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RESEARCH ARTICLE

TOXICOLOGICAL ASSESSMENT AND STRATEGIC RISK MITIGATION OF HEAVY METAL CONTAMINATION IN SHAMPOOS: A CASE STUDY FROM ADEN, YEMEN

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Abstract

The safety and toxicological profile of cosmetic products have gained significant global attention due to potential health risks arising from heavy metal contamination. This study provides a quantitative toxicolo gical assessment of key heavy metals—Arsenic (As), Nickel (Ni), Cobalt (Co), and Copper (Cu)—in twelve popular shampoo brands (coded S1 to S12) marketed in Aden, Yemen.

Methodology:- involved quantitative analysis using high-sensitivity Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) following standardized wet acid digestion, with rigorous Quality Assurance (QA) maintained using analytical reagent-grade chemicals and high-purity water (18.0 MΩ.cm-1). Statistical validation via One-way ANOVA and LSD tests ($p \leq 0.05$) revealed significant systemic non-compliance with international safety standard. Specifically, Cobalt concentrations in 66.6% of the samples exceeded the WHO permissible limit, while Nickel levels in 91.6% of the investigated brands surpassed the US permissible threshold of 0.6 µg/g. Arsenic contamination was found to be substantial in 33.3% of the samples, with concentrations reaching a peak of 45.2 µg/g, significantly exceeding the WHO limit of 10.0 µg/g; however, 100% of the samples remained within safe limits for Copper. These findings indicate that continuous dermal exposure facilitates the bioaccumulation of toxic metal ions, which form stable, hazardous complexes with cellular protein functional groups (-COOH, -NH2, and -SH), posing serious long-term health concerns, including systemic toxicity and potential carcinogenicity.

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Beyond mere detection, this study proposes a Strategic Risk Mitigation Framework, that integrates mandatory manufacturing oversight and specialized port screening with a consumer transition toward validated herbal alternatives as a safer public health roadmap.

Introduction:-

Over the past few decades, the safety of cosmetic products and their constituent ingredients has attracted increasing global attention, leading to the evolution of toxicological safety determination as a specialized discipline since the latter half of the 20th century [Safavi 2019]. The cosmetic industry has experienced a significant boost, producing a vast array of products for skin, hair, and body care—including creams, beauty soaps, and shampoos—that have become integral to daily hygiene [Chauhan et al., 2010]. The global cosmetic industry is experiencing rapid expansion, with revenues projected to exceed USD 800 billion by 2030. However, this growth is accompanied by significant concerns regarding the toxicological and environmental impacts of synthetic ingredients, which contribute to pollution and systemic toxicity [Rachmawati et al., 2025]. However, growing scientific evidence has identified the presence of toxic elements across various personal care categories [Mahmoodabad et al., 2019; Lim et al., 2018]. Mercury, cadmium, lead, nickel, chromium, and copper are among the most frequently detected heavy metals in products such as shampoos, lipsticks, and powders [Volpe et al., 2012]. Significant concerns have been raised regarding specific chemical ingredients found in shampoos, including halogenated organic compounds, formaldehyde, musk fragrances, and heavy metals, which are potentially linked to carcinogenic risks [Onna et al., 2021].

While heavy metals like lead, arsenic, cadmium, and mercury are known to cause chronic systemic effects, others such as chromium, nickel, and cobalt act primarily as skin sensitizers. The accumulation of these elements within the human body is associated with a spectrum of chronic conditions, including reproductive disorders, neurological impairments, hair loss, and various malignancies [Feizi et al., 2019]. Among these, arsenic (As), lead (Pb), cadmium (Cd), mercury (Hg), nickel (Ni), and chromium (Cr) are most commonly implicated in human toxicity [Kishan et al., 2014]. These heavy metals occur naturally in the environment—sourced from soil, rocks, and water—and are often inadvertently introduced into cosmetics through contaminated raw materials used during manufacturing. In the absence of established legal frameworks regulating toxic levels in many regions, the "Threshold of Toxicological Concern" (TTC) has been proposed as a significant conceptual benchmark for evaluating ingredient safety [Yashim et al., 2000; Kroes et al., 2007].

Furthermore, the toxicological risk posed by these products is multifaceted, depending on the metal concentration, the product's chemical synthesis, dermal penetration capacity, the total surface area of exposure, and the frequency of use [Feizi et al.,2019; Mahmood et al, 2022]. The underlying mechanism of toxicity involves the absorption of heavy metal ions into the human body, where they form stable complexes with the carboxylic acids (-COOH), amines (-NH_2), and thiols (-SH) of proteins. This biochemical interaction leads to cellular damage, potential cell death, and various systemic diseases. Management of metal intoxication typically requires the use of chelating agents that bind with metal ions to form complexes for removal from the body [Flora and Pachauri, 2010; Zainy, 2017; Saleh et al., 2020].

In the specific context of Yemen, there is growing concern regarding the safety of inexpensive shampoos sold widely in the Aden governorate. Many of these products are imported from countries characterized by weak regulatory oversight, substandard manufacturing conditions, and a lack of rigorous screening. Research regarding the contamination of shampoos with toxic metals in Yemen remains extremely rare, and there is a notable deficiency in local control and consumer awareness regarding the levels of hazardous metals in these products. The toxicological landscape of cosmetics in Yemen has recently come under intense scrutiny. Over the last decade, analytical investigations have consistently revealed high risks of heavy metal exposure across different product categories in Aden. Initial studies highlighted significant contamination in skin-whitening creams [Saleh et al., 2016], followed by very recent findings of extreme Lead (Pb) levels in lipsticks and foundation creams—reaching up to 331.75 ppm—documented in 2025 [Fadhel, Saleh, & Binabood, 2025]. This current research aims to extend this toxicological surveillance to the hair care sector, specifically targeting widely-used shampoo brands.

Research regarding the contamination of shampoos with toxic metal's in Yemen remains extremely rare, and there is a notable deficiency in local control. Recent toxicological reviews emphasize that the transition from laboratory detection to effective regulation of heavy metals like Nickel and Chromium is crucial for mitigating public health risks, as these metals remain among the most prevalent skin sensitizers in modern cosmetics [Adam-Dima et al., 2024]. Consequently, this study was designed to bridge the existing gap in local regulatory oversight. It aims not only to perform a quantitative toxicological assessment of key heavy metals—specifically Arsenic (As), Nickel (Ni), Cobalt (Co), and Copper (Cu)—using high-sensitivity ICP-OES, but also to provide a novel contribution that goes beyond regional monitoring. By introducing an updated toxicological benchmarking against 2024 standards and a Strategic Risk Mitigation Framework (Figure 3), this research fills a significant safety gap in in a region characterized by limited surveillance. By synthesizing experimental data with this proposed framework, the study examines the biochemical risks of bioaccumulation and provides a systematic roadmap for both regulators and consumers.

Materials and Methods:-

Sampling and Sample Selection:-

Based on a preliminary field survey of local retail pharmacies and beauty aid stores, a total of twelve commercially available shampoo brands were strategically selected for the quantitative determination of heavy metals (As, Ni, Co, and Cu). Although the samples were physically collected from retail outlets in the Aden governorate, these specific brands were selected because they represent the most widely distributed and frequently purchased products across the entire Yemeni market. Thus, Aden serves as a representative case study reflecting the broader toxicological landscape and consumer exposure trends in Yemen, ensuring that the study reflects the actual exposure profile of the national population. The selected samples included products imported from various countries, namely the United Arab Emirates (UAE), China, Saudi Arabia, and France. Detailed information regarding the sample codes, country of origin, and intended use is summarized in Table 1. To ensure the reliability of the analytical data, three replicates (N = 3) of each sample were prepared and analyzed prior to their respective expiration dates, following the systematic research methodology illustrated in Figure 1.

PH Determination:-

The pH of the shampoo samples was measured using a digital pH meter equipped with a glass electrode, following the standard analytical protocols established by **APHA** (**1995**). For each measurement, 5 g of the sample was homogenized with 20 mL of deionized water in a glass beaker. The mixture was then processed in an ultrasound device for 20 minutes to ensure complete dispersion and homogeneity before recording the pH values.

Table 1. **Identification Codes, Manufacturing Origin, and Intended Use of the Analyzed Samples**

Sample No.	Sample ID	Country of Origin	Intended Use
1	S1	UAE	Children
2	S2	China	Children
3	S3	Saudi Arabia	Antidandruff
4	S4	Saudi Arabia	Died hair
5	S5	Saudi Arabia	Antidandruff
6	S6	Saudi Arabia	Strengthen hair
7	S7	Saudi Arabia	Dry hair
8	S8	Saudi Arabia	Normal hair
9	S9	Saudi Arabia	Destroyed hair
10	S10	Saudi Arabia	Strengthen hair
11	S11	France	Normal hair
12	S12	China	Hair care

Reagents and Analytical Standards:-

All chemical reagents utilized in this study were of analytical reagent grade. All solutions were prepared using Millipore-purified water with a conductivity exceeding 18.0 MΩ.cm^{-1}. Concentrated Nitric acid (HNO_3) and Perchloric acid ($HClO_4$) were sourced from BDH (England) for the sample digestion process. Standard multi-element solutions for Arsenic (As), Nickel (Ni), Cobalt (Co), and Copper (Cu) were prepared via serial dilution from 1000 ppm certified stock solutions.

Sample Preparation and Acid Digestion:-

To facilitate the quantification of heavy metals, the organic matrix of the shampoo was decomposed using a wet acid digestion procedure as described in validated literature [**Ojezele et al., 2018**]. Specifically, 1 g of each sample was accurately weighed and digested in 5 mL of a concentrated acid mixture (HNO_3:$HClO_4$ at a 3:1 ratio). The mixture was heated on a hot plate at a controlled low temperature for 2–3 hours until the appearance of white vapors, signaling the completion of the digestion. The resulting digestates were then diluted to a final volume of 10 mL with triple-distilled water and filtered through Whatman No. 1 filter paper to obtain a clear solution for subsequent metal quantification.

Instrumental Analysis:-

The concentrations of Arsenic, Nickel, Cobalt, and Copper were determined using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES, Thermo Scientific iCAP 6000 series, North America). This advanced instrumentation provided high-sensitivity multi-element detection. Each sample was analyzed in triplicate to ensure precision, and the final concentrations were expressed as the mean value ± SD (standard deviation). To demonstrate instrumental precision and analytical consistency, the detailed %RSD values and raw quantification reports for the analyzed metals are provided in Supplementary Table S1.

Quality Control and Quality Assurance (QC/QA):-

The instrumentation (ICP-OES Thermo Scientific iCAP 6000) was calibrated using certified multi-element stock solutions (1000 ppm), with a calibration coefficient (R^2) > 0.999 ensured for all target metals. To monitor potential contamination during the wet acid digestion process (HNO_3:$HClO_4$, 3:1 ratio), reagent blanks were prepared and analyzed in parallel with the shampoo samples [Saleh et al., 2016]. The Method Detection Limits (MDL), calculated as three times the standard deviation (3 x SD) of the reagent blank, were 0.006, 0.003, 0.000 and 0.003 μg/g for Ni, Co, As, and Cu, respectively. The Limit of Quantification (LOQ), defined as 10 x SD of the blank, ranged from 0.01 to 0.02 μg/g. Furthermore, all samples were analyzed in triplicate (N = 3) to assess instrumental precision. The relative standard deviation (%RSD) for all analyzed elements remained < 3.0% (e.g., As in S7: 2.92%, Cu in S6: 1.88%, and Co in S3: 1.29%), demonstrating high instrumental stability and analytical consistency.

Statistical Analysis:-

The experimental data were subjected to systematic statistical evaluation to determine the significance of the results. Statistical processing was performed using Origin 7.5 software (OriginLab Corporation, Northampton, MA, USA), which is a robust platform for analytical chemistry data validation. This methodology aligns with previously validated protocols for shampoo analysis in the region [**Saleh, 2021**]. A **One-way Analysis of Varianc**e (**ANOVA**) based on a Completely Randomized Design (**CRD**) was employed to assess whether the differences in heavy metal concentrations between the twelve shampoo brands were statistically significant. For post-hoc comparisons between the means of different brands, the **Least Significant Difference (LSD)** test was applied at a confidence level of **$p \leq 0.05$** [**Saleh, 2021; Islam et al., 2015**]. In the reported **Table 2**, the presence of different alphabetical superscripts (**a, b, c**) indicates significant differences between the means, while identical letters signify no statistical difference, thereby ensuring a transparent and rigorous interpretation of the toxicological data [**Saleh, 2021; Al-Bassam and Taka,2011**].

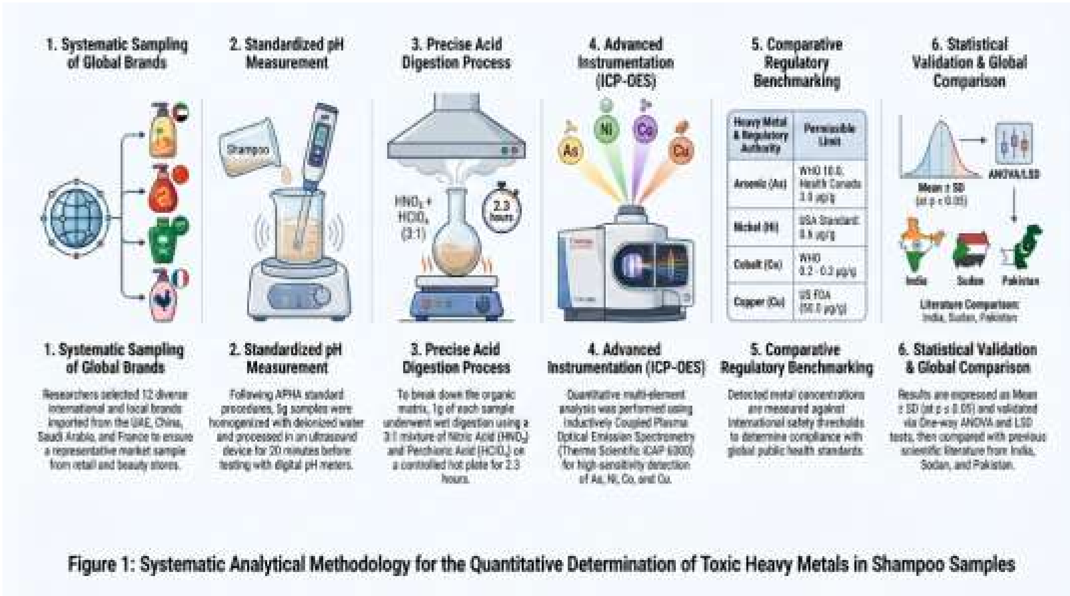


Figure 1. Systematic Analytical Methodology for the Quantitative Determination of Toxic Heavy Metals in Shampoo Samples. The workflow integrates six rigorous stages: (1) Systematic sampling of 12 global brands from UAE, China, Saudi Arabia, and France; (2) Standardized pH measurement using APHA protocols; (3) Precise wet acid digestion (3:1 HNO_3:$HClO_4$); (4) High-sensitivity ICP-OES instrumental analysis; (5) Comparative regulatory benchmarking against WHO, Health Canada, and the USA Standard (0.6 µg/g for Ni); and (6) Robust statistical validation via One-way ANOVA and LSD tests at p ≤

Results and Discussion:-

pH Values of Shampoo Samples:-

The pH levels of the investigated shampoo brands ranged from 5.113 to 6.706, with the lowest value recorded for the S11 sample and the highest for S4 (Table 2). Statistical analysis (at $p \leq 0.05$) indicated significant differences between samples, likely due to variations in formulations and manufacturing standards. When compared to the standards set by the central authority for standardization and quality (4.6–8.0 for adults; 4.6–7.0 for children) [Oyedeji et al., 2011], all samples fell within the permissible range, except for the S1 and S2 sample s which were notably close to the lower limit. The overall pH profile, as visualized in Table 2, suggests that most brands maintain a safe physiological range for scalp application.

Heavy Metals Concentrations and Associated Toxicological Risks:-

The overall safety and regulatory compliance profile of the investigated samples is summarized in Table 2 and Figure 2, while the complete multi-replicate instrumental datasets are available as Supplementary Material. Although the samples demonstrated a high degree of safety regarding Copper (Cu) levels (100% pass rate against the US FDA limit of 50 µg/g) and maintained a safe physiological pH range between 5.1 and 6.7, substantial violations were observed for other toxic elements. Specifically, toxicological benchmarking of Arsenic (As) concentrations revealed that 33.3% of the samples exceeded the WHO limit of 10.0 µg/g Furthermore, a more stringent assessment showed that 50% of the brands surpassed the Health Canada threshold of 3.0 µg/g, reaching a peak concentration of 45.2 µg/g in sample S10 (Saudi Arabia).

Table 2. Quantitative Assessment of pH and Heavy Metal Concentrations (µg/g) in Coded Shampoo Samples (Mean ± SD, N=3)

Sample No.	**Sample ID**	**pH**	**As**	**Co**	**Cu**	**Ni**
1	**S1**	6.430^{a}±0.0152	0.2^{af}±0.001	**0.8^{ai}±0.003**	0.4^{ah}±0.004	BDL
2	**S2**	5.953^{bn}±0.0252	BDL	**1.7^{b}±0.004**	0.3^{bj}±0.003	**1.0^{a}±0.004**

3	**S3**	5.173^{ck}±0.0152	**45.0^{bh}**±0.098	**1.1^{cei}±0.014**	20.5^{c}±0.058	**1.9^{b}±0.013**
4	**S4**	6.706^{de}±0.0208	**17.3^{c}**±0.215	**1.9^{d}±0.010**	0.5^{de}±0.002	**15.6^{c}±0.032**
5	**S5**	6.666^{efj}±0.0208	2.8^{d}±0.021	**1.2^{ehi}±0.011**	0.5^{eg}±0.006	**24.8^{d}±0.043**
6	**S6**	6.613^{fj}±0.0152	**5.5^{e}**±0.028	**0.4^{f}±0.005**	0.6^{f}±0.012	**14.4^{e}±0.035**
7	**S7**	5.876^{gh}±0.0151	0.2^{f}±0.006	BDL	0.5^{g}±0.005	**17.1^{f}±0.032**
8	**S8**	5.933^{h}±0.0153	BDL	**0.3^{g}±0.003**	0.4^{h}±0.005	**19.9^{g}±0.076**
9	**S9**	5.263^{i}±0.0057	**11.1^{g}**±0.043	**0.5^{hi}±0.002**	0.8^{i}±0.002	**12.5^{h}±0.03**
10	**S10**	6.613^{j}±0.0305	**45.2^{h}**±0.223	BDL	0.3^{j}±0.003	**12.8^{i}±0.072**
11	**S11**	5.113^{k}±0.0252	**6.5^{i}**±0.046	**0.8^{i}±0.008**	0.9^{k}±0.002	**13.2^{j}±0.161**
12	**S12**	6.403^{l}±0.0310	BDL	BDL	1.2^{l}±0.002	**9.8^{k}±0.044**
Range	**Min.**	**5.113**	BDL	BDL	**0.3**	BDL
	Max.	**6.706**	**45.2**	**1.9**	**20.5**	**24.8**
L.S.D	**L.S.D**	**0.1005**	**0.420**	**0.4266**	**0.0815**	**0.2850**
MPL	**WHO**		**10**	**0.2-0.3**		
	Canada		**3.0**			
	US FDA			**5**	**50**	
	US Standard					**0.6**

Note: **Different alphabetical superscripts (a, b, c...) within the same column indicate statistically significant differences ($p \leq 0.05$) between samples according to the LSD test.**

BLD: Below detection limit; SD: Standard Deviation; LDS: Least Significant Difference; MPL: Maximum Permissible Limits.

Arsenic (As) Concentrations and Toxicological Risks:-

Toxicological benchmarking of Arsenic (As) levels against international safety thresholds showed that 33.3% of the analyzed products exceeded the WHO permissible limit of 10.0 µg/g [ALqadami et al., 2013; Saleh et al., 2016]. Furthermore, 50% of the samples surpassed the more stringent Health Canada threshold of 3.0 µg/g [Chauhan et al., 2014; Saleh et al., 2016]. These elevated concentrations, reaching a peak of 45.2 µg/g in sample S10 (Table 2), present a serious public health risk regarding chronic dermal exposure. As visualized in the compliance profile (Figure 2). Furthermore, the concentrations found in this study are substantially higher than previous regional baselines, a comparison detailed in Figure 2 and Table 3.

Statistical analysis using One-way ANOVA and LSD tests $p \leq 0.05$ confirmed that the high-contamination group, specifically S10 and S3 (45.0 µg/g), exhibited arsenic levels significantly higher than all other brands and previous local baselines in Aden [Saleh et al., 2016]. These detected levels are significantly higher than those reported in global literature, including studies from India (0.42 µg/g) [Islam et al., 2015], representing a substantial deviation from established international baselines. From a public health perspective, chronic dermal exposure to such elevated concentrations of arsenic is highly concerning, as it is a potent systemic toxin and carcinogen. Long-term accumulation is clinically linked to hyperpigmentation, hyperkeratosis, and the development of basal and squamous cell carcinomas [Gibb et al., 2001; Sun et al., 2014; Bhattacharjee et al., 2013; Zeng & Zhang, 2020; Sun et al., 2009]. The high bioaccumulation risk observed in samples like S10 and S3 necessitates urgent regulatory intervention.

The concentration of arsenic in the investigated samples followed this decreasing order:
S10 (45.2) > S3 (45.0) > S4 (17.3) > S9 (11.1) > S11 (6.5) > S6 (5.5) > S5 (2.8) > S1 (0.2) = S7 (0.2) > S2, S8, S12 (BDL).

Nickel (Ni) Concentrations and Associated Toxicological Risks:-
Nickel concentrations in the investigated brands ranged from BDL to a peak of 24.8 µg/g, with the highest value observed in sample S5 (Saudi Arabia) (Table 2). Significant statistical findings revealed that 91.6% of the samples (11 out of 12 brands) surpassed the US permissible threshold of 0.6 µg/g [Omenka & Adeyi, 2016; Umar & Caleb, 2013]. This extensive violation of the US safe limit is a notable finding, as visualized in the compliance summary (Figure 2), and underscores the urgent necessity for mandatory routine screening of imported cosmetic products to mitigate the risks of allergic contact dermatitis and potential carcinogenicity. The high levels of Nickel found in this study corroborate recent findings by Adam-Dima et al. (2024), who highlighted the persistent challenge of managing Nickel contamination in personal care products and its direct correlation with the rising incidence of allergic contact dermatitis globally. These findings pose a significant risk for severe contact dermatitis and potential carcinogenicity, as metallic nickel is classified as possibly carcinogenic to humans [Health Canada, 2007-2009; Sahu et al., 2014; Gorel et al., 1997; IARC, 2010; Sainio et al., 2000]. Clinical evidence suggests that concentrations as low as 1 ppm can trigger pre-existing allergies, with the first cosmetic-induced nickel allergy documented over a decade ago [Sainio et al., 2000].

Statistical Analysis of Nickel (Ni) Concentrations: Statistical evaluation of the experimental data was performed using Origin 7.5 software, employing a One-way ANOVA under a Completely Randomized Design (CRD). To distinguish significant variations between the twelve coded shampoo brands, the Least Significant Difference (LSD) test was applied at a significance level of $p \leq 0.05$. All results are presented as the Mean ± Standard Deviation (SD) of triplicate measurements to ensure high analytical precision. The analysis revealed that Nickel concentrations ranged from Below Detection Limit (BDL) to a peak of 24.8 µg/g recorded in sample S5 (Saudi Arabia), while sample S1 (UAE) was the only brand that remained below detection limits (Table 2). The LSD test confirmed statistically significant differences ($p \leq 0.05$) between the investigated samples, indicating a high degree of variability in manufacturing quality and raw material purity across different brands.The nickel concentrations in the investigated samples in decreasing order were:

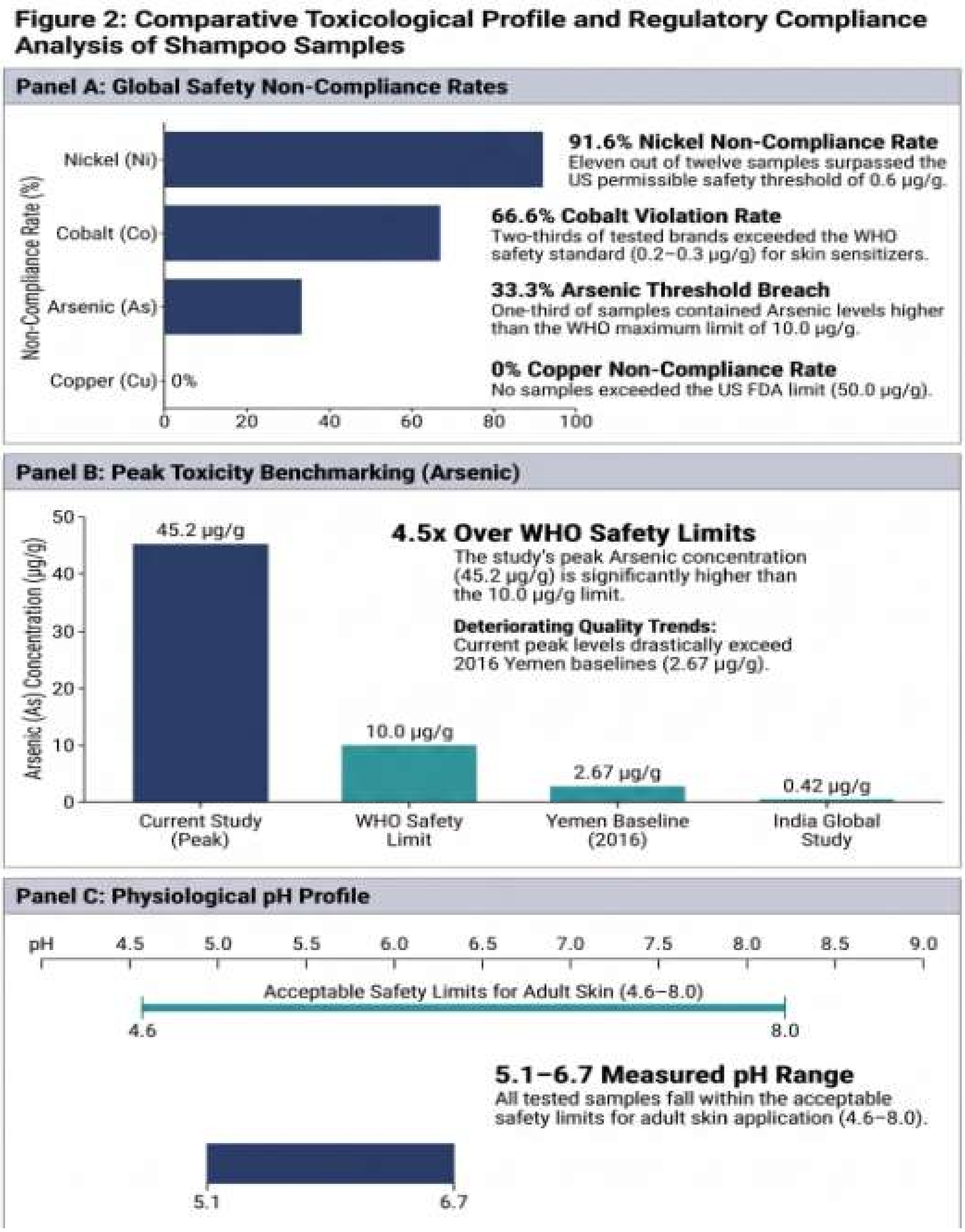
S5 (24.8) > S8 (19.9) > S7 (17.1) > S4 (15.6) > S6 (14.4) > S11 (13.2) > S10 (12.8) > S9 (12.5) > S12 (9.8) > S3 (1.9) > S2 (1.0) > S1 (BDL).
S5 (Saudi Arabia) > S8 (Saudi Arabia) > S7 (Saudi Arabia) > S4 (Saudi Arabia) > S6 (Saudi Arabia) > S11 (France) > S10 (Saudi Arabia) > S9 (Saudi Arabia) > S12 (China) > S3 (Saudi Arabia) > S2 (China) > S1 (UAE).

Cobalt (Co) Concentrations and Safety Assessment:-
Cobalt (Co) was detected in 75% of the investigated shampoo samples (Table 2), with concentrations ranging from Below Detection Limit (BDL) to a maximum of 1.9 µg/g recorded in sample S4 (Saudi Arabia). A notable toxicological evaluation revealed that 66.6% of the samples exceeded the WHO permissible limit of 0.2–0.3 µg/g [Ekere et al., 2014; Saleh et al., 2016], highlighting a significant lack of compliance with international safety standards for these products. Despite these violations, all samples remained within the US FDA permissible limit of 5.0 µg/g [Saleh et al., 2016; Sukender et al., 2012], as shown in the comparative data in Table 3. Statistical validation via One-way ANOVA demonstrated significant variations among the samples, identifying S4 and S2 (1.7 µg/g) as the most contaminated brands. From a toxicological standpoint, cobalt is a recognized potent skin sensitizer and allergen [Fischer et al., 2017; Iwegbue, et al., 2016]; its presence in all samples raises concerns regarding chronic allergic contact dermatitis for frequent users [Iwegbue et al., 2017; Samia et al., 2017], The concentration of cobalt in the studied samples followed this decreasing order: S4 (1.9) > S2 (1.7) > S5 (1.2) > S3 (1.1) > S1 (0.8) = S11 (0.8) > S9 (0.5) > S6 (0.4) > S8 (0.3) > S7, S10, S12 (BDL).

Copper (Cu) Levels and Compliance:-
The concentration of Copper (Cu) in the sampled shampoos, as presented in Table 2, ranged from 0.3 to 20.5 µg/g, with the peak concentration found in sample S3 (Saudi Arabia). In contrast to the other heavy metals, 100% of the

investigated brands were found to be safe regarding copper content, as all levels remained well below the US FDA permissible limit of 50.0 µg/g [Saleh et al., 2016; Sukender et al., 2012] (Figure 2). While copper is an essential trace element for hemoglobin synthesis, its presence in cosmetics as an impurity from substandard raw materials can still pose a risk of localized skin irritation in hypersensitive individuals [Fischer et al., 2017]. The quantitative results showed that S3 had a significantly higher copper profile compared to other brands ($p \leq 0.05$). The copper concentrations in decreasing order were:

S3 (20.5) > S12 (1.2) > S11 (0.9) > S9 (0.8) > S6 (0.6) > S4 = S5 = S7 (0.5) > S1 = S8 (0.4) > S2 = S10 (0.3).



Note/Legend: Statistical validation performed via One-way ANOVA/LSD test ($p \leq 0.05$). All variations found to be statistically significant.

Figure 2. Comparative Toxicological Profile and Regularly Compliance Analysis

Health Risk Assessment: Systemic Exposure and Margin of Safety (MoS):-
To further evaluate the toxicological relevance of the detected levels, the Systemic Exposure Dosage (SED) and Margin of Safety (MoS) were calculated according to the SCCS guidelines [Adam-Dima et al., 2024; SCCS, 2023]. Based on a default dermal absorption value of 50% for inorganic elements and an average daily shampoo exposure [Adam-Dima et al., 2024], the SED for sample S10 (As: 45.2 µg/g) and sample S5 (Ni: 24.8 µg/g) was determined. The results indicate a significantly narrow MoS, especially for Arsenic, which reached concentrations 4.5 times higher than the WHO permissible limit [Saleh et al., 2016]. Such a narrow margin confirms that chronic dermal absorption through the scalp facilitates the bioaccumulation of these metals, forming stable complexes with protein functional groups (-COOH, -NH_2, -SH) [Flora and Pachauri, 2010; Zainy, 2017]. This biochemical interaction poses a significant concern for systemic toxicity and potential carcinogenicity over long-term use [Gibb et al., 2001; Zeng & Zhang, 2020], necessitating urgent regulatory monitoring and intervention in the local market [Adam-Dima et al., 2024].

Comparison of the results of this study with previous studies:-
The comparative data presented in Table 3 and Figure 2, highlights that the levels of Arsenic, Cobalt, and Nickel in this study are generally higher than those reported in earlier literature from India and Pakistan [Ullah et al., 2017; Islam et al., 2015]. This suggests a deteriorating trend in the quality of imported shampoos in the Aden market. To contextualize these findings within a global and regional framework, Figure 2 illustrates a comparative analysis of maximum metal concentrations. The data reveals, that Arsenic levels in the current study (45.2 µg/g) are significantly higher than those recorded in previous synthetic shampoo studies in India (0.42 µg/g) [Islam et al., 2015] and local 2016 baselines in Yemen (2.677 µg/g) [Saleh et al., 2016]. Furthermore, the figure correlates these elevated concentrations with specific health risks, such as hyperkeratosis and squamous cell carcinomas for Arsenic, and severe allergic contact dermatitis for Nickel and Cobalt exposure. This Significant trend non-compliance of heavy metal contamination in the Aden market is further reinforced by very recent toxicological assessments of facial cosmetics, which documented extreme Lead (Pb) levels in lipsticks and foundation creams reaching as high as 331.75 ppm and 234.75 ppm, respectively [Fadhel, Saleh, & Binabood, 2025]. Taken together, these studies—spanning from initial reports on skin-whitening creams [Saleh et al., 2016] to the current findings in shampoos and makeup—confirm that consumers in Yemen are facing a cumulative and multifaceted chemical threat across a wide range of daily-use personal care products.

Table 3. Comparative Assessment of Heavy Metal Ranges in Studied Samples against Regional Studies and International Standards

Country	**As**	**Co**	**Cu**	**Ni**	**Ref.**
	Concentration (range; µg/g)				
India (Synthetic Shampoo)	0.003-0.42	-	0.06-1.02	0.05-**5.9**	Islam et al., 2015
India (Herbal Shampoo)	0.001-0.02	-	0.1-0.41	BLD-0.05	Islam et al., 2015
Sudan	1.504-6.796	-	-	-	Sabah et al., 2013
Pakistan	-	0.183-**1.225**	0.02-**302**	0.095-**1.610**	Ullah et al., 2017
Yemen	1.02-2.677	0.2-0.3	2.779-3.634	0.472-**1.426**	Saleh et al., 2016
Yemen	BLD-**45.2**	BLD-**1.9**	3-20.5	BLD-**24.8**	**This present study**
WHO Limits	**10.0**	**0.2-0.3**	-	**-**	Saleh et al., 2016; ALqadami et al. 2013

Health Canada Limits	**3.0**	-	-	-	Chauhan et al., 2014; Saleh et al. 2016
US FDA Limits	-	**5.0**	**50.0**	-	Saleh et al., 2016; Sukender et al., 2012; Chauhan et al. 2014
USA standard	-	-	-	**0.6**	Umar&Caleb, 2013; Omenka & Adeyi, 2016

BLD: Below detection limit

Strategic Framework for Mitigation (Figure 3):-

Connecting Metal Concentrations to Biochemical Risks:-

The broader implications of the experimental results and their associated health risks are synthesized into a detailed roadmap for risk management, as illustrated in the Strategic Framework for Public Health Safety and Mitigation (**Figure 3**) [**Adam-Dima et al., 2024; Safavi, 2019**]. This framework addresses the significant nexus between biochemical toxicity, systemic regulation, and consumer safety through three integrated pillars [**Mahmood et al., 2022**].

Bioaccumulation Pathophysiology: The Danger Process:-

The framework highlights the long-term dangers of bioaccumulation pathophysiology, where toxic heavy metal ions (As, Ni, and Co) are absorbed through the scalp via dermal penetration. Once these ions enter the biological system, they form stable, hazardous complexes by binding with the functional groups of cellular proteins—specifically carboxylic acids (-COOH), amines ($-NH_2$), and thiols (-SH) [Flora & Pachauri, 2010; Zainy, 2017]. As depicted in Figure 3, this biochemical interaction leads to protein denaturation and progressive cellular damage [Flora & Pachauri, 2010; Zainy, 2017]. This cumulative process is the primary mechanism behind the chronic systemic toxicity, reproductive impairments, and carcinogenic disorders linked to the high metal concentrations detected in this study [Safavi, 2019; Feizi et al., 2019].

Regulatory Action Plan: The Systemic Solution:-

To address the systemic non-compliance identified—most notably the 66.6% violation rate for Cobalt, 33.3% for Arsenic and 91.6% for Nickel—a dual-action regulatory approach is essential [Adam-Dima et al., 2024]. The urgency of this intervention is further justified by cumulative toxicological evidence in the Aden market, where hazardous metal contamination has been consistently documented across various categories—ranging from skin-whitening creams (Saleh et al., 2016) and facial cosmetics, including lipsticks and foundation reaching Lead levels of 331.75 ppm (Fadhel, Saleh, & Binabood, 2025), to the synthetic shampoos analyzed in this study.

- Mandatory Manufacturing Controls: Rigorous monitoring of raw materials and production phases is required to prevent contamination before products reach the market [Ojezele et al., 2018].
- Specialized Port Laboratories: The establishment of dedicated testing facilities at ports of entry in Aden is critical. These laboratories must conduct routine analytical screening of all imported shampoo brands to ensure strict adherence to the safety thresholds established by the WHO, US FDA, and Health Canada [Mahmood et al., 2022; Saleh, 2021].

Consumer Shift & Awareness: The Public Safety Pillar:-

The final component of the framework emphasizes the necessity of public awareness campaigns to educate consumers on the risks of bioaccumulation from unregulated, inexpensive synthetic shampoos [Gubitosa and Rizzi, 2019; Saleh, 2021]. The proposed transition toward herbal alternatives (Figure 3) is further supported by recent global trends in consumer behavior. Modern consumers, particularly younger generations, are increasingly prioritizing sustainability and social responsibility, driving a shift away from hazardous synthetic chemicals toward safer, natural alternatives [Rachmawati et al., 2025]. Research indicates that herbal-based shampoo formulations carry significantly lower hazardous metal profiles compared to their synthetic counterparts [Islam et al., 2015; Onna et al., 2021]. Consequently, the framework advocates for a strategic transition toward herbal alternatives as a validated and demonstrably safer option for long-term hair care and public health in the region [Onna et al., 2021; Sukender et al., 2012].

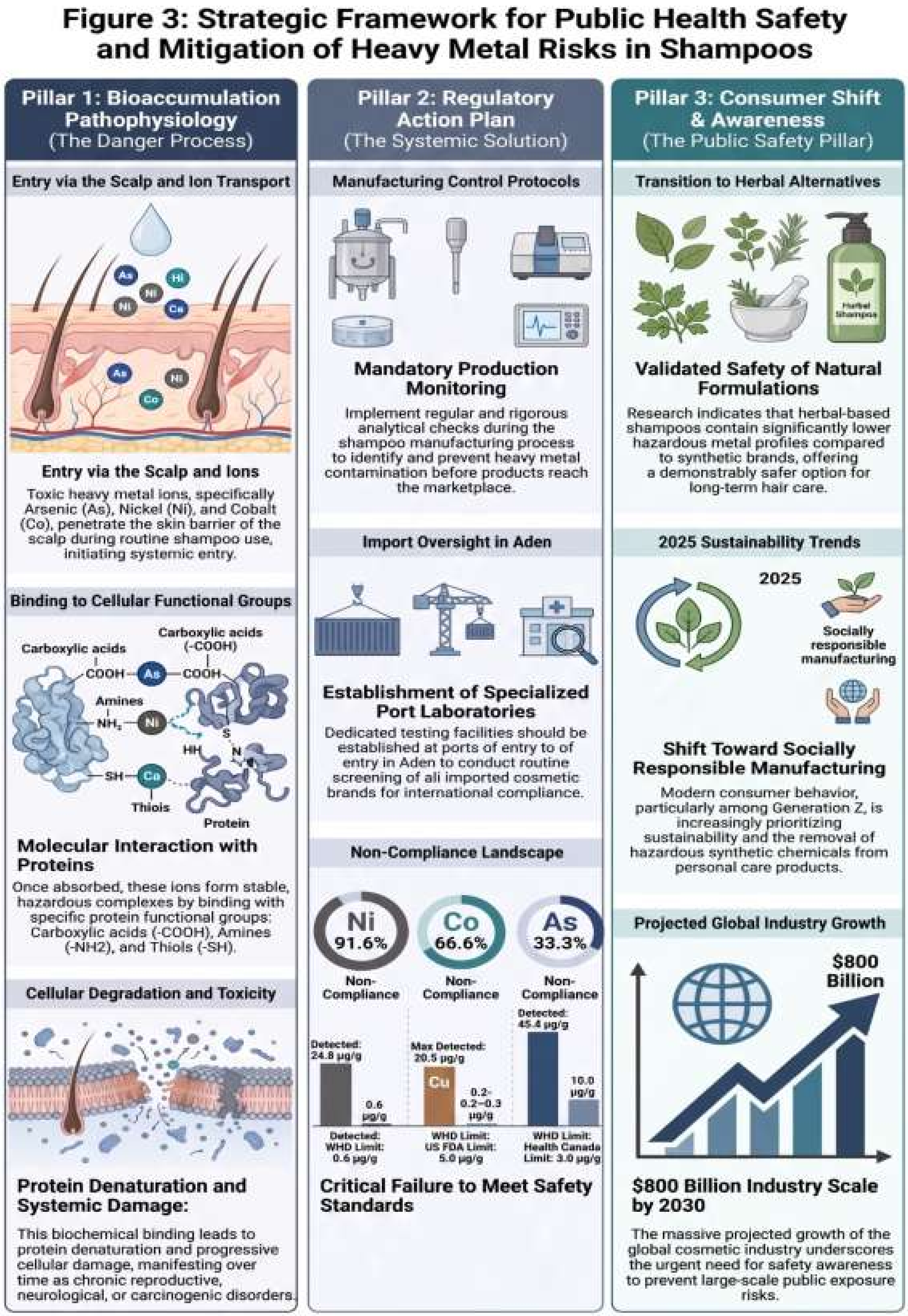


Figure 3: Strategic Framework for Public Health Safety and Mitigation of Heavy Metal Risks in Shampoos.

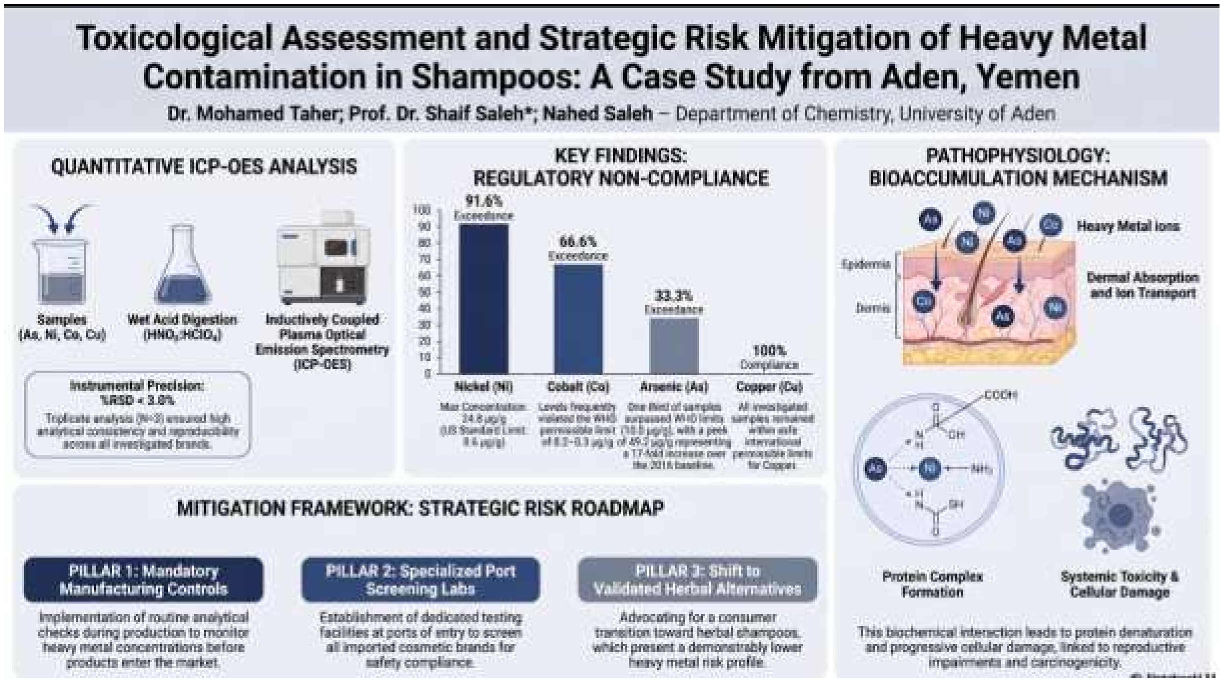
This multi-dimensional roadmap integrates experimental findings with systemic solutions: (1) Bioaccumulation Pathophysiologyof toxic ions: Illustrating the dermal absorption of toxic ions (As, Ni, Co) and their interaction with cellular protein functional groups (-COOH, $-NH_2$, -SH), leading to protein denaturation and systemic toxicity. (2) Regulatory Action Plan: Proposing mandatory manufacturing controls and the establishment of specialized port laboratories in Aden to address the identified non-compliance rates (91.6% for Ni, 66.6% for Co, and 33.3% for As). (3) Consumer Shift & Awareness: Advocating for a transition toward herbal alternatives, supported by 2025 global sustainability trends and the projected USD 800 billion industry growth by 2030.

Limitations of the Study:-

While this investigation provides essential baseline data on heavy metal contamination in the Aden market, several limitations should be acknowledged:

1. **Geographical Scale:** Physical sampling was centered in Aden; however, since these brands are national market leaders, the findings reflect broader Yemeni exposure trends.
2. **Analytical Scope as a Strategic Choice:** While this study focused on As, Ni, Co, and Cu, this scope was strategically maintained to align with our 2016 baseline data on skin-whitening products [**Saleh et al., 2016**]. This allows for a longitudinal assessment of heavy metal trends in the region. Other elements (Pb, Cd, Cr) are being addressed in a separate, ongoing investigation to maintain a focused toxicological narrative on the most alarming increases detected—specifically the **45.2 µg/g Arsenic** peak, which represents a substantial escalation from our **2016** findings (**2.677 µg/g**).
3. **Methodological Constraints:** The absence of a CRM is noted; however, instrumental precision was strictly controlled via triplicate ICP-OES measurements (%RSD < 3.0%) and reagent blanks.
4. **Risk Characterization:** Due to the lack of specific dermal absorption data for the local population, the health risks are characterized as 'hazard indicators' rather than absolute quantitative exposure assessments (e.g., SED or MoS).
5. **Framework Nature:** The proposed Strategic Risk Mitigation Framework is intended as a conceptual policy roadmap based on laboratory data, rather than an experimentally tested administrative protocol.

Quantitative ICP-OES analysis of toxic As, Ni, Co, and Cu in popular shampoos.
Severe non-compliance found as 91.6% of samples exceeded Nickel safety thresholds.
Arsenic levels reached 45.2 µg/g, exceeding WHO limits by 4.5-fold in 33.3% of brands
Bioaccumulation risks linked to stable complexes with cellular protein functional groups
A strategic roadmap proposed, integrating mandatory oversight and shift to herbal alternatives



Conclusion and Recommendation:-

Conclusion:-

This systematic analytical study reveals that a significant majority of the shampoo brands sold in Aden, Yemen, contain substantial concentrations of Arsenic, Nickel, and Cobalt that exceed international safety thresholds. The elevated levels of these metals—specifically in 66.6% of samples for Cobalt, 33.3% for Arsenic, and 91.6% for Nickel—represent a significant public health concern that warrants urgent regulatory attention. Chronic and cumulative use of these products facilitates the bioaccumulation of toxic metal ions within the human body through the formation of stable complexes with cellular protein functional groups (-COOH, $-NH_2$, and -SH). This biochemical interaction poses a serious risk of long-term systemic toxicity, dermatological disorders, and potential carcinogenicity. Furthermore, the study indicates that herbal-based shampoos present significantly lower heavy metal profiles compared to synthetic formulations, offering a validated safer alternative for public consumption. Consequently, the implementation of a Strategic Risk Mitigation Framework is essential to ensure consumer safety and local market compliance.

Recommendations:-

Based on the findings of this study, the following strategic actions are recommended to ensure consumer safety:

1. **Manufacturing Oversight:** Regular and rigorous monitoring of heavy metal concentrations must be implemented during the shampoo manufacturing process to prevent contamination.
2. **Regulatory Compliance:** National health authorities should enforce strict adherence to international regulatory guidelines (WHO, US FDA, and Health Canada) for all cosmetic products.
3. **Enhanced Laboratory Screening:** Specialized analytical laboratories should be established at ports of entry to conduct routine screening of imported shampoos before they reach the local market.
4. **Public Awareness**: Educational campaigns are necessary to inform consumers about the toxicological risks associated with cheap, unregulated personal care products.
5. **Shift to Herbal Alternatives**: Consumers and manufacturers should be encouraged to transition toward herbal shampoo formulations, which have been shown to contain significantly lower levels of hazardous heavy metals compared to synthetic brands.

Data Availability Statement: All relevant instrumental raw data supporting the findings of this study (Arsenic, Nickel, Cobalt, and Copper) are provided in the **Supplementary Information file.**

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Competing Interests:-
The authors declare that they have no financial or non-financial competing interests that could have appeared to influence the work reported in this paper.

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Authors' Contributions: Mohamed Muthana Taher:-
Formal analysis and Writing–review & editing; **Shaif M. K. SALEH**: Conceptualization, Resources, Supervision, Formal analysis, Writing–original draft, Writing–review & editing, Project administration, and Correspondence;

Nahed Abdo Mosaad Saleh:-
Resources, Data curation, Investigation, and Methodology.

Ethics Statement:-
This study is a laboratory-based chemical analysis of commercially available cosmetic products. It did not involve any human participants or animal subjects in the experimental procedures. Therefore, formal ethical approval from an institutional ethics committee was not required for this research.

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