.G.A. of Yobe State, North East Nigeria. Another study [15] conducted in Lagos, South West, Nigeria found that the concentration of lead and cadmium in some sachet water and bottle water samples obtained from various markets were above the WHO guideline. In contrast, [16] reported that the concentration of heavy metals and trace elements in sachet water samples from Lagos were generally within acceptable threshold limits, with the exception of nitrates. Furthermore, a review of regional variations in physicochemical parameters, heavy metals, and microbial loads in sachet water samples across Nigeria's six geopolitical

zones between 2020 and 2023 raised concerns about elevated levels of pH, total hardness, magnesium, calcium, nickel, iron, lead, mercury, arsenic, and cadmium [17].

The continued reliance of the Nigerian population on sachet water as a primary source of drinking water highlights the urgent need for enhanced quality control, stricter regulatory enforcement, and sustainable solutions to ensure its safety and reliability. Both the WHO, Standard Organization of Nigeria (SON) / Nigerian Industrial Standards (NIS) and the National Agency for Food and Drug Administration and Control (NAFDAC) have established guidelines to safeguard the quality and safety of these products. However, routine assessments of the safety of water sources available to the population remain essential. Such evaluations provide a critical evidence base for regulatory decision-making and help identify potential health risks associated with sachet water consumption. The objective of this study is to evaluate the trace element and heavy metal composition in commercially available sachet water samples sold in Lagos, Nigeria, and assess their compliance with regulatory standards.

Materials and Methods

Study Area

Lagos State is located in southwestern Nigeria and is characterized by coastal and sedimentary geology. It spans the Guinea coast of the Atlantic Ocean for over 180 km, from the Republic of Benin on the west to its boundary with Ogun state on the east (Figure 1). It extends approximately from latitude 6˚23' North to 6˚41' North and from longitude 2˚42' East to 3˚42' East. Lagos state has a total area of 3577 sq. km, and about 787 sq. km or 22% is water. It has 20 Local Government Areas and 37 Local Council Development Areas. About 70% of the industries in Nigeria are located in Lagos State, and 80% of the population resides in the metropolitan (central) Lagos, making the state the most urbanized and industrialized State in Nigeria [18].
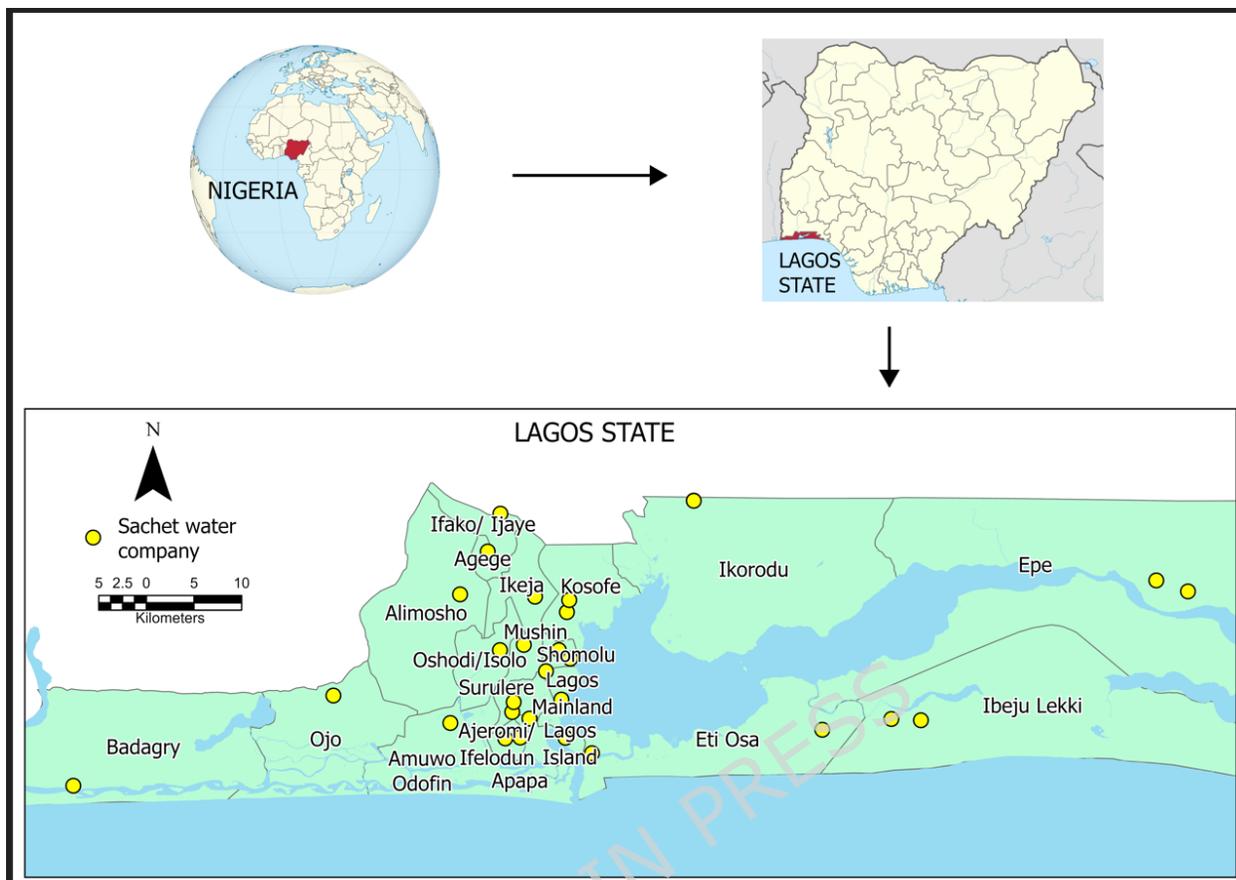
Figure 1: Map showing the location of Sachet water companies in the study area

(Source: produced by authors using ArcGIS Pro 3.5.0)

Sample collection

This cross-sectional study analyzed 29 sachet water samples from the 20 Local Government Areas (LGAs) in the three Senatorial Districts of Lagos State. Ten sachet water samples were collected from each Senatorial district. Lagos East and Lagos Central Senatorial districts has 5 LGAs, 2 samples were collected per LGA except in Lagos Island LGA that has only one sachet water company while in Lagos West Senatorial district with 10 LGAs one sample was collected per LGA. The sachet water companies were randomly chosen from a list of NAFDAC approved providers in each LGA that voluntarily consented to participate in the study.

A bag of sachet water from a batch was collected randomly from the selected companies. The identities of the sachet water brands were anonymized and were marked for easy

identification using the study code that comprised of LGA code and study number, and transported to the laboratory in a cold box containing ice packs at a temperature between $4^0C – 8^0C$. All samples were then stored at a temperature of 4°C and analyzed within twenty-four hours of collection to minimize any potential alterations in their composition. To visualize the spatial distribution of the collected samples, we superimposed the sample locations on a map of Lagos State using ArcGIS Pro 3.5.0 (Figure 1). ArcGIS Pro is a powerful Geographic Information System (GIS) software for creating maps and analyzing spatial data [19].

Physical Analysis of the Sachet Water Samples

All the glassware was washed with distilled water and sterilized in an autoclave at 121 ° C for 15 minutes. The sachet water samples were physically examined, and the product name, manufacturer address, batch number, NAFDAC registration number, mineral composition, manufacturing, and expiry dates were recorded. The edge of the package of the sachet water was cut with sterilized scissors and carefully placed in a sterilized beaker. 50 ml of water was collected in a sterile sample bottle.

Determination of Heavy metal and Trace element composition of the sachet water samples

The concentration of Ag, As, Ca, Cl, Cu, Cr, Cd, Hg, Mn, Na, Pb, Ni, U, Mg, Fe, K and Zn in the sachet water was determined using inductively coupled plasma optical emission spectrometry (ICP-OES). In this technique, the water sample is nebulized, and the resulting aerosol is transported into a high-frequency plasma, where the constituent elements are atomized and partially ionized. A monochromator or polychromator then disperses the characteristic emission lines of the atoms and ions. Appropriate spectral lines are selected to ensure that the elements of interest can be accurately measured, while minimizing potential interference from other elements, particularly at low concentrations.

To ensure the quality of the analytical results, commercially available multi-element solutions (Part No. 661003000, Lot No. 0010445783) purchased from Agilent Technologies were used as standards within their shelf life. Sets of known standards with a minimum of five concentrations (0.1, 0.25, 0.5, 2.5, and 5.0) ppm were used for calibration based on the equipment-generated internal standard curve. Standard concentrations for heavy metals and trace elements were used for the internal calibration of the equipment for the analysis. Daily calibration of the equipment was also done using the appropriate program options of the apparatus with multi-element standard solutions diluted according to the required working range.

Instrumentation Parameter; Rate1450W, Plasma Gas Flow Rate at 15L per min, Auxiliary Gas Flow Rate 0.2L per min, and Equilibration Time Rate 15S with a read delay of 45S, and Argon gas at heavy metal-specific wavelength.

Reagent blank which is an aqueous solution with the same acid concentration as the calibration solutions and is treated in the same manner as the digestion solutions under analysis was used during the analysis. This was done in order to check for potential contamination from reagents, digestion processes, and containers, as well as to ensure that the rinsing time between measurements was adequate. Furthermore, the analyte concentrations were then compared with allowable limits set by the World Health Organization (WHO) [4] and Nigerian Standard of Drinking Water Quality (NSDWQ) standard (2015)[5].

The ICP-OES technique was also verified by adding various concentrations (50% and 100%) of the analyte standard to aliquots of the unknown sample, these spiked samples, along with an additional partial sample, were subsequently analyzed. The concentration of the sample was determined by extrapolating the straight lines in the calibration curve drawn from the analyte measurement signals as described in the German Institute of Standard DIN 32633

[20]. All methods were carried out in accordance with applicable guidelines and regulatory requirements.

Statistical analysis

Data analysis was performed using Microsoft Excel (version 2019) and R. Descriptive statistics were employed to summarize the presence or absence of an address, date of manufacture, expiry date, batch number, chemical composition, and NAFDAC registration number. The frequencies and proportions of sachet water brands with heavy metal concentrations exceeding standard safety thresholds were calculated. The minimum and maximum concentrations of lead, cadmium, copper, and nickel in the samples were also reported. Pearson's correlation coefficient was applied to evaluate the strength and significance of associations among the variables examined. The health risk assessment to quantitatively calculate the exposure doses of heavy metals and trace elements in the sachet water samples via oral ingestion was done using the model recommended by the United States Environmental Protection Agency (EPA)[21].

Health risk assessment for heavy metals and trace elements

The health risk assessment evaluated the potential non-carcinogenic effects of heavy metals and trace elements in sachet water samples through oral ingestion. The exposed populations were categorized into adults (general population, ≥ 18 years of age) and children (sensitive group, 0–18 years). The health risk assessment model recommended by the United States Environmental Protection Agency (EPA) [21] was adopted to quantitatively calculate the exposure doses of available heavy metals and trace elements via oral ingestion. The Chronic daily intake (CDI) through ingestion was calculated according to the modified equation from Chrostowski [22]. The assumptions were; ingestion rates: adults 2.0 L/day, children 1.0 L/day, body weights: adults 70 kg, children 15 kg.

Chronic daily intake:

CDI= $\underline{C \times IR}$

BW

Where C, IR and BW represent the concentration of heavy metal/ trace element (mg/L) in sachet water, average daily ingestion rate (L/day) and body weight (kg), respectively.

Hazard Quotient (HQ) for non-cancer risk:

HQ = $\underline{EDI}$

　　　　RfD

　RfD = Reference dose (mg/kg-day) [21]

Results

The physical examination of the information on the sleeves of the 29 sachet water samples studied (Table 1) showed that all (100%) had product names, manufacturing addresses, and NAFDAC registration numbers. However, none of the samples included batch numbers, manufacturing/expiry dates, or mineral composition on their labeling. All sachet water analyzed was colourless and odourless and without suspended solids.

Table I: Provision of relevant information on the Sachet Water Sleeves

Information	Present n (%)	Absent n (%)
Product Name	29 (100)	0 (0)
Manufacturer Address	29 (100)	0 (0)
Batch Number	0 (0)	29 (100)
Manufacturing Date	0 (0)	29 (100)
Expiry Date	0 (0)	29 (100)
NAFDAC Registration Number	29 (100)	0 (0)
Mineral Composition	0 (0)	29 (100)

The concentration of various heavy metals and trace elements in sachet water samples collected across Lagos State
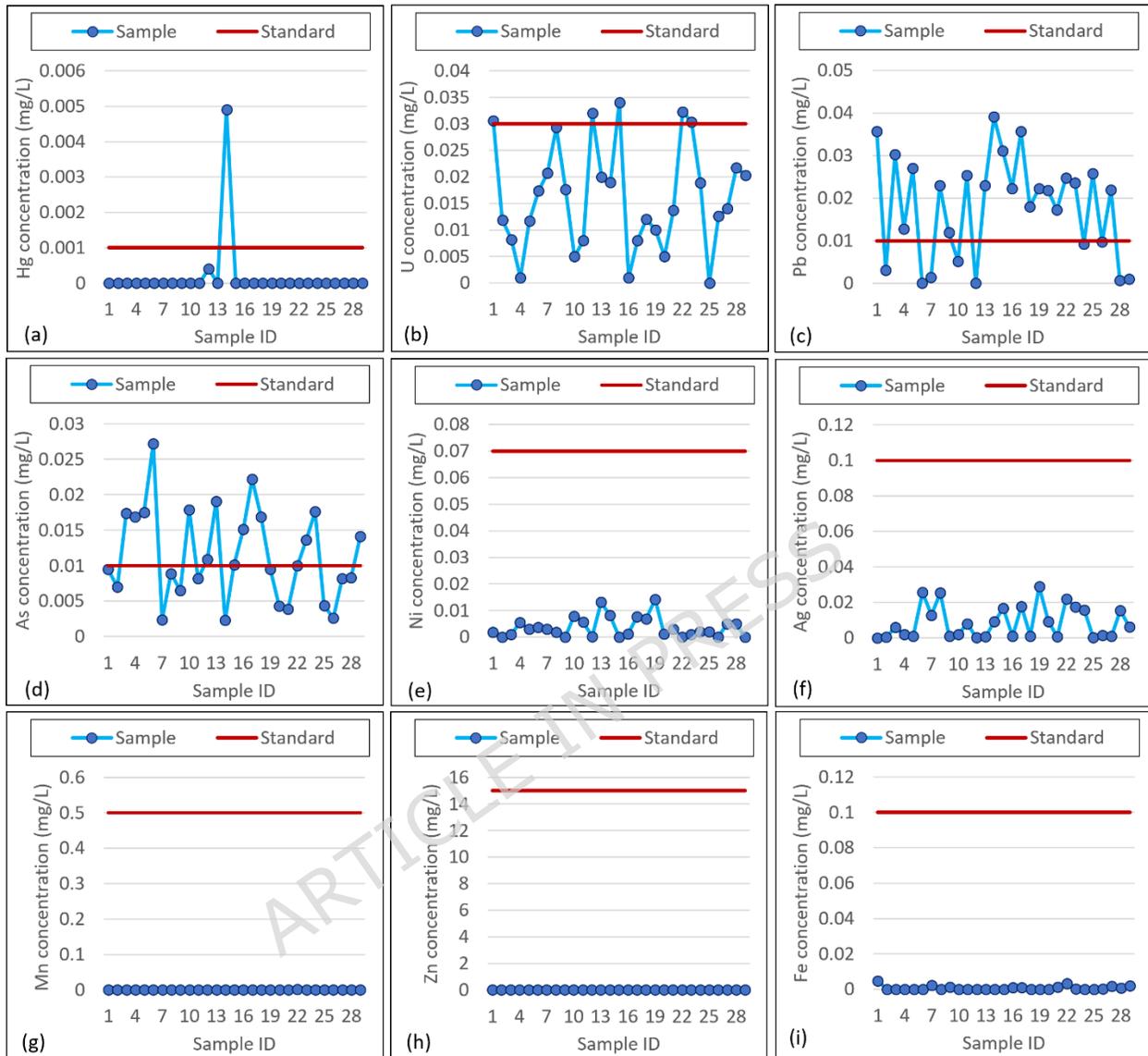
Figure 2a -q: Comparing Mercury, Uranium, Lead, Arsenic, Nickel, Silver, Manganese, Zinc, Iron, Copper Chromium, Cadmium, Calcium, Chloride, Potassium, Sodium and Magnesium concentration in the sachet water samples across Lagos State with the WHO safety limit.

The figure 2a -q showed the heavy metals and trace elements concentration in the sachet water samples collected across Lagos State. The concentration of nickel, silver, manganese, zinc, iron, copper, chromium, cadmium, calcium, chloride, potassium, sodium and

magnesium, were below the WHO /NIS recommended standard values as shown in Figures 2e, 2f, 2g, 2h, 2i, 2j, 2k, 2l, 2m, 2n, 2o, 2p and 2q respectively.

Lead concentration of the sachet water samples ranged from 0.039093 mg/L - 0.000661 mg/L, and the lead content in 65.5% (19) of these samples were above the WHO safety level of 0.01mg/L (Figure 2c). An elevated concentration of arsenic was reported in 51.7% (15) of the sachet water samples collected across Lagos State, as shown in Figure 2d. Its concentration ranged from 0.027194 mg/L to 0.002305 mg/L, with a WHO standard level of 0.01 mg/L. In addition, uranium concentration of the sachet water samples from this study ranged from 0.0342 - 0.000954 mg /L (Figure 2b), and 17.2% (5) of the samples had uranium levels above WHO standard concentration of 0.03 mg/L. Mercury was not detected in 93.1% (19) of the samples, while 3.5% (1) of the samples had a mercury concentration above the WHO permissible limit of 0.001 mg/L (Figure 2a), with concentrations ranging from 0.000358 to 0.00493 mg/L.
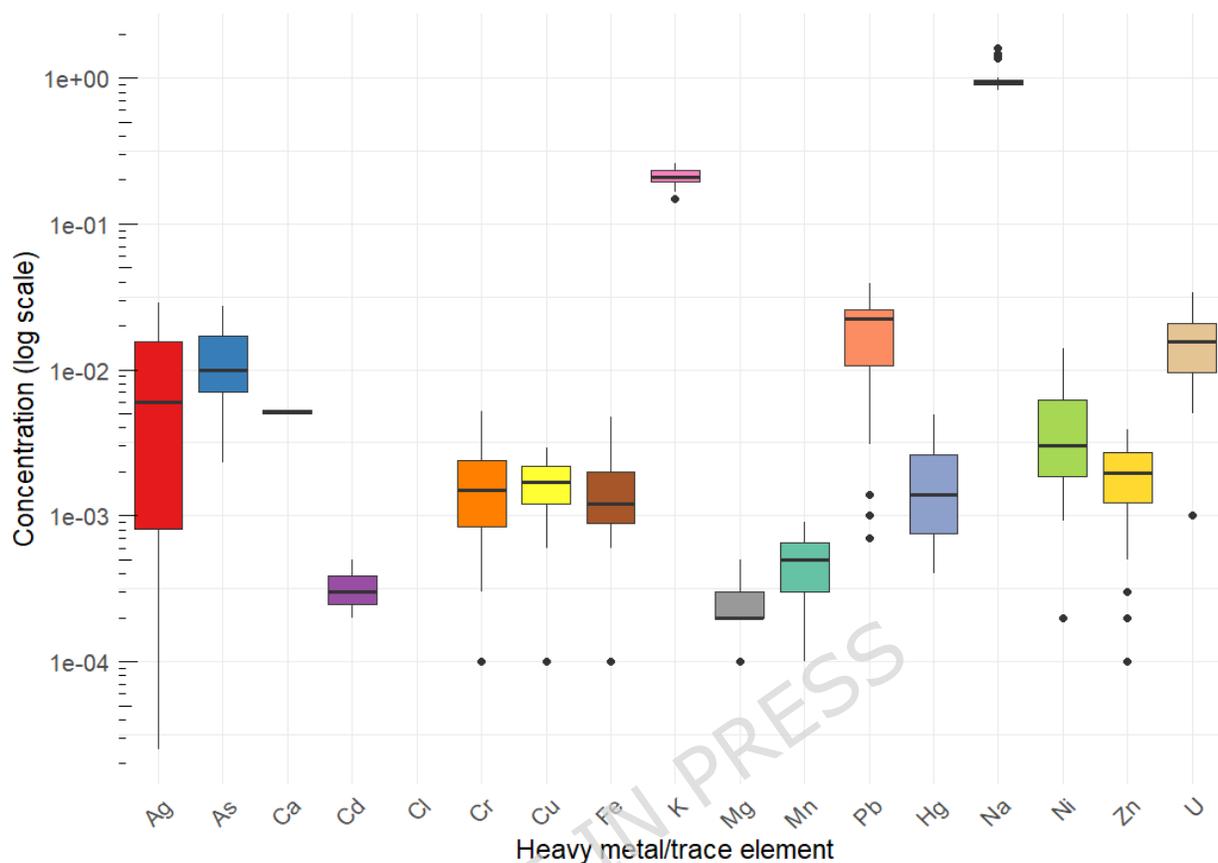
Figure 3: Variations in concentration of heavy metal and trace element in sachet water samples: Silver (Ag), Arsenic (As), Calcium (Ca), Cadmium (Cd), Chloride (Cl), Chromium (Cr), Copper (Cu), Iron (Fe), Potassium (K), Magnesium (Mg), Manganese (Mn), Lead (Pb), Mercury (Hg), Sodium (Na), Nickel (Ni), Zinc (Zn), Uranium (U).

Understanding the distribution of trace elements and heavy metal concentrations in drinking water is essential for exposure and risk assessment. Figure 3 illustrates this distribution using boxplots, a proven method for showing variability and differences among samples [23]. Potassium (K) and Sodium (Na) recorded the highest concentrations, with median values of 0.2083 mg/L and 0.9394 mg/L, respectively, both below the WHO/NIS permissible limits. The distributions of K and Zn appear slightly symmetric. Both right-skewed (e.g., Ag, As, Ni, Ca) and left-skewed (e.g., Mn, Pb) distributions may pose health risks, although the nature and extent of these risks vary. For instance, as shown in the preceding analysis, the concentrations of Pb and As in several samples exceeded their respective WHO limits.

The interrelationships between concentration of heavy metals and trace elements in the sachet water.

The correlation analysis presented in Supplementary Figure 1 measured the strength and direction of the linear relationships among the trace elements and heavy metals. Correlation strength was classified as weak for coefficients < 0.5, moderate for coefficients between 0.5 and 0.6999, and strong for coefficients ≥ 0.7. The correlation heatmap showed a mixture of positive and negative correlations, ranging from very weak to very strong. There was a very weak negative correlation between Hg and Na (r = –0.18), and weak positive correlations between Pb and Hg (r = 0.32) and Na and Ni (r = 0.25). Moderate negative correlations were observed between Mn and Ni (r = –0.53), Mg and Na (r = –0.59), and K and Hg (r = –0.50). Weak positive correlation was seen between Pb and Ni (r = 0.20), and a weak negative correlation between Ca and Cr (r = –0.38).

Negative correlations may suggest antagonistic relationships, where the presence of one element reduces the concentration of another. Conversely, a moderate positive correlation between Cr and Na (r = 0.60) may indicate synergistic effects or a shared source or pathway of contamination in sachet water. Weak positive correlations were also noted between Fe and U (r = 0.36) and Ag and U (r = 0.35).

These interrelationships among elements can guide targeted risk mitigation strategies. Further investigation is required to identify the potential sources of contamination.

Table 2: Chemical Composition of Sachet Water sold in Lagos West Senatorial District, Lagos Stat**e

LGA	Ag (µg/L)	As (µg/L)	Ca (µg/L)	Cd (mg/L)	Cl (mg/L)	Cr (µg/L)	Cu (µg/L)	Fe (µg/L)	K (µg/L)	Mg (µg/L)	Mn (µg/L)	Pb (µg/L)	Hg (µg/L)	Na (µg/L)	Ni (µg/L)	Zn (µg/L)	U (µg/L)
WHO/NIS	100	10.0	50.0	0.003	200,-600	50	5-1500	100.0	120 00	5000	5-500	10.0	1.0	200,000	70	5.00-15.00	30.0
Oshodi Isolo	0.03	10.0	ND	ND	ND	1.0	3.0	5.0	203	0.2	0.7	36.0	ND	964	18	2.3	31.0
Ojo	0.4	7.0	ND	ND	ND	0.1	2.0	ND	231	0.3	0.5	3.0	ND	959	ND	1.4	12.0
Badagry	6.0	17.0	ND	ND	ND	5.0	1.0	ND	192	0.3	0.6	30.0	ND	943	0.9	0.2	8.0
Alimosho	2.0	17.0	ND	ND	ND	3.0	3.0	ND	182	ND	0.3	13.0	ND	1,457	6.0	1.7	1.0
Amuwo Odofin	1.0	16.0	ND	ND	ND	1.0	3.0	ND	232	0.2	0.3	27.0	ND	939	3.0	0.1	12.0
Ifako Ijaiye	26.0	27.0	5.0	ND	ND	1.0	1.0	ND	199	0.3	0.4	ND	ND	886	4.0	3.3	17.0
Mushin	13.0	2.0	5.0	ND	ND	1.0	2.0	2.0	212	0.2	0.6	1.0	ND	922	3.0	1.5	21.0
Agege	25.0	9.0	5.0	ND	ND	1.0	2.0	ND	203	0.3	0.7	23.0	ND	877	2.9	2.8	20.0
Ikeja	1.0	6.0	ND	ND	ND	0.1	1.0	1.0	234	ND	0.6	12.0	ND	960	ND	0.3	18.0

Key: ND = Not Detected

Table 2 shows that in Lagos West Senatorial District, the sachet water samples with arsenic, lead and uranium concentrations above WHO permissible limits were about 44.4%, 66.7% and 11.1% respectively while other elements measured were below the safety limits.

Table 3: Chemical Composition of Sachet Water Brands sold in Lagos East Senatorial District, Lagos State

LGA	Ag (µg/L)	As (µg/L)	Ca (µg/L)	Cd (µg/L)	Cl (mg/L)	Cr (µg/L)	Cu (µg/L)	Fe (µg/L)	K (µg/L)	Mg (µg/L)	Mn (µg/L)	Hg (µg/L)	Na (µg/L)	Ni (µg/L)	Pb (µg/L)	Zn (µg/L)
WHO/NIS	100.0	10.0	50.0	3.0	200-600	0.05	5.0 - 1500	100	12,000	50,000	5 - 500	1.0	200,000	70	10	50-15
Epe	2.0	18.0	ND	ND	ND	ND	1.0	ND	197	ND	0.5	ND	967	8.0	5	3.
Epe	8.0	8.0	ND	ND	ND	1.0	1.0	ND	213	0.1	0.5	ND	920	6.0	25	3.
Ibeju	0.2	11.0	ND	ND	ND	2.0	2.0	ND	164	0.2	0.3	0.4	910	0.2	ND	N
Ibeju	0.6	19.0	5.0	ND	ND	0.4	2.0	ND	211	0.4	0.1	ND	940	13.0	23	2.
Ikorodu	9.2	2.0	5.0	ND	ND	2.0	1.0	ND	147	0.2	0.2	4.9	817	8.0	39	1.
Ikorodu	16.67	10.0	ND	ND	ND	5.0	2.0	ND	182	ND	0.7	ND	1373	ND	31	1.
Ikorodu	0.9	15.0	ND	ND	ND	4.0	2.0	1.0	211	ND	0.6	ND	1436	1.0	22	2.
Kosofe	17.8	22.0	ND	ND	ND	2.0	2.0	1.0	220	0.2	0.5	ND	940	8.0	36	3.
Kosofe	1.0	17.0	5.0	0.2	ND	0.3	1.0	ND	207	0.3	ND	ND	926	7.0	18	3.
Shomolu	28.8	10.0	ND	0.5	ND	3.0	2.0	ND	176	ND	0.3	ND	1589	14.0	22	1.
Shomolu	9.2	4.0	5.0	0.3	ND	2.0	1.0	ND	208	0.3	0.7	ND	907	1.0	22	4.

Key: ND = Not Detected

Table 3 shows that the sachet water samples collected from Lagos East Senatorial District had arsenic, lead, uranium, and mercury concentrations above WHO permissible limits in about 63.6%, 81.8%, 18.2%, and 9.1% respectively while other metals measured were below the safety limit.

Table 4: Chemical Composition of Sachet Water sold in Lagos Central Senatorial District, Lagos State

LGA	Ag (µg/L)	As (µg/L)	Ca (µg/L)	Cd (µg/L)	Cl (mg/L)	Cr (µg/L)	Cu (µg/L)	Fe (µg/L)	K (µg/L)	Mg (mg/L)	Mn (mg/L)	Hg (mg/L)	Na (µg/L)	Ni (µg/L)	Pb (µg/L)	Zn (µg/L)	U (µg/L)
WHO/NIS	100.0	10.0	50.0	3.0	200-600	50	5.0-1500	100	12,000	50.0	5-500	0.001	200,000	70.0	10.0	5.00 - 15.00	30.0
Apapa	1.0	4.0	ND	ND	ND	2.0	2.0	1.3	213.7	0.2	0.1	ND	1000.0	3.0	17.0	02.0	14.0
Apapa	22.0	10.0	5.0	ND	ND	ND	1.0	3.3	236.1	0.2	0.9	ND	879.0	ND	25.0	3.0	32.0
Eti Osa	17.0	14.0	ND	ND	ND	2.0	2.0	0.1	257.4	0.3	ND	ND	960.0	1.0	24.0	3.0	30.0
Eti Osa	16.0	18.0	ND	ND	ND	1.0	2.0	ND	242.8	0.1	0.5	ND	898.0	2.0	9.0	1.0	19.0
Lagos Island	0.2	4.0	ND	ND	ND	3.0	0.1	ND	235.5	0.5	0.6	ND	959.0	2.0	26.0	2.0	ND
Lagos Mainland	1.0	3.0	5.0	ND	ND	1.0	1.0	0.1	208.2	0.3	0.7	ND	896.0	ND	10.0	2.0	13.0
Lagos Mainland	1.0	8.0	5.0	ND	ND	1.0	3.0	1.6	193.0	0.3	0.2	ND	898.0	5.0	22.0	2.0	14.0
Surulere	15.0	8.0	ND	ND	ND	3.0	1.0	0.6	238.5	0.1	0.4	ND	921.0	5.0	1.0	3.0	22.0
Surulere	6.0	14.0	5.0	ND	ND	1.0	3.0	1.9	181.0	0.2	0.8	ND	875.0	ND	1.0	2.0	20.0

Key: ND = Not Detected

Table 4 showed that about 44.4%, 55.6% and 22.2% of the sachet water samples collected in Lagos Central Senatorial District had arsenic, lead and uranium concentrations above WHO permissible limits were about respectively while the metals measured were below the limit.

Table 5: Hazard Quotients and Hazard Index of Adults due to Ingestion of Sachet Water in Lagos State

ID	Ag HQ (µg/L)	AS HQ ((µg/L)	Cd HQ (µg/L)	Cr HQ (µg/L)	Cu HQ (µg/L)	Fe HQ (µg/L)	Mn HQ (µg/L	Pb HQ (µg/L)	Hg HQ (µg/L)	Ni HQ (µg/L)	Zn HQ (µg/L)	U HQ (µg/L)
RfD	5	0.3	1	3	40	700	140	3.5	0.1	20	300	0.6
1	0.1	905	0	11	2	2	0.1	291	0	3	0.2	1457.1
2	2.5	667	0	1	1	0	0.1	87	0	0	0.1	566.7
3	34.5	1657	0	50	0.4	0	0. 1	247	0	1	0	390.5
4	10.8	1610	0	31	2	0	0.1	422	0	8	0.2	47.6
5	4.7	1667	0	13	2	0	0.1	220	0	4	0	557.1
6	146.3	2591	0	18	1	0	0.1	0	0	5	0.3	828.6
7	72.6	229	0	11	1	0.1	0.1	11	0	4	0.1	985.7
8	144.7	848	0	11	2	0	0.1	188	0	3	0.3	1395.2
9	4.7	619	0	1	0.4	0	0.1	517	0	0	0	838.1
10	11.4	1705	0	0	1	0	0.1	437	0	11	0.2	238.1
11	45.7	781	0	7	1	0	0.1	207	0	8	0.2	381
12	1	1038	0	17	2	0	0.1	0	114	0.3	0	1523.8
13	3.5	1819	0	4	2	0	0	188	0	19	0.2	952.4
14	52.3	219	0	22	0.4	0	0	319	1400	12	0.1	904.8
15	95.2	962	0	44	1	0	0.1	254	0	0	0.1	1619
16	5.1	1438	0	40	2	0	0.1	182	0	2	0.2	47.6
17	101.6	2114	0	20	2	0	0.1	291	0	11	0.3	381
18	5.8	1610	6	3	1	0	0	147	0	10	0.3	571.4
19	164.6	905	14	32	1	0	0.1	181	0	20	0.1	476.2
20	52.5	410	9	20	1	0	0.1	982	0	2	0.4	238.1
21	4	371	0	16	1	0.1	0	789	0	4.3	0.2	652.4
22	125.7	952.4	0	0	0.9	0.1	0.2	201.6	0	0	0.3	1538.1
23	99.4	1295.2	0	14.3	1.2	0	0	955.5	0	1.4	0.3	1442.9
24	89.7	1676.2	0	9.5	1.3	0	0.1	389.8	0	2.9	0	900
25	1.1	419	0	23.8	0.1	0	0.1	210.6	0	2.9	0	0
26	8	247.6	0	1	1	0	0.1	376	0	0	0.2	600

27	4.6	781	0	12.4	1.8	0.1	0	178.8	0	7.1	0.2	666.7
28	87.4	790.5	0	24.8	0.4	0	0.1	32	0	7.1	0.3	1033.3
29	34.9	1342.9	0	2.9	1.9	0.1	0.2	1428.6	0	0	0.2	966.7
Hazard Index	**1.4145**	**31667**	**0.029**	**461**	**34.1**	**0.8**	**0.002**	**9735.6**	**1.5143**	**147.9**	**5**	22200

Table 6: Hazard Quotients and Hazard Index of Children due to Ingestion of Sachet Water in Lagos State

ID	Ag HQ (µg/L)	AS HQ (µg/L)	Cd HQ (µg/L)	Cr HQ ((µg/L)	Cu HQ (µg/L)	Fe HQ (µg/L)	Mn HQ (µg/L	Pb HQ (µg/L)	Hg HQ (µg/L)	Ni HQ (µg/L)	Zn HQ (µg/L)	U HQ (µg/L)
RfD	5	0.3	1	3	40	700	140	3.5	0.1	20	300	0.6
1	0.3	2111.1	0	26.7	4.8	0.4	0.3	680	0	6.1	0.5	3400
2	5.9	1555.6	0	2.2	2.8	0	0.2	59	0	0	0.3	1322.2
3	80.4	3866.7	0	115.6	1	0	0.3	577.1	0	3.1	0	911.1
4	25.1	3755.6	0	73.3	4.3	0	0.1	243.8	0	18.2	0.4	111.1
5	10.9	3888.9	0	31.1	4.7	0	0.1	514.3	0	9.8	0	1300
6	341.3	6044.4	0	42.2	2.3	0	0.2	0	0	11.9	0.7	1933.3
7	169.3	533.3	0	26.7	2.8	0.2	0.3	26.7	0	9.8	0.3	2300
8	337.7	1977.8	0	26.7	3.7	0	0.3	438.1	0	6.2	0.6	3255.6
9	11	1444.4	0	2.2	1	0.1	0.3	226.7	0	0	0.1	1955.6
10	26.7	3977.8	0	0	1.8	0	0.2	99	0	26.3	0.6	555.6
11	106.7	1822.2	0	15.6	1.8	0	0.2	483.8	0	19	0.6	888.9
12	2.4	2422.2	0	40	3.7	0	0.1	0	533.3	0.7	0	3555.6
13	8.1	4244.4	0	8.9	4	0	0	438.1	0	44	0.4	2222.2
14	122	511.1	0	51.1	1	0	0.1	744.8	6533.3	27	0.2	2111.1
15	222.1	2244.4	0	102.2	2.5	0	0.3	592.4	0	0	0.3	3777.8
16	11.9	3355.6	0	91.1	3.5	0.1	0.3	424.8	0	4	0.4	111.1
17	237.1	4933.3	0	46.7	4	0.1	0.2	680	0	25.7	0.6	888.9
18	13.5	3755.6	3.8	6.7	2	0	0	342.9	0	22.7	0.8	1333.3
19	384.1	2111.1	9.5	75.6	3.2	0	0.1	422.9	0	47	0.2	1111.1
20	122.5	955.6	5.7	46.7	2.2	0	0.3	415.2	0	3.7	0.9	555.6
21	9.3	866.7	0	37.8	2.7	0.1	0	327.6	0	10	0.5	1522.2
22	293.3	2222.2	0	0	2	0.3	0.4	470.5	0	0	0.6	3588.9
23	232	3022.2	0	33.3	2.8	0	0	449.5	0	3.3	0.7	3366.7
24	209.3	3911.1	0	22.2	3	0	0.2	175.2	0	6.7	0.1	2100
25	2.7	977.8	0	55.6	0.2	0	0.3	491.4	0	6.7	0	0
26	18.7	577.8	0	2.2	2.3	0	0.3	184.8	0	0	0.4	1400

27	10.7	1822.2	0	28.9	4.2	0.2	0.1	417.1	0	16.7	0.4	1555.6
28	204	1844.4	0	57.8	1	0.1	0.2	13.3	0	16.7	0.6	2411.1
29	81.3	3133.3	0	6.7	4.3	0.2	0.4	19	0	0	0.4	2255.6
Hazard Index	**3300.5**	**73889**	**0.019**	**1075.6**	**79.7**	**1.8**	**6.3**	**9958.1**	**7066.7**	**345.1**	**11.7**	**51800**

The hazard quotient (HQ) and hazard index (HI) values for adults and children due to the consumption of sachet water were calculated and presented in Tables 5 and 6, respectively. The results showed that most of the evaluated metals including Cd, Cu, Zn, Fe, Ni, and Mn had HQ values below 1, suggesting minimal health risks from these elements for both adult and children consumers. However, certain samples exhibited elevated HQs for toxic metals such as As, U, Pb, Hg, and Ag, indicating potential exposure concerns.

The study also demonstrated that children consistently exhibited higher HQs than adults for all metals (Figure 4), largely due to their smaller body weight and comparable intake volume. Arsenic (As) stood out prominently, with HQ values greater than 1 for both adults and children, indicating potential non-carcinogenic health risks. Uranium (U) also showed elevated HQs in several samples, occasionally exceeding the safety threshold (HQ = 1). In contrast, metals such as Cu, Mn, Zn, Ni, and Fe remained well below HQ = 1, indicating low concern.

The mean non-carcinogenic hazard indexes (HI) (the sum of HQs) across all metals were 5.60 for adults and 12.296 for children. Since the HI values for both groups were > 1, the non-carcinogenic health risks posed by metals in sachet water were insignificant for all groups.
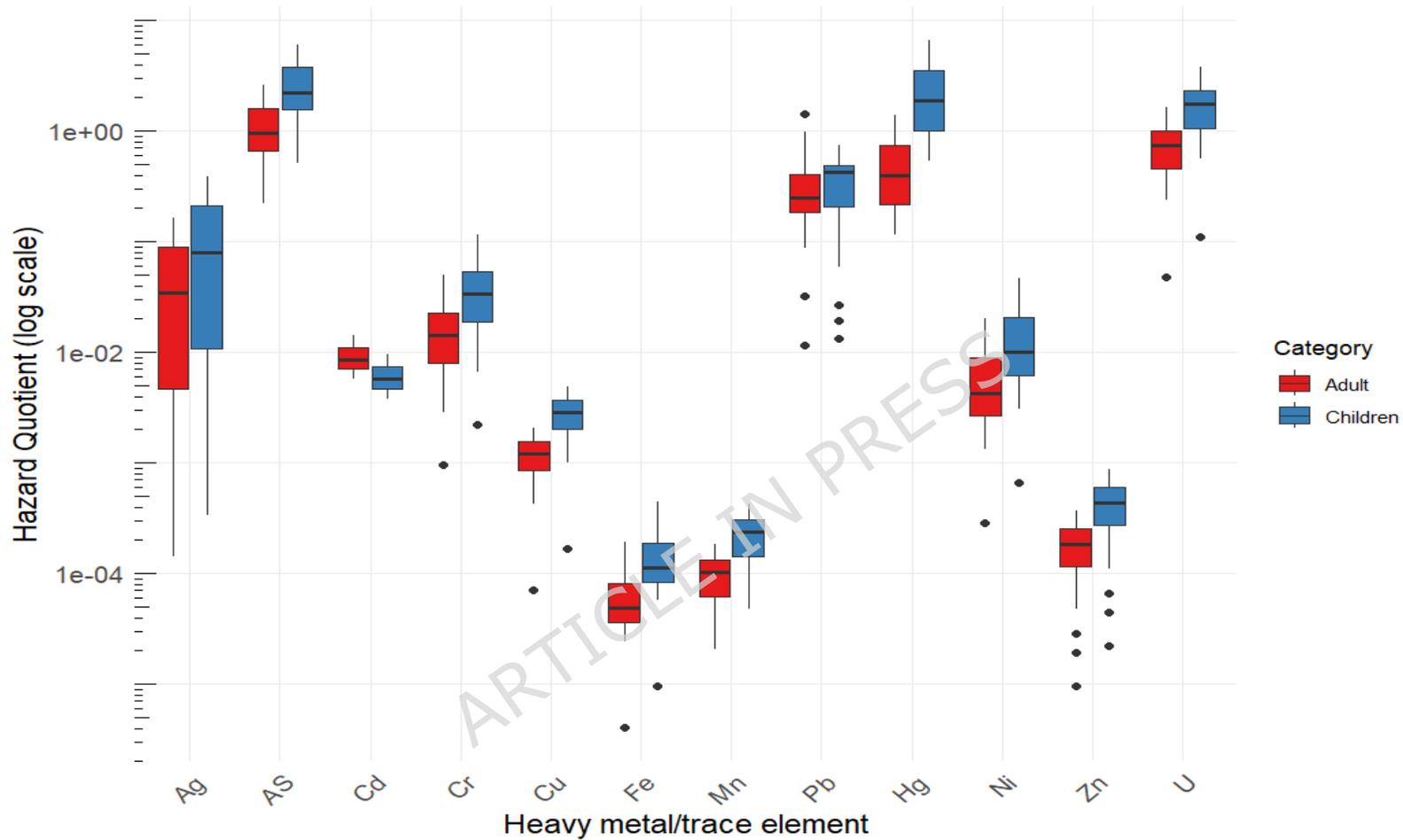
Figure 4: The Hazard Quotient distribution per element in the Sachet water across Lagos State.

Box plots (log-scale) (Figure 4) revealed wide variability, particularly for As, Pb, and U, reflecting inconsistent contamination levels across the samples.

Discussion

A lot of concern has been raised about the sustainability of sachet water production and consumption, especially in some developing countries, in view of its inadequate regulation, monitoring, safety rule compliance, as well as its potential environmental and health impact. Sachet water has been linked to possible outbreak of water-borne diseases like cholera, found questionable microbiological qualities [24], and has been established as a major contributor to solid waste pollution in some West African countries including Nigeria [25]. In Nigeria, lack of access to potable drinking water has led to the populace to rely on sachet water as an alternative source of drinking water [26]. In this study, an evaluation of the sachet water nylon sleeves showed that all sampled products had the manufacturer's name, address, contact phone numbers, and NAFDAC registration number displayed. However, none of the samples included critical labeling information such as batch number, mineral composition, manufacturing date, or expiry date. These findings are consistent with previous studies [27] [26], highlighting a widespread lack of compliance with standard labeling and safety regulations among sachet water manufacturers. This non-compliance poses potential health risks to consumers, as the absence of expiry dates makes it difficult to determine whether the water remains within its shelf life. Moreover, the batch number is essential for product traceability and is critical for effective recall in the event of contamination or other safety concerns.

Potential sources of lead contamination in sachet water include naturally occurring deposits in rocks and soils, anthropogenic activities, industrial processes, lead-containing components in water supply systems and production equipment [28]. Lead, a potent neurotoxin, affects nearly every organ in the body in both children and adults, and is recognized as the most common cause of human metal toxicosis. Prolonged exposure to lead has been associated with anemia and increased blood pressure, particularly among middle-aged and elderly individuals [29]. In addition, behavioral problems, learning difficulties, and reduced intelligence quotient (IQ) have been reported in infants and young children, even at low levels of lead exposure [30].

In this study, lead concentrations in 65.5% of the sachet water samples were higher than the WHO/NIS safety limits. The highest recorded lead concentration exceeded twice the permissible limit, potentially placing the population at considerable risk of chronic lead toxicity and its associated health consequences. A similar finding was reported by [31], who investigated heavy metal concentrations in sachet water consumed in Bukuru Metropolis, Jos South Local Government Area, Plateau State, North Central Nigeria, and found lead levels exceeding WHO permissible limits. Another study conducted in Gashua, Bade Local Government Area, Yobe State, Northeast Nigeria, reported significantly elevated concentrations of lead and arsenic in some sachet water samples above the WHO/NIS standard limits. Furthermore, zinc was not detected in any of the samples, while iron was present at concentrations lower than the WHO recommended levels.

In contrast, a study by [32] on the physicochemical and bacteriological characteristics of sachet water produced and distributed in Sagamu Local Government Area, Ogun State, Southwest Nigeria, found that most parameters were within acceptable limits set by WHO, the Environmental Protection Agency (EPA) of Canada, and NIS.

This study also reported that arsenic and uranium levels exceeded safety limits in approximately 51.7% and 17.2% of the sachet water samples, respectively. This is particularly concerning considering the potential exposure of a large segment of the population to the health risks associated with heavy metal contamination in sachet water.

Groundwater from boreholes and dug wells provides a significant proportion of the water used in sachet water production in Lagos State. [33]. Arsenic is among the toxic naturally occurring groundwater contaminant [34]. [31] reported that an estimated 137 million individuals across 70 countries were exposed to arsenic through contaminated drinking water. Additionally, [35] noted that by 2022, arsenic contamination in groundwater had been identified in 107 countries, affecting a total population of approximately 230 million people. The presence of arsenic above the WHO permissible limit of 0.01 mg/L, particularly in groundwater, has become a matter of global concern. This is especially critical in countries

such as China, Pakistan, Bangladesh, the United States, Canada, Brazil, India, Nepal, and Thailand, where groundwater serves as the primary source of drinking water and is extensively used for food preparation and agricultural irrigation [35] [36].

Prolonged exposure to arsenic through drinking water and food has been associated with skin lesions, increased risk of cardiovascular disease, diabetes [37] and kidney cancer [38]. Exposure during pregnancy and early childhood has also been linked to impaired cognitive development and higher mortality rates in young adults [39].

Arsenic contamination in groundwater is often attributed to natural sources both anthropogenic and natural origins. Anthropogenic sources include smelting, waste incineration, pesticide application, non-ferrous metal mining, wood combustion, and coal combustion. While natural contributors include hydrothermal and geothermal activity, dust storms, forest fires, pedogenesis, and volcanic eruptions [40].

Uranium is not essential in normal human biochemical processes or metabolic functions [41], but excessive exposure to uranium can lead to oxidative stress, metabolic disorders, cell death, and inflammation [42].

In this study, mercury was detected at levels exceeding the permissible limit in about 3.5% of the sachet water samples analyzed. Previous reports have also documented mercury contamination in sachet water samples across Nigeria [17] [43].

Mercury contamination of sachet water is primarily caused by environmental pollution of the raw water sources resulting from activities such as mining, pulp and paper production, coal-fired power generation, volcanic activity, various industrial processes, inadequate purification processes, and corrosion of water distribution equipment. Pregnant women, infants, and children represent the most vulnerable populations to the toxic health effects of excessive mercury exposure [44]. Mercury contamination poses serious public health concerns, as exposure has been linked to neurological disorders, developmental delays, and cardiovascular diseases.

The concentrations of other chemical parameters assessed in this study namely calcium, cadmium, chloride, chromium, copper, iron, magnesium, manganese, nickel, potassium, silver, sodium, and zinc were all below the WHO/NIS permissible safety limits.

Additionally, this study also reported that the Lagos East senatorial zone had the highest proportion of sachet water samples exceeding WHO safety thresholds for arsenic, lead, uranium, and mercury. This observation may be attributed to marine and coastal influences, as Epe and Ikorodu are located in close proximity to large water bodies. Heavy metals may be transported into these areas through tidal movements or groundwater flow.

A study by [45] reported that water samples collected from Ikorodu contained higher concentrations of nickel and copper compared to those from Lagos Central. These findings are consistent with historical data that indicated that forested areas in Ikorodu and Epe were dumpsites for many years prior to the implementation of afforestation programs. As a result, the elevated concentrations of certain heavy metals in groundwater may be attributed to the long-term infiltration of leachates into the water table.

The interrelationships among several chemical water quality parameters were assessed using correlation analysis, which is commonly applied to examine associations between physicochemical properties. In this study, Pearson's correlation analysis showed moderate positive correlations between Cr and Na, and weak positive correlation between Fe and U and Ag and U, while the study [46] reported strong positive correlation between Pb and Na, and Hg and Ni suggesting a common contamination source of these elements. However, strong negative correlation between Ca and Cr was reported in this study, in contrast to the study by [47] that reported a strong positive correlation.

The public health implications of sachet water consumption are significant, given its widespread and frequent use across the population. Sachet water manufacturers also face

several socioeconomic challenges, including unreliable power supply, limited access to clean water sources, and inadequate government infrastructure and regulatory oversight conditions that often prioritize production output over quality assurance.

In conclusion, sachet water in the study area generally meets safety limits for heavy metal and trace element exposure, however, the presence of elevated levels in some samples and poor compliance with the laid down regulations for the sachet water labels calls for strengthened regulatory monitoring. Regular quality control, strict enforcement of NAFDAC and NIS standards, and adherence to Standard Operating Procedures (SOPs) are essential to safeguard public health and ensure the consistent production of safe drinking water.

We recommend that NAFDAC and SON carry out regular monitoring to ensure continuous compliance with regulatory standards in sachet water factories, rather than limiting inspections to the pre-registration stage. Strict penalties should be imposed on any factory found violating these regulations or compromising water quality. Furthermore, mandatory inclusion of batch numbers, manufacturing, and expiry dates on sachet water packaging are recommended, in order to strengthen quality control and ensure consumer safety. Adherence to SOPs should be enforced to maintain the consistent production of safe and high-quality sachet water.

Seasonal variations, production practices, and storage conditions were not evaluated, which may have influenced the contaminant levels observed and represent key limitations of the study.

Ethical responsibilities of Authors

All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors".

Ethics approval and consent to participate

The Nigerian Institute of Medical Research Institutional Review Board approved the study protocol (Protocol number: IRB/19/055). The participants were informed about the study protocol and were assured of their right to willingly participate or withdraw from the study

at any stage. Following this explanation, informed written consent was obtained from the participants. All study documents including the consent documents were safely stored in access-controlled cabinet.

Consent for publication

Not applicable

Availability of data and materials

All data generated during this study are analyzed and included in this manuscript.

Competing interests

The authors declare that they have no competing interests

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Authors' contributions

Authors' contributions: UTI, OA, EFA, EEC, and PLG collected the samples; UTI, OA, EEA, PLG, CO, CAE, and MA collated and analyzed the data. UTI wrote the first draft; UTI, OA, and AR designed the experiments, guided the manuscript development, and revised the first draft. CJO - contributed to the data and geographical information analysis. All authors read and approved the final manuscript.

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