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## ORIGINAL STUDY

# Health Implications of Heavy Metal Contamination in Commercially Available Deodorant and Antiperspirant Products Sold in Benghazi, Libya

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## Abstract

The extensive usage of deodorants and antiperspirants raises concerns about the potential health risks posed by heavy metal content. This study quantified the levels of five heavy metals: Aluminum, Zirconium, Lead, Cadmium, and Chromium in 22 commercial products widely used in Benghazi, Libya, and assessed the associated health risks. Samples, categorized into gel, stick, and roll-on formulations, were analyzed using iCAP TQ ICP-MS. Al and Zr showed the widest concentration ranges, reflecting their intentional use as active ingredients. Al levels ranged from trace amounts (0.032 mg/kg) up to a maximum of 99.10 mg/kg, while Zr was found exclusively in gel and stick formulations, reaching 36.81 mg/kg. In contrast, the trace metal contaminants (Pb, Cd, and Cr) were consistently found at extremely low levels, ranging from non-detectable up to a maximum of only 0.013 mg/kg (Cd). Health risks were estimated for males and females at 50 % and 100 % bioaccessibility using the systemic exposure dose (SED), Margin of Safety (MoS), Hazard Index (HI), and Lifetime Cancer Risk (LCR). The LCR values remained overwhelmingly within the acceptable range, indicating low carcinogenic concern. However, non-carcinogenic risk was suggested in a small subset of samples where the Hazard Quotient (HQ) and HI exceeded the threshold of 1. These results indicate that while the majority of products pose little overall health danger, continuous monitoring of specific high-Al and Zr formulations is essential to guarantee long-term consumer safety.

**Keywords:** Health risk assessment, Heavy metals, Cosmetics, Deodorants, Antiperspirants

## 1. Introduction

Since ancient times, cosmetics have played a crucial role in human civilization for both sanitary and aesthetic reasons [1]. Due to cultural pressures and growing awareness of personal grooming, their demand has expanded throughout the decades on a global scale [2]. These cosmetics, which include eye makeup, kajal, lipsticks, creams, and powders, are used to preserve the health of the skin and improve look [3]. However, dozens of inorganic and organic components, including waxes, oils, pigments, and fillers like mica or titanium dioxide, are used in complicated formulations in modern cosmetics, which may unintentionally

introduce heavy metals and other hazardous pollutants [2,4]. Some cosmetics are safe, but others have serious health hazards, such cancer, allergic responses, or reproductive issues, which are frequently connected to exposure to hazardous metals [5]. Hazardous materials including lead, mercury, and coal tar have been outlawed by regulatory agencies such as the US FDA (U.S. Food and Drug Administration) and the EU (European Union), but worries about long-term exposure and insufficient safety testing still exist [1,6].

Whether included purposefully or as impurities, heavy metals are one of the alarming pollutants in cosmetics that provide serious health hazards. Certain metals, including arsenic (As), cadmium

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Received 6 September 2025; revised 23 October 2025; accepted 4 November 2025.  
Available online 12 December 2025

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<https://doi.org/10.55810/2313-0083.1112>

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(Cd), lead (Pb), and mercury (Hg), are prohibited by regulatory authorities, while others, like cobalt and chromium, are allowed under tight guidelines (EU Regulation No. 1223/2009) [7]. Nevertheless, disparities continue to exist around the world; for example, the US FDA allows 5 ppm of As and Pb, whereas the WHO suggests lower limits (e.g., 0.3 ppm for Cd) (Cosmetic Ingredient Review Expert Panel, WHO) [8]. Mineral pigments, preservatives, and UV filters are common ways for these metals to enter cosmetics [9], and environmental pollution can even expose “natural” products like plant oils to them [10]. While nickel (Ni) and chromium (Cr) may cause allergic dermatitis, the systemic buildup of metals like Pb and Cd through dermal absorption can affect organs including the kidneys, liver, and brain [11]. Exposure is increased when topical treatments like lipsticks and cosmetic powders are used orally [12]. Sadly, metals like aluminum (Al) have been connected to neurological diseases while being safe in antiperspirants [13]. The persistence of trace pollutants in spite of legislation emphasises the necessity of standardised criteria and thorough testing to reduce long-term health effects, such as endocrine disruption and carcinogenesis [14].

According to recent studies, there is rising worry about the inclusion of heavy metals in cosmetic products because of the possible health hazards associated with long-term dermal exposure. In Rivers State, Nigeria, Mgbemena et al. (2024) [15] examined 22 cosmetic goods and discovered measurable quantities of Pb, Cd, Zn, Cr, Cu, and Ni, but all results were below allowable bounds. Some metals, including copper and zinc, however, went above the advised margin of safety, indicating a potential risk with continued usage. In a similar vein, Hreeba et al. (2024) [16] evaluated cosmetics in Al-Ajilat City and found that lead and iron contents in many samples exceeded WHO recommendations, suggesting possible systemic toxicity and the need for more regulatory monitoring. Measurable quantities of Mn, Ni, Cu, Cd, Cr, and Pb were also found in a variety of items marketed in Kano, Nigeria, according to Sani et al. (2016) [17], who cautioned that even low concentrations might bioaccumulate over time and provide health risks.

Ghaderpoori et al. (2020) [18] estimated the Margin of Safety (MoS) and Hazard Quotients (HQs) for cosmetics using data from 11 publications as part of a larger Iranian investigation. Their findings showed increased exposure to Fe and Hg in a variety of product kinds, with creams exhibiting the greatest HQ for Pb. While HQ and HI values were generally within acceptable ranges, Kicińska

and Kowalczyk (2025) [19] evaluated 23 cosmetic samples from online markets and noted that the wide variability in Cr, Fe, Ni, Mn, and Zn concentrations suggested inconsistent safety levels, especially for products imported from countries with lax regulations. Increased lifetime cancer risks (LCRs) were detected in the majority of items by Arshad et al. (2020) [2], who also discovered higher amounts of Cd, Cr, Fe, Ni, and Pb in a number of cosmetic brands, with sunscreen creams and lotions above Ni and Pb limitations. While most cosmetic products posed low non-carcinogenic and sensitisation risks, heavy users, particularly of lip cosmetics, may experience metal exposures beyond acceptable daily intake levels for Pb, Mn, and Cr, according to a thorough health risk assessment across multiple metals by Lim et al. (2018) [20].

Therefore, the primary aim of this study was to quantify the levels of five heavy metals—chromium (Cr), lead (Pb), cadmium (Cd), zirconium (Zr), and aluminum (Al)—in a range of commercially available deodorant and antiperspirant products sold in Benghazi, Libya, and to conduct a comprehensive health risk assessment using systemic exposure dose (SED), margin of safety (MoS), hazard index (HI), and lifetime cancer risk (LCR) to determine the potential carcinogenic and non-carcinogenic risks to consumers.

## 2. Materials and methods

### 2.1. Sample collection

This study focused on the most commonly used deodorant and antiperspirant products, specifically those with a usage frequency exceeding 70 %. The selection was informed by consumer preferences gathered from over 150 surveys, along with verbal input from 35 chemists regarding the most popular and best-selling goods in Benghazi, Libya. Based on this combined data, a total of 22 distinct commercial samples were purchased from local pharmacies including Alyansun, Al-Rahiq, Al-Qalea, and others. One entire commercial unit (a whole bottle/stick) of each product was acquired. The samples were immediately classified by their formulation type—gel deodorants (GD), stick deodorants (SD), roll-on deodorants (RD), gel antiperspirants (GA), stick antiperspirants (SA), and roll-on antiperspirants (RA)—and given a unique identification code (1–22) as shown in Table 1. All samples were stored in their original containers at room temperature (approximately 25 °C) in a clean, dry, and dark cabinet to prevent potential degradation and were analyzed within one month of purchase. For the

Table 1. Antiperspirant and deodorant samples from various brands purchased from local pharmacies.

Code	Types	Product Trade Name	Formulation	Country of Origin
GA1	Gel	Gillette	Antiperspirant	USA
GD2		L'Oréal	Deodorant	France
SA3	Stick	Dove	Antiperspirant	Russia
SA4		Ultra Max	Antiperspirant	USA
SD5		Essentials	Deodorant 0 % Al	USA
SA6		Lady Speed	Antiperspirant	USA
RD7	Rol-on	Lycia	Deodorant 0 % Al	Italy
RD8		Lycia	Deodorant	Italy
RD9		Neutro Roberts (Derma Zero)	Deodorant 0 % Al	Italy
RD10		Neutro Roberts (Invisible)	Deodorant Anti-stains	Italy
RD11		Fa (Fresh & Dry)	Deodorant 0 % Al	UAE
RA12		Fa (Freshly Free)	Antiperspirant	UAE
RD13		L'Oréal (Barber Club)	Deodorant Al Free	France
RA14		L'Oréal (Shirt Protect)	Antiperspirant	France
RA15		Nivea (Dry & Fresh)	Antiperspirant	Germany
RD16		Felce Azzurra	Deodorant	Italy
RA17		Enchanteur	Antiperspirant	Vietnam
RD18		Men Only	Deodorant	Malta
RA19		Yves Rocher	Antiperspirant	France
RA20		Garnier Mineral	Antiperspirant	South Africa
RA21		Rexona	Antiperspirant	South Africa
RD22		Lactovit	Deodorant	Spain

chemical analysis, a homogeneous portion of approximately 0.5 g from each sample was accurately weighed and used for digestion.

## 2.2. Reagents and standards

All glassware and polyethylene containers were thoroughly cleaned by steeping in a 10 % v/v HNO<sub>3</sub> bath for a minimum of 24 h. Following acid steeping, they were rinsed three times with deionised water and dried before use. To ensure accurate measurement and control the background, a reagent blank (containing only the acid matrix and deionised water) was prepared with every batch of samples and analyzed to correct for any elemental contamination in the reagents or environment.

All reagents utilized were of analytical grade. Nitric acid (HNO<sub>3</sub>, 69 %) and Perchloric acid (HClO<sub>4</sub>, 60 %) were used for sample digestion, both sourced from BDH Ltd., Poole, England, and Riedel-de Haën AG, Germany, respectively, and used without further purification. Deionised water, with a resistivity of 18.2 MΩ-cm, was obtained from a Milli-Q water purification system (Millipore, Bedford, MA, USA) and was used for all dilutions and preparations.

Certified single-element stock standard solutions of chromium (Cr), lead (Pb), cadmium (Cd), zirconium (Zr), and aluminum (Al), each at a concentration of 1000 mg/L, were purchased from BDH (BDH Ltd., Poole, England).

Working calibration standards were prepared daily by serial dilution of the 1000 mg/L stock solutions using 2 % v/v HNO<sub>3</sub> as the diluent. The concentration range of the final working standards was 0.01–100 µg/L for the analysis.

## 2.3. Instrumentation and method

Using an iCAP TQ Inductively Coupled Plasma Mass Spectrometer (iCAP TQ ICP-MS, Thermo Scientific, USA) and Qtegra Intelligent Scientific Data Solution software, the concentrations of heavy metals, specifically aluminum (Al), cadmium (Cd), chromium (Cr), lead (Pb), and zirconium (Zr), were measured. To increase sensitivity and reduce background interference, instrumental parameters such radiofrequency (RFerq) power, nebuliser gas flow rate, and sample position inside the plasma were optimised. Table 2 provides a summary of the operating conditions.

Table 2. Operating conditions and instrumental parameters for iCAP TQ ICP-MS.

ICP-MS Parameter	Value
Radio frequency (RFerq) power	1550 W
Sample flow rate	1.0 mL \ min
Coolant gas flow rate	14 L \ min
Auxiliary gas flow rate	0.8 L \ min
Nebulizer gas flow rate	1.08 L \ min
Replicates per sample	4
Nebulizer	Glass concentric
Spray chamber	Quartz cyclonic

#### 2.4. Digestion method

With certain modifications, the sample preparation process was carried out according to Elbagermi et al. (2020) [21]. Ten millilitres of concentrated  $\text{HNO}_3$  were introduced to a 250 mL beaker containing around 1.0 g of material. To oxidise organic materials, the mixture was cooked for 45 min. Following cooling, 5 mL of  $\text{HClO}_4$  was added, and heating was maintained until white vapours appeared. After adding 20 mL of distilled water, the liquid was brought to a boil in order to remove any remaining gases. Whatman No. 42 filter paper was used to filter the resultant mixture. An iCAP Triple Quadrupole Inductively Coupled Plasma Mass Spectrometer (iCAP TQ ICP-MS) was then used to measure the amounts of the elements.

#### 2.5. Health risk assessment based on data analysis

A methodical technique for estimating the possible negative impacts of chemical pollutants on human health is health risk assessment. Measured concentrations of the target elements and recognised toxicological reference values were used in this study's evaluation. To ascertain if exposure levels represent a substantial danger to public health, both cancer and non-cancer risk factors were assessed.

##### 2.5.1. Non-cancer risk assessment

Evaluating the possibility of harmful health outcomes other than cancer that might result from exposure to pollutants is the main goal of non-cancer risk assessment. This is typically achieved by comparing estimated exposure doses to established safe thresholds. To evaluate the risk of hazardous consequences under the reported exposure settings, parameters such as the Hazard Quotient (HQ), Hazard Index (HI), and Margin of Safety (MOS) were computed.

**2.5.1.1. Margin of safety (MoS).** The Margin of Safety (MoS) is a critical metric used to represent the degree of risk in non-carcinogenic risk evaluation. It is determined by the ratio of the no-observed-adverse-effect level (NOAEL), or a similar toxicological reference dose, to the systemic exposure dose (SED), as shown in the following equation [22]:

$$\text{MOS} = \frac{\text{NOAEL}}{\text{SED}} \quad (1)$$

In terms of consumer safety, the MoS quantifies how much greater the level of exposure that causes no adverse effects is compared to the actual

exposure experienced by the consumer. A value of  $\text{MoS} \geq 100$  is generally considered acceptable for cosmetic ingredients by regulatory bodies, indicating an adequate safety margin for the consumer. Results where the  $\text{MoS} < 100$  are indicative of a potential safety concern that warrants further investigation and are directly integrated with the Hazard Quotient (HQ) and Hazard Index (HI) to provide a comprehensive non-carcinogenic risk profile [2,18].

SED is the systemic exposure dosage and NOAEL is the no observed adverse effect level. The SED, which is derived from Eq. (2) [22], calculates the amount of a material that enters the body via the product's skin.

$$\text{SED} = \frac{C_s \times \text{AA} \times \text{SSA} \times \text{RF} \times \text{F} \times \text{BF} \times 10^{-3}}{\text{BW}} \quad (2)$$

A single axilla's median surface area (SSA,  $64.5 \text{ cm}^2$  for females and  $135.5 \text{ cm}^2$  for males) [23], the amount applied daily (AA,  $0.0038 \text{ g/cm}^2$  for men and  $0.0062 \text{ g/cm}^2$  for women) [23], the measured concentration of metals in the product ( $C_s$ , mg/kg), and the average body weight (BW, 70 kg) [22,24] were all used to calculate SED. Additional factors included the application frequency (F) of once daily and the retention factor ( $R_f$ ) of 1.5 for roll-on formulations and 3.5 for gel and stick formulations [23,24]. Two exposure scenarios were examined for the bioaccessibility factor (BF): 50 % and 100 %. A  $10^{-3}$  (mg/kg) unit conversion factor was used [25].

Dermal reference doses (RfDs) published by the USEPA (2006) were used to construct the NOAEL, which stands for the exposure level at which no negative effects are shown [25]:

$$\text{NOAEL} = \text{RfD} \times \text{UF} \times \text{MF} \quad (3)$$

where the modifying factor (MF), which is determined by scientific judgement, was set to 100 and the uncertainty factor (UF) was set to 1. According to the U.S. EPA (2012) [26], the target metals' dermal RfDs [ $\mu\text{g/kg/day}$ ] are as follows: Al (0.0004), Zr (0.08), Pb (0.0058), Cd (0.015), and Cr (0.42 mg/kg/day).

According to the U.S. EPA's 2005 Guidelines for Carcinogen Risk Assessment, there is inadequate information currently available on zirconium's carcinogenic potential. Limited research on humans and animals has shown conflicting results. The U.S. EPA has set a preliminary oral RfD of  $0.00008 \text{ mg/kg/day}$  ( $0.08 \mu\text{g/kg/day}$ ) for soluble zirconium compounds, such as zirconium sulphate [27]. The dermal RfD for zirconium is calculated using a default dermal absorption factor of 10 % as follows:

$$\begin{aligned} \text{RfD}_{\text{Dermal}} &\approx \text{RfD}_{\text{Oral}} \times \text{Dermal Absorption Factor} \\ &\approx 0.08 \mu\text{g}/\text{kg}/\text{day} \times 0.10 = 0.008 \mu\text{g}/\text{kg}/\text{day} \end{aligned} \quad (4)$$

**2.5.1.2. Hazard quotient (HQ) and hazard index (HI).** For every metal under study, the Hazard Quotient (HQ) measures the proportion of the systemic exposure dose (SED) to the dermal reference dose (RfD) [28]. A HQ value > 1 suggests possible health hazards, whereas a number <1 is often regarded as safe for human health. The following formula is used to determine the HQ:

$$\text{HQ} = \frac{\text{SED}}{\text{RfD}} \quad (5)$$

An overall evaluation of the combined health risk from exposure to several metallic pollutants is provided by the Hazard Index (HI), which is the sum of the hazard quotients for all metals under examination. The HI is calculated using the following equation in accordance with the connection given in Ref. [29]:

$$\text{HI} = \sum \text{HQ} = \text{HQ}_{\text{Al}} + \text{HQ}_{\text{Zr}} + \text{HQ}_{\text{Cd}} + \text{HQ}_{\text{Cr}} + \text{HQ}_{\text{Pb}} \quad (6)$$

### 2.5.2. Cancer risk assessment

Cancer Risk Assessment assesses the likelihood that a person or community may get cancer as a result of prolonged exposure to a carcinogenic material. Toxicological metrics like the cancer slope factor (CSF), which measures the increased cancer risk per unit of daily consumption over a lifetime, and predicted exposure levels are usually the basis for this evaluation. By combining these factors, the evaluation offers a numerical representation of possible cancer risk, which aids in directing policy choices and public health initiatives.

**2.5.2.1. Lifetime cancer risk (LCR).** Lifetime cancer risk (LCR) is assessed for metals with known carcinogenic potential. LCR was computed using the procedure outlined in Ref. [29] as follows:

$$\text{LCR} = \text{SED} \times \text{CSF} \quad (7)$$

where CSF is the cancer slope factor (mg/kg/day)<sup>-1</sup> and SED is the systemic exposure dosage. Over the course of a typical lifetime, the CSF shows the predicted risk of cancer per unit consumption of a carcinogenic substance. According to previously published research, the slope factors for Al, Zr, Pb,

Cr, and Cd are 0.001, 0.0005, 0.0085, 0.5, and 6.7 (mg/kg/day)<sup>-1</sup>, respectively [30].

## 3. Results and discussion

The levels of aluminum, zirconium, lead, cadmium, and chromium in 22 samples of deodorant and antiperspirant products from different manufacturers were measured. A comparison was made between the findings and the FDA-approved limits for metals allowed in over-the-counter antiperspirants. Table (3) shows the detected concentrations of heavy metals (mg/kg) in the tested items, grouped according to category.

The levels of heavy metals in Libyan deodorants and antiperspirants were varied depending on the kind of product, according to the findings (Table 3). Roll-on deodorants (RD8) had the greatest concentration of aluminum (Al), which exhibited the broadest range, ranging from 0.03 to 99.10 mg/kg (average 33.93 mg/kg). Zirconium (Zr) peaked in stick antiperspirants (SA3) and varied from 0.0008 to 36.81 mg/kg (average 1.82 mg/kg). On the other hand, the maximum levels of lead, cadmium, and chromium were continuously found at significantly lower levels: 0.0023 mg/kg, 0.0130 mg/kg, and 0.0023 mg/kg, respectively. Importantly, the concentrations of Pb and Cr were well below the widely recognized recommended maximum acceptable concentration of 10 mg/kg for unavoidable trace contaminants in cosmetics, and the Cd maximum concentration 0.013 mg/kg was also significantly below this limit [31].

The results obtained support a typically decreased contamination profile when compared to earlier research. Nigerian face powders had Pb concentrations as high as 0.33 mg/kg and Cd concentrations as high as 1.74 mg/kg, according to Sani et al. (2016) [17], which is significantly higher than the levels in our samples. Similarly, Pb was 6.37 mg/kg in sunblock creams, Cd was 0.26 mg/kg in lotions, and Cr was 0.43 mg/kg in sunblock creams, among other significantly higher values in Pakistani cosmetics, according to Arshad et al. (2020) [2]. In contrast to our findings, which indicated that only a small number of samples slightly surpassed the insignificant cancer risk level, the analysis also revealed lifetime cancer risk values beyond allowable criteria for the majority of goods. Al, Cd, and Pb have been detected in European cosmetics by Lara-Torres et al. (2021) [31], who also noted that while Cd and Pb were within FDA standards, they did not adhere to EU laws, which completely forbid their presence. In contrast, our samples' levels of Pb and Cd were much below the

Table 3. Aluminum, zirconium, lead, cadmium, and chromium concentrations; (mg/kg), in antiperspirant and deodorant samples.

Sample No.	Metal concentration (mg/kg)				
	Al	Zr	Pb	Cd	Cr
GA1	5.47 ± 0.27	1.85 ± 0.09	0.0014 ± 0.0001	0.0011 ± 0.0001	0.0010 ± 0.0001
GD2	5.04 ± 0.25	1.33 ± 0.07	0.0021 ± 0.0001	0.0080 ± 0.0003	0.0023 ± 0.0001
SA3	42.12 ± 2.11	36.81 ± 1.74	0.0021 ± 0.0001	0.0020 ± 0.0008	0.0019 ± 0.0001
SA4	78.75 ± 3.94	0.04 ± 0.00	0.0018 ± 0.0001	0.0020 ± 0.0010	0.0017 ± 0.0001
SD5	0.08 ± 0.00	0.01 ± 0.00	0.0016 ± 0.00008	0.0030 ± 0.0009	0.0012 ± 0.0001
SA6	0.19 ± 0.01	0.08 ± 0.00	<0.0005	<0.0010	0.0014 ± 0.0001
RD7	0.04 ± 0.00	<0.0008	0.0011 ± 0.0001	<0.0010	0.0011 ± 0.0000
RD8	99.10 ± 4.96	<0.0008	0.0012 ± 0.0001	0.0020 ± 0.0004	0.0020 ± 0.0001
RD9	0.12 ± 0.01	<0.0008	0.0023 ± 0.0001	0.0070 ± 0.0003	0.0014 ± 0.0000
RD10	38.12 ± 1.91	<0.0008	0.0023 ± 0.0001	0.0070 ± 0.0004	0.0021 ± 0.0001
RD11	0.04 ± 0.00	<0.0008	0.0020 ± 0.0001	0.0060 ± 0.0008	0.0015 ± 0.0001
RA12	56.41 ± 2.82	<0.0008	0.0012 ± 0.0001	0.0020 ± 0.0001	0.0016 ± 0.0001
RD13	0.03 ± 0.00	<0.0008	0.0017 ± 0.0001	0.0040 ± 0.0001	0.0014 ± 0.0001
RA14	47.51 ± 2.38	<0.0008	0.0013 ± 0.0001	0.0130 ± 0.0001	0.0015 ± 0.0001
RA15	54.04 ± 2.70	<0.0008	0.0015 ± 0.0000	0.0002 ± 0.0000	0.0016 ± 0.0001
RD16	48.25 ± 2.41	<0.0008	0.0011 ± 0.0001	0.0030 ± 0.0001	0.0020 ± 0.0001
RA17	0.06 ± 0.00	<0.0008	0.0012 ± 0.0001	<0.0010	0.0017 ± 0.0001
RD18	59.73 ± 2.99	<0.0008	0.0011 ± 0.0001	0.0030 ± 0.0001	0.0016 ± 0.0001
RA19	73.48 ± 3.67	<0.0008	0.0014 ± 0.0001	<0.0010	0.0022 ± 0.0001
RA20	39.84 ± 1.97	<0.0008	<0.0005	<0.0010	0.0021 ± 0.0001
RA21	53.51 ± 2.64	<0.0008	<0.0005	<0.0010	0.0021 ± 0.0001
RD22	44.56 ± 2.19	<0.0008	0.0012 ± 0.0001	0.0011 ± 0.0001	0.0014 ± 0.0001

FDA criteria and the European reference values, whereas their levels of Al were significantly higher (up to 99.1 mg/kg).

More recently, Mgbemena et al. (2024) [15] examined cosmetics from Rivers State, Nigeria, and discovered that lipsticks, foundations, eyeliners, and khol had up to 0.31 mg/kg of Pb, 0.62–1.42 mg/kg of Cd, and 20.62 mg/kg of Zn. The margin of safety values for Zn in foundations and Cu in lipsticks were below the WHO safety threshold of 100, indicating possible worry, even though none of the metals exceeded the applicable limits. Both investigations showed minimal non-carcinogenic risk overall, with hazard quotient values remaining below 1, even though the reported Pb and Cd amounts in Nigerian items were greater than those in our Libyan samples.

### 3.1. Aluminum levels

Aluminum salts are the main active element of antiperspirants, which have been around since 1903 and are used to stop perspiration. However, negative skin responses like burning, inflammation, and the development of granulomas have been linked to these products [32].

The analysis of aluminum Al concentrations revealed a clear distinction based on product claims and formulation type (Table 3, Fig. 1). A notable finding was the detection of Al in seven samples marketed as “aluminum-free,” where

concentrations ranged from a minimum of 0.03 mg/kg (RD13) to a maximum of 0.12 mg/kg (RD9). Similarly, other samples not explicitly labeled as Al-free, such as RA17 (0.06 mg/kg) and SA6 (0.19 mg/kg), also contained trace amounts, suggesting background contamination.

In contrast, the remaining samples demonstrated a wide concentration gradient indicative of intentional inclusion. The gel antiperspirant (GA1) and gel deodorant (GD2) samples showed relatively lower, yet substantial, Al levels (5.47 mg/kg and 5.04 mg/kg, respectively). The majority of the high-concentration antiperspirant and deodorant samples contained Al concentrations ranging from 38.12 mg/kg (RD10) up to the highest detected level of 99.10 mg/kg (RD8). This significant variability highlights a clear distinction between trace contamination in “aluminum-free” products and the intentional inclusion of Al compounds as active antiperspirant ingredients in other commercial formulations.

Antiperspirant-induced skin absorption of aluminum can result in aluminum overload, which can cause anaemia, bone disease, or even dementia, especially in people with compromised kidney function [33]. Aluminum buildup has been connected to diseases including Parkinson's, Alzheimer's, encephalopathy, and osteomalacia [35] because of its possible neurotoxic nature [34]. Additionally, localised skin problems including rashes, burning sensations, desquamation, or necrosis may result with daily usage of antiperspirants

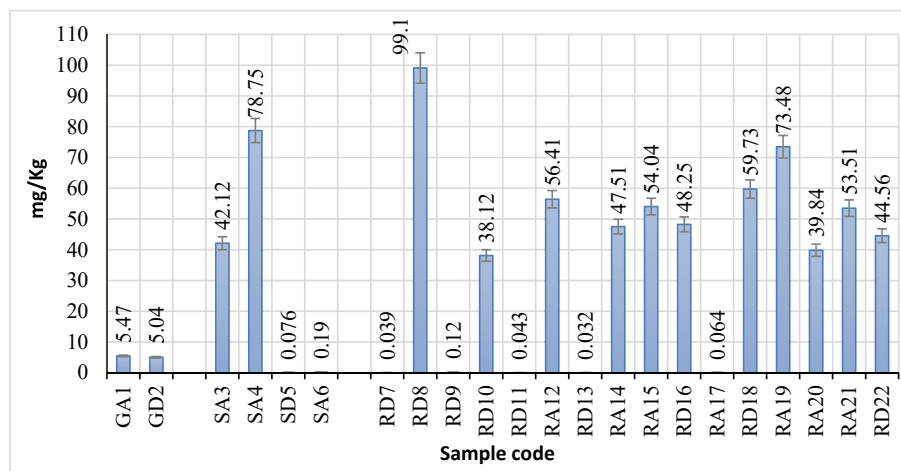


Fig. 1. Aluminum concentration in antiperspirant and deodorant samples.

[36]. By encouraging the formation of cancer cells, aluminum salts included in underarm antiperspirants may raise the risk of breast cancer, according to many studies [37]. Studies on humans and animals have also demonstrated the neurotoxic and embryotoxic effects of aluminum, a genotoxic heavy metal [33]. Breast cancer risk may be increased by prolonged exposure to even modest amounts of absorbed aluminum [35,36].

Various aluminum compounds are often used as active components in antiperspirant products. Aluminum zirconium octachlorohydrate concentrations can reach 20 % and 25 % by weight in the US and Europe, respectively, notwithstanding the absence of aluminum hydroxide and aluminum oxide (alumina) in these formulations. Aluminum chloride, which usually makes about 15 % of the product, is a popular active ingredient in Europe. Depending on their exact makeup, the U.S. FDA allows the sale of over-the-counter antiperspirants that include 15–25 % aluminum compounds [37].

Unlike the trace heavy metal contaminants (Pb and Cd), aluminum (Al) compounds are intentionally included as active ingredients in antiperspirants to achieve their intended function of blocking sweat ducts. Accordingly, regulatory bodies define high maximum permissible levels for these compounds. The U.S. FDA permits concentrations of 15 % to 25 % aluminum compounds in over-the-counter antiperspirants, with similar high limits set across Europe. Our highest detected Al concentration of 99.10 mg/kg (RD8) translates to only 0.0099 % w/w of total aluminum in the product. Crucially, all Al concentrations found in the samples are several orders of magnitude below the legal regulatory limits for active antiperspirant ingredients. Therefore, the subsequent discussion of Al toxicity and

risk is warranted not because the products exceed legal composition limits, but rather to assess the theoretical risk posed by systemic absorption of even these legally permissible amounts [35,37].

### 3.2. Zirconium content

As shown in Table 3 and Fig. 2, a strong correlation was observed between Zr concentration and the product formulation type. Specifically, Zirconium was not detectable (<0.0008 mg/kg) in any of the roll-on antiperspirant or deodorant samples (RD7 to RD22). In contrast, the element was readily quantifiable in gel and stick formulations, which typically utilize Zr-containing compounds as antiperspirant actives. The highest concentration was observed in a stick antiperspirant, SA3, which contained 36.81 mg/kg of Zr. Lower concentrations were found in other stick-type samples, ranging from a minimum of 0.01 mg/kg (SA5) to 0.08 mg/kg (SA7). The two gel-type samples, GA1 (1.85 mg/kg) and GD2 (1.33 mg/kg), both exhibited moderate levels slightly exceeding 1 mg/kg, highlighting the use of Zr across different non-roll-on formats.

Granulomatous lesions have been linked in studies to cutaneous exposure to zirconium found in poison ivy treatments and deodorant sticks. A granulomatous response has been reported following ingestion of a diluted solution of sodium zirconium lactate, while some people may not experience adverse reactions to daily usage of aluminum deodorant sticks. Additionally, following treatment for poison ivy dermatitis with a 4 % zirconium oxide cream, a 15-year-old girl had skin irritations, despite the fact that her undamaged skin exhibited no evidence of infection, according to a case report [37].

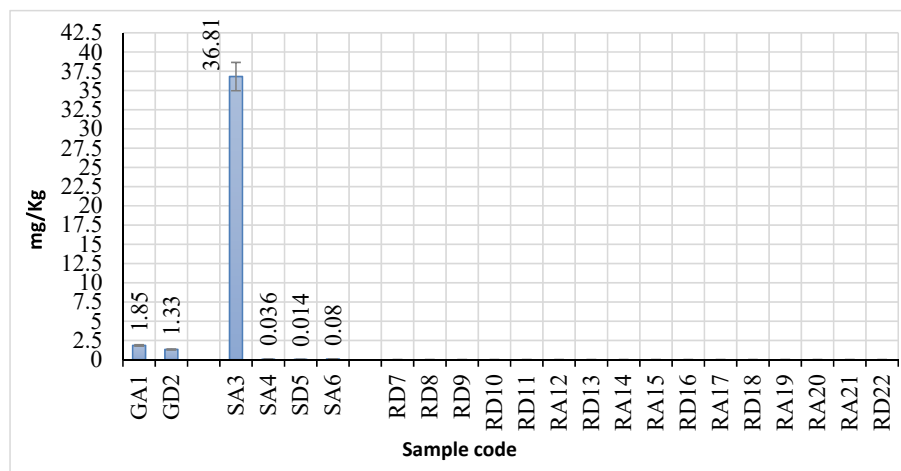


Fig. 2. Zirconium concentration in antiperspirant and deodorant samples.

Zirconium aluminum chlorohydrates are commonly used as active ingredients in antiperspirants. The Zirconium Aluminum Glycine (ZAG) complex is now widely used due to its enhanced efficiency. The quality of these products is maintained by carefully controlling the ratio of aluminum and zirconium in the complex [38].

It is essential to recognize that Zr is not merely a contaminant but is often incorporated into antiperspirant formulations, typically alongside aluminum, as part of compounds such as aluminum zirconium tetrachlorohydrate [4,5,36]. Regulatory bodies, including the U.S. FDA, permit these compounds to be used at concentrations up to 20 % in non-aerosol products. The observed distribution—where Zr was detected only in stick and gel samples but was non-detectable in all roll-on products (RD7 to RD22) is a direct result of manufacturer formulation decisions. Zr is often intentionally excluded from aqueous-

based roll-on formulations due to stability issues (e.g., hydrolysis leading to precipitation) and regulatory restrictions often imposed on liquid or spray products over concerns of lung inhalation toxicity. Thus, the presence of Zr in stick/gel products is intentional, and its absence in roll-on samples is a characteristic of their chemistry and design [4,6,7].

### 3.3. Lead content

One naturally occurring pollutant that has a long history of being extremely toxic is lead (Pb). Skin contact is a proven exposure pathway, and even if the skin is rapidly cleaned, even a brief touch can improve skin penetration. Lead is regarded as the most toxic of the metals, according to the USEPA [39].

Lead levels were assessed in 22 samples, as indicated in Table 3 and Fig. 3. The distribution of

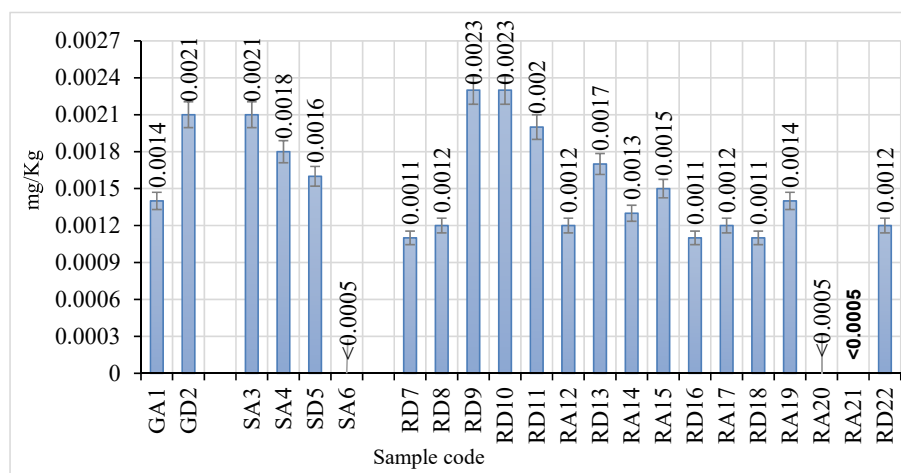


Fig. 3. Lead concentration in antiperspirant and deodorant samples.

Pb was largely uniform across different product categories, with an average concentration of 0.0013 mg/kg across all samples. Trace Pb was detected in the majority of products, with only three samples (SA6, RA20, and RA21) registering levels below the detection threshold (<0.0005 mg/kg). The concentrations found were extremely narrow, ranging from a minimum of 0.0011 mg/kg (found in RD7, RD16, and RD18) to a maximum of 0.0023 mg/kg (RD9 and RD10).

Numerous harmful consequences, such as neurological and behavioural disorders, cardiovascular conditions, reduced renal function, hypertension, and reproductive concerns, have been connected to lead exposure. Based on enough evidence in animals, the International Agency for Research on Cancer (IARC) categorises inorganic lead compounds as probably carcinogenic to humans. Lead poisoning is especially harmful to the neurological system, and prolonged exposure can cause weakness in the hands, wrists, or ankles as well as a little rise in blood pressure. Elevated exposure levels may raise a pregnant woman's risk of miscarriage and seriously harm the kidneys and brain [40].

The U.S. Food and Drug Administration (FDA) has set a limit of 10 parts per million (ppm) for lead in cosmetics in order to reduce human exposure. The lead concentrations found in each of the 22 examined samples fall well short of this accepted threshold [41].

#### 3.4. Cadmium content

The heavy metal cadmium is known for its long-term toxicity and has a bright yellow-to-orange colour. Because of a link between occupational

exposure and a higher risk of lung cancer, regulatory agencies have categorised it and its constituents as non-threshold human carcinogens. Chronic toxicity from exposure to cadmium can also cause cumulative harm to the respiratory and skeletal systems, as well as renal disease [42].

As demonstrated in Table 3 and Fig. 4, Cd concentrations exhibited greater variability than Pb. Six samples registered levels below the detection limit (<0.0010 mg/kg). For the samples where Cd was quantifiable, concentrations ranged from a low of 0.0002 mg/kg in sample RA15 to a maximum of 0.013 mg/kg in sample RA14. Across all analyzed samples, the average cadmium concentration was 0.0029 mg/kg, confirming that Cd is generally present at very low, trace levels.

Cadmium is not regarded as safe, even in trace doses, because it can damage tissues and blood vessels in many organs. Its release into the body has been connected to a number of detrimental health outcomes, such as heart failure and harm to the brain, liver, and kidneys. Additionally, it may interfere with the hormonal system by acting as an endocrine disruptor [43]. Common activities like shaving before using these products might result in skin abrasions, possibly weakening the skin's protective barrier and raising the risk of exposure, even though the FDA has made it plain that they should not be used to broken or irritated skin [42].

#### 3.5. Chromium content

One known corrosive and skin-allergenic substance is chromium. Numerous dermatological conditions, including as ulceration, dermatitis, and other allergic responses, can result from exposure. Chromium is a common toxin that has been

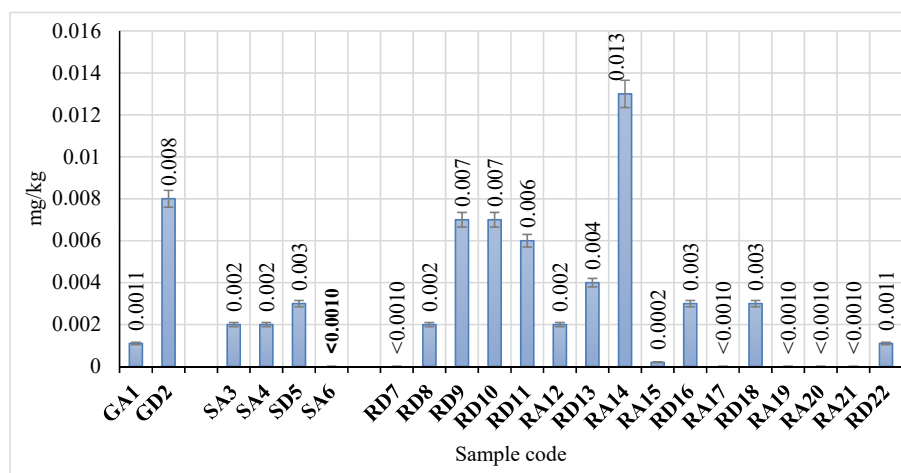


Fig. 4. Cadmium concentration in samples of antiperspirant and deodorants.

connected to a number of health issues, including neurological, endocrine, cardiovascular, and developmental illnesses, as well as a number of malignancies and immunological disorders, after skin contact and inhalation [44].

Chromium concentrations were detected in all 22 samples analyzed, showing virtually no discernible change in concentration across any of the different product types (Table 3, Fig. 5). The detected values were extremely narrow, ranging only from a minimum of 0.0010 mg/kg to a maximum of 0.0023 mg/kg. This consistency resulted in a tight mean concentration of 0.0017 mg/kg for Cr across the entire sample set.

### 3.6. Health risk assessment based on data analysis

Health risk assessment was conducted by computing standard parameters for both endpoints. Non-carcinogenic risk was evaluated using the Hazard Quotient (HQ), Hazard Index (HI), and Margin of Safety (MoS). The potential carcinogenic risk from known carcinogens was assessed using the Lifetime Cancer Risk (LCR), calculated according to the procedure outlined in Ref. [29].

#### 3.6.1. Non-cancer risk assessment

Through predominantly cutaneous contact, exposure to deodorants and antiperspirants aids in the absorption of several substances into the human body. Taking into account 50 % and 100 % bioaccessibility rates, the systemic exposure dose (SED) of certain heavy metals (HMs) in these goods was calculated independently for males and females. Fig. 6 (gel and stick formulations) and Fig. 7 (roll-on formulations) show the distribution of SED values across various product types.

The systemic exposure dose (SED) calculations demonstrated a wide range in exposure levels across the samples, with Al and Zr showing significantly higher values than the trace metals Pb, Cd, and Cr. At 50 % bioaccessibility, the SED for Zr in males ranged from  $1.80 \times 10^{-7}$  to  $4.74 \times 10^{-4}$  mg/kg/day, and for Al, the range was  $1.77 \times 10^{-7}$  to  $1.01 \times 10^{-3}$  mg/kg/day. Female SED ranges were comparable, with Zr varying from  $3.60 \times 10^{-7}$  to  $3.68 \times 10^{-4}$  mg/kg/day and Al from  $1.37 \times 10^{-7}$  to  $7.87 \times 10^{-4}$  mg/kg/day. In contrast, the SED values for the trace metals Pb, Cd, and Cr were consistently several orders of magnitude lower, confined within the  $10^{-6}$  to  $10^{-9}$  mg/kg/day range for both genders, confirming minimal systemic exposure from this contaminant group.

As expected, the calculated SED values were significantly greater at 100 % bioaccessibility, reflecting a maximum potential exposure scenario. For males, the systemic exposure range for Zr was from  $3.60 \times 10^{-7}$  to  $9.48 \times 10^{-4}$  mg/kg/day, while Al ranged from  $3.53 \times 10^{-7}$  to  $2.03 \times 10^{-3}$  mg/kg/day. Female SED values maintained a similar scale but were slightly lower, with Zr varying from  $2.80 \times 10^{-7}$  to  $7.36 \times 10^{-4}$  mg/kg/day and Al from  $2.74 \times 10^{-7}$  to  $1.58 \times 10^{-3}$  mg/kg/day. In contrast, the SED values for the trace metals Pb, Cd, and Cr remained consistently very low for both genders, tightly clustered within the  $10^{-6}$  to  $10^{-8}$  mg/kg/day range, indicating that even under this maximum absorption assumption, exposure to contaminants remains minimal.

The results demonstrated that SED values rose in direct proportion to metal concentrations and that, mainly as a result of their larger axillary surface area, men typically had higher SED values than females. The Margin of Safety (MOS) method

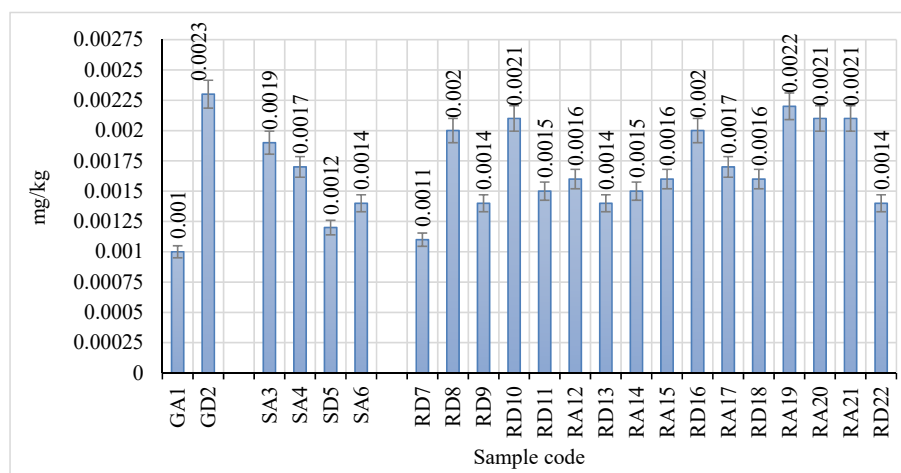


Fig. 5. Chromium concentration in samples of antiperspirant and deodorants.

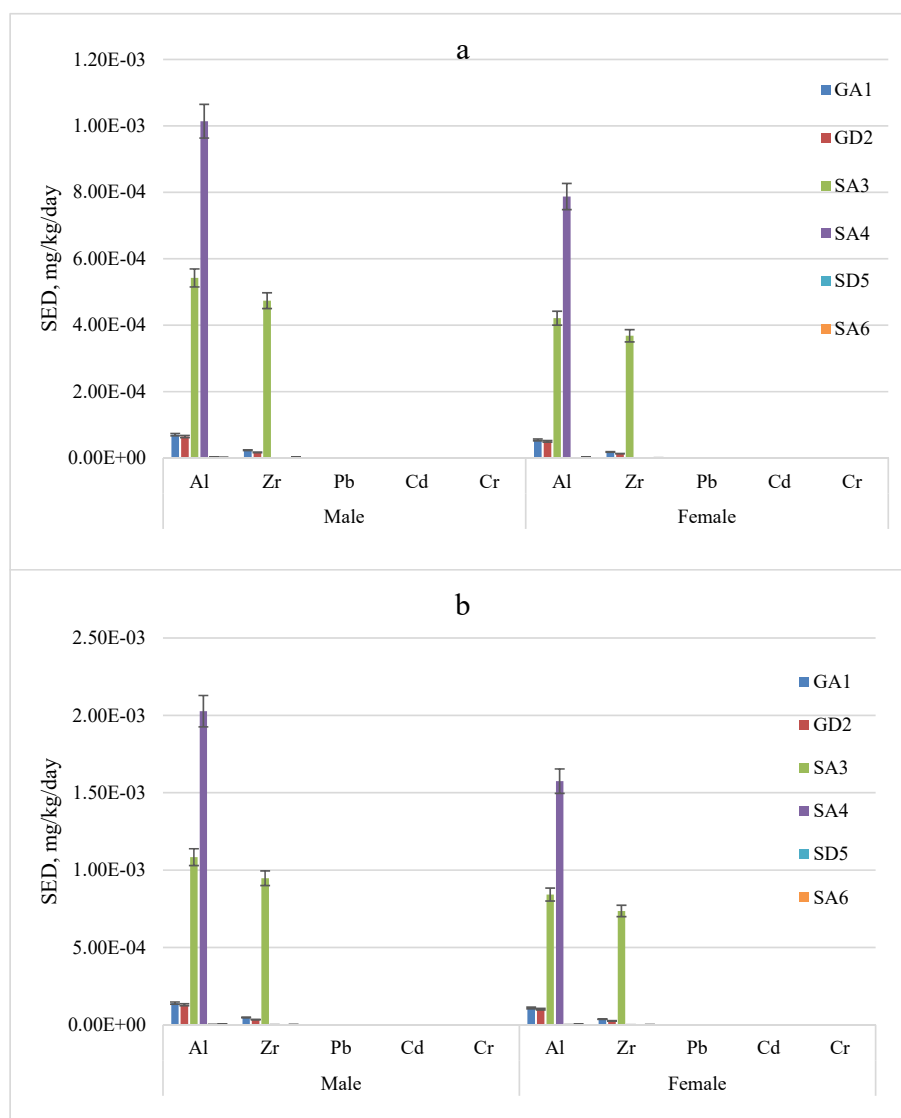


Fig. 6. SED for metals in gel and stick formulations at BF of (a) 50 % and (b) 100 %, bioaccessibility.

was used to assess the health risk. MOS values for HMs at 50 % and 100 % bioaccessibility are shown in Fig. 8. The World Health Organisation (WHO) [24] states that goods with MOS values greater than 100 are safe for human consumption. All of the tested samples in this study were over this threshold, suggesting that there is no discernible non-carcinogenic risk associated with the antiperspirants and deodorants under investigation.

Based on the RfD and SED values, the non-carcinogenic risk assessment was carried out for both boys and females at 50 % and 100 % bioaccessibility, as shown in Figs. 6 and 7. HQ values were used to further assess dermal exposure routes (Tables 4 and 5 and Fig. 9). No substantial health risk is anticipated for consumers when HQ and HI values are less than

1; however, values more than 1 suggest a possible worry for non-carcinogenic consequences [45]. All of the HQ values for zirconium, lead, cadmium, and chromium were less than 1 in all of the examined samples (Tables 4 and 5). On the other hand, at 50 % bio-accessibility, aluminum had HQ values higher than 1 in four male and three female samples, while at 100 % bio-accessibility, it had higher HQ values in 13 male and 10 female samples. Likewise, at 50 % bio-accessibility, HI values were higher than 1 in 18.182 % of male samples and 13.364 % of female samples, rising to 59.091 % for men and 45.455 % for females at 100 % bio-accessibility. According to these results, samples with higher HQ and HI values are more likely to present non-carcinogenic health hazards.

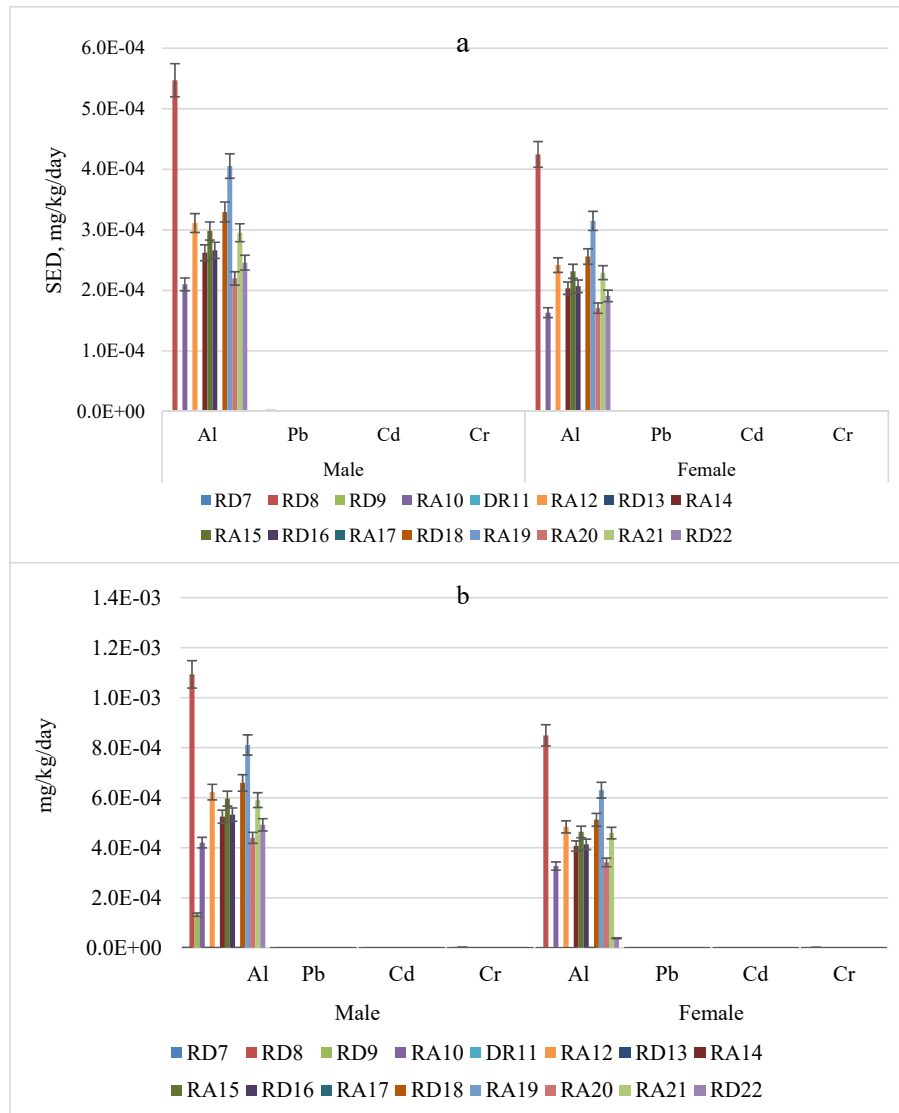


Fig. 7. SED for metals in roll-on formulations at BF of: (a) 50 % and (b) 100 % bioaccessibility.

### 3.6.2. Cancer risk assessment

Heavy metals (HMs) have a tendency to build up in the human body over time due to their non-biodegradable nature. In addition to changing regular cellular processes, this buildup disrupts intracellular processes [14], resulting in oxidative stress, DNA damage, and cell death—all of which are linked to disorders connected to cancer [46]. The Lifetime Cancer Risk (LCR) is frequently used to determine the likelihood of getting cancer as a result of such exposures. This measure calculates a person's risk of developing cancer based on their exposure to HMs found in cosmetics.

The U.S. Environmental Protection Agency (USEPA) defines an LCR value as inconsequential if it is less than  $1 \times 10^{-6}$ , acceptable if it is between

$1 \times 10^{-6}$  and  $1 \times 10^{-4}$ , and undesirable if it is greater than  $1 \times 10^{-4}$  [47].

The LCR was assessed in this study at 50 % and 100 % bioaccessibility levels for the carcinogenic elements aluminum (Al), zirconium (Zr), lead (Pb), cadmium (Cd), and chromium (Cr), as shown in Fig. 10. According to the results, the majority of the examined samples had LCR values less than  $1 \times 10^{-6}$ , suggesting that Libyan users' dermal exposure to deodorants and antiperspirants has a very little risk of developing cancer. A few samples, nonetheless, came within the permissible range ( $1 \times 10^{-6}$  to  $1 \times 10^{-4}$ ) but went above the insignificant threshold ( $1 \times 10^{-6}$ ).

At 50 % bioaccessibility, the LCR for males was negligible, with only one stick sample (SA5) slightly

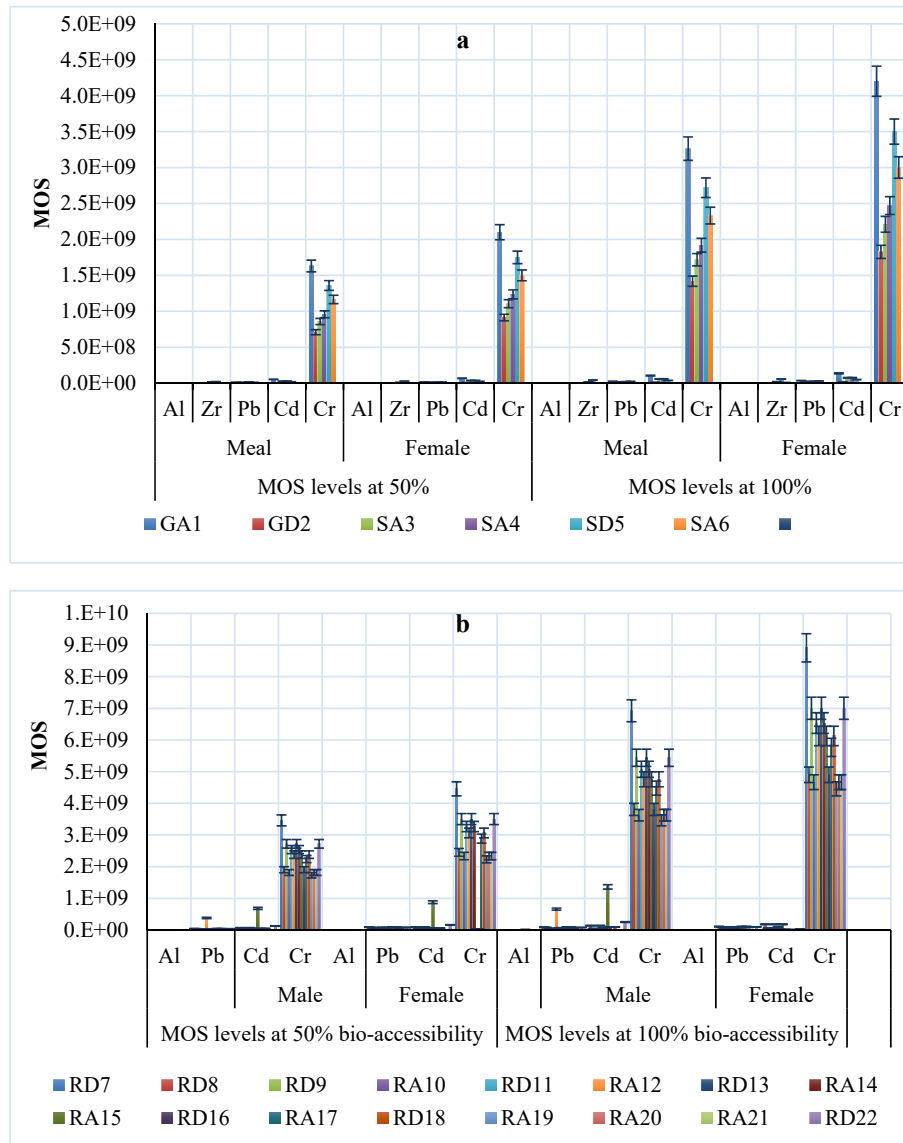


Fig. 8. MOS values for all metals in: (a) Gel/Stick and (b) Roll-On products at BF 50 % and 100 % bioaccessibility.

surpassing the  $1 \times 10^{-6}$  insignificant threshold ( $LCR = 1.22 \times 10^{-6}$ ). However, at the maximum 100 % bioaccessibility, a greater number of products showed LCR values above this threshold. For males, the highest risks were concentrated in stick samples (SA3 and SA4), reaching a maximum of  $2.40 \times 10^{-6}$  (SA4). Other formulations, including roll-on (RD8, RD9, RA14) and gel (GD2) samples, also exceeded the threshold, with values ranging up to  $1.56 \times 10^{-6}$ . For females, 100 % bioaccessibility similarly pushed several samples above the insignificant threshold, particularly the stick samples (SA3 and SA4) with a maximum LCR of  $1.86 \times 10^{-6}$  (SA4). Overall, despite several products marginally exceeding the inconsequential level, the calculated LCR values generally remained well within the

acceptable risk range (defined as  $1 \times 10^{-4}$  to  $1 \times 10^{-6}$ ). Since the majority of analyzed samples had LCR values less than  $1 \times 10^{-6}$ , the use of these deodorants and antiperspirants does not significantly increase the cancer risk in the studied population.

### 3.6.3. Comparison of health risk assessment with previous studies

SED, MOS, HQ, HI, and LCR were used in this investigation to assess the carcinogenic and non-carcinogenic hazards related to heavy metals in deodorants and antiperspirants. Because of their bigger axillary surface area, males had higher SED values than females at 50 % and 100 % bio-accessibility. A fraction of samples had HQ and HI

Table 4. Hazard Quotient (HQ) and Hazard Index (HI) for Gel and Stick Antiperspirants and Deodorants at BF 50 % and 100 %, presented separately for males and females.

BF %	HMs	Gel			Stick			
		GA1	GD2	SA3	SA4	SD5	SA6	
50 %	Male		<b>HQ</b>					
		Al	0.176	0.162	1.355	2.534	0.0025	0.0061
		Zr	2.98E <sup>-04</sup>	2.14E <sup>-04</sup>	5.92E <sup>-01</sup>	5.79E <sup>-06</sup>	2.25E <sup>-06</sup>	1.29E <sup>-05</sup>
		Pb	3.60E <sup>-06</sup>	5.41E <sup>-06</sup>	5.41E <sup>-04</sup>	4.63E <sup>-07</sup>	4.12E <sup>-06</sup>	—
		Cd	9.44E <sup>-07</sup>	6.87E <sup>-06</sup>	1.72E <sup>-04</sup>	1.72E <sup>-06</sup>	2.58E <sup>-06</sup>	—
		Cr	3.07E <sup>-08</sup>	7.05E <sup>-08</sup>	5.82E <sup>-06</sup>	5.21E <sup>-08</sup>	3.68E <sup>-08</sup>	4.29E <sup>-08</sup>
		HI	0.176	0.162	1.361	2.534	0.0025	0.00613
	Female		<b>HQ</b>					
		Al	0.137	0.126	1.053	1.968	0.0019	0.0048
		Zr	2.31E <sup>-04</sup>	1.66E <sup>-04</sup>	0.0046	4.50E <sup>-06</sup>	1.75E <sup>-06</sup>	1.00E <sup>-05</sup>
		Pb	2.80E <sup>-06</sup>	4.20E <sup>-06</sup>	4.20E <sup>-06</sup>	3.60E <sup>-06</sup>	3.20E <sup>-06</sup>	—
		Cd	7.33E <sup>-07</sup>	5.33E <sup>-06</sup>	1.33E <sup>-06</sup>	1.33E <sup>-06</sup>	2.00E <sup>-06</sup>	—
Cr		2.38E <sup>-08</sup>	5.48E <sup>-08</sup>	4.52E <sup>-08</sup>	4.05E <sup>-09</sup>	2.86E <sup>-08</sup>	3.33E <sup>-08</sup>	
100 %	Male		<b>HQ</b>					
		Al	0.352	0.324	2.711	5.069	0.0049	0.0122
		Zr	5.95E <sup>-04</sup>	4.28E <sup>-04</sup>	0.0118	1.16E <sup>-04</sup>	4.51E <sup>-06</sup>	2.58E <sup>-05</sup>
		Pb	7.21E <sup>-06</sup>	1.08E <sup>-05</sup>	1.08E <sup>-05</sup>	9.27E <sup>-06</sup>	8.24E <sup>-06</sup>	—
		Cd	1.89E <sup>-06</sup>	1.37E <sup>-05</sup>	3.43E <sup>-06</sup>	3.43E <sup>-06</sup>	5.15E <sup>-06</sup>	—
		Cr	6.13E <sup>-08</sup>	1.41E <sup>-07</sup>	1.17E <sup>-07</sup>	1.04E <sup>-07</sup>	7.36E <sup>-08</sup>	8.58E <sup>-08</sup>
		HI	0.353	0.325	2.723	5.0686	0.0049	0.012
	Female		<b>HQ</b>					
		Al	0.273	0.252	2.105	3.937	0.0038	0.0095
		Zr	4.62E <sup>-04</sup>	3.32E <sup>-04</sup>	0.009	9.00E <sup>-06</sup>	3.50E <sup>-06</sup>	2.00E <sup>-05</sup>
		Pb	5.60E <sup>-06</sup>	8.40E <sup>-06</sup>	8.40E <sup>-06</sup>	7.20E <sup>-06</sup>	6.40E <sup>-06</sup>	—
		Cd	1.47E <sup>-06</sup>	1.07E <sup>-05</sup>	2.67E <sup>-06</sup>	2.67E <sup>-06</sup>	4.00E <sup>-06</sup>	—
Cr		4.76E <sup>-08</sup>	1.10E <sup>-07</sup>	9.05E <sup>-08</sup>	8.09E <sup>-08</sup>	5.71E <sup>-08</sup>	6.67E <sup>-08</sup>	
	HI	0.274	0.252	2.115	3.937	0.0038	0.0095	

Table 5. Hazard Quotient (HQ) and Hazard Index (HI) for Roll-On Antiperspirants and Deodorants at BF 50 % and 100 %, presented separately for males and females.

BF%	HM	Roll-On																
		RD7	RD8	RD9	RA10	RD11	RA12	RD13	RA14	RA15	RD16	RA17	RD18	RA19	RA20	RA21	RD22	
50%	Male	Al	5.4E <sup>-4</sup>	1.40	1.7E <sup>-3</sup>	0.53	5.9E <sup>-4</sup>	0.78	4.4E <sup>-4</sup>	0.66	0.75	0.67	0.09	0.82	1.01	0.55	0.74	0.62
		Pb	1.2E <sup>-6</sup>	1.3E <sup>-6</sup>	2.5E <sup>-6</sup>	2.5E <sup>-6</sup>	2.2E <sup>-6</sup>	1.3E <sup>-6</sup>	1.9E <sup>-6</sup>	1.4E <sup>-6</sup>	1.7E <sup>-6</sup>	1.2E <sup>-8</sup>	1.3E <sup>-6</sup>	1.2E <sup>-6</sup>	1.5E <sup>-6</sup>	—	—	1.3E <sup>-6</sup>
		Cd	—	7.4E <sup>-6</sup>	2.6E <sup>-5</sup>	2.6E <sup>-5</sup>	2.2E <sup>-5</sup>	7.4E <sup>-6</sup>	1.5E <sup>-5</sup>	4.8E <sup>-5</sup>	7.4E <sup>-7</sup>	1.1E <sup>-5</sup>	—	1.1E <sup>-5</sup>	—	—	—	4.0E <sup>-6</sup>
	Cr	3.0E <sup>-9</sup>	5.5E <sup>-9</sup>	3.9E <sup>-7</sup>	5.8E <sup>-9</sup>	4.1E <sup>-9</sup>	4.4E <sup>-8</sup>	3.9E <sup>-9</sup>	4.1E <sup>-9</sup>	4.4E <sup>-9</sup>	5.5E <sup>-9</sup>	4.7E <sup>-9</sup>	4.4E <sup>-9</sup>	6.1E <sup>-9</sup>	5.8E <sup>-9</sup>	5.8E <sup>-10</sup>	3.9E <sup>-9</sup>	
		HI	5.4E <sup>-4</sup>	1.4	1.7E <sup>-3</sup>	0.53	6.2E <sup>-4</sup>	0.78	4.6E <sup>-4</sup>	0.66	0.75	0.67	0.089	0.82	1.01	0.55	0.74	0.62
	Female	Al	4.2E <sup>-04</sup>	1.06	1.3E <sup>-03</sup>	0.41	4.6E <sup>-04</sup>	0.60	3.4E <sup>-04</sup>	0.51	0.58	0.52	6.9E <sup>-04</sup>	0.64	0.79	0.43	0.57	0.48
Pb		9.4E <sup>-7</sup>	1.0E <sup>-6</sup>	2.0E <sup>-6</sup>	2.0E <sup>-6</sup>	1.7E <sup>-6</sup>	1.0E <sup>-6</sup>	1.5E <sup>-6</sup>	1.1E <sup>-6</sup>	1.3E <sup>-6</sup>	9.4E <sup>-7</sup>	1.0E <sup>-6</sup>	9.4E <sup>-7</sup>	1.2E <sup>-6</sup>	—	—	1.0E <sup>-6</sup>	
Cd		—	5.7E <sup>-7</sup>	2.0E <sup>-6</sup>	2.0E <sup>-6</sup>	1.7E <sup>-6</sup>	5.7E <sup>-7</sup>	1.1E <sup>-6</sup>	3.7E <sup>-6</sup>	5.7E <sup>-8</sup>	8.6E <sup>-7</sup>	—	8.6E <sup>-7</sup>	—	—	—	3.1E <sup>-7</sup>	
Cr		1.1E <sup>-8</sup>	2.0E <sup>-8</sup>	1.4E <sup>-8</sup>	2.1E <sup>-8</sup>	1.5E <sup>-8</sup>	1.6E <sup>-8</sup>	1.4E <sup>-8</sup>	1.5E <sup>-8</sup>	1.6E <sup>-8</sup>	2.0E <sup>-8</sup>	1.7E <sup>-8</sup>	1.6E <sup>-8</sup>	2.2E <sup>-8</sup>	2.1E <sup>-8</sup>	2.1E <sup>-8</sup>	1.4E <sup>-8</sup>	
		HI	4.2E <sup>-4</sup>	1.06	1.3E <sup>-3</sup>	0.41	4.6E <sup>-4</sup>	0.60	3.5E <sup>-4</sup>	0.51	0.58	0.52	6.9E <sup>-4</sup>	0.64	0.79	0.43	0.57	0.48
100%		Male	Al	1.1E <sup>-3</sup>	2.73	3.3E <sup>-3</sup>	1.05	1.2E <sup>-3</sup>	1.56	8.8E <sup>-4</sup>	1.31	1.49	1.33	1.8E <sup>-3</sup>	1.65	2.03	1.10	1.48
	Pb		2.4E <sup>-6</sup>	2.6E <sup>-6</sup>	5.1E <sup>-6</sup>	5.1E <sup>-6</sup>	4.4E <sup>-6</sup>	2.6E <sup>-6</sup>	3.8E <sup>-6</sup>	2.9E <sup>-6</sup>	3.3E <sup>-6</sup>	2.4E <sup>-6</sup>	2.6E <sup>-6</sup>	2.4E <sup>-6</sup>	3.1E <sup>-6</sup>	—	—	2.6E <sup>-6</sup>
	Cd		—	1.5E <sup>-5</sup>	5.2E <sup>-5</sup>	5.1E <sup>-5</sup>	4.4E <sup>-5</sup>	1.5E <sup>-5</sup>	2.9E <sup>-5</sup>	9.6E <sup>-5</sup>	1.5E <sup>-6</sup>	2.2E <sup>-5</sup>	—	2.2E <sup>-4</sup>	—	—	—	8.1E <sup>-0</sup>
	Cr	2.9E <sup>-8</sup>	1.1E <sup>-8</sup>	7.7E <sup>-9</sup>	1.2E <sup>-8</sup>	8.3E <sup>-9</sup>	8.8E <sup>-9</sup>	7.7E <sup>-9</sup>	8.3E <sup>-9</sup>	8.8E <sup>-8</sup>	1.1E <sup>-8</sup>	9.4E <sup>-9</sup>	8.8E <sup>-9</sup>	1.2E <sup>-8</sup>	1.2E <sup>-8</sup>	1.2E <sup>-8</sup>	7.7E <sup>-8</sup>	
		HI	1.1E <sup>-3</sup>	2.73	3.4E <sup>-3</sup>	1.05	1.2E <sup>-3</sup>	1.56	9.2E <sup>-4</sup>	1.31	1.49	1.33	1.8E <sup>-3</sup>	1.65	2.03	1.10	1.48	1.23
	Female	Al	8.4E <sup>-4</sup>	2.12	2.6E <sup>-3</sup>	0.82	9.2E <sup>-4</sup>	1.20	6.9E <sup>-4</sup>	1.02	1.16	1.03	1.4E <sup>-3</sup>	1.28	1.57	0.85	1.15	0.96
Pb		1.9E <sup>-6</sup>	2.1E <sup>-6</sup>	3.9E <sup>-6</sup>	3.9E <sup>-6</sup>	3.4E <sup>-6</sup>	2.1E <sup>-6</sup>	2.9E <sup>-6</sup>	2.2E <sup>-6</sup>	2.6E <sup>-6</sup>	1.9E <sup>-6</sup>	2.1E <sup>-6</sup>	1.9E <sup>-6</sup>	2.4E <sup>-6</sup>	—	—	2.1E <sup>-6</sup>	
Cd		—	1.1E <sup>-6</sup>	4.0E <sup>-6</sup>	4.0E <sup>-6</sup>	3.4E <sup>-6</sup>	1.1E <sup>-6</sup>	2.3E <sup>-6</sup>	7.4E <sup>-6</sup>	1.1E <sup>-7</sup>	1.7E <sup>-6</sup>	—	1.7E <sup>-6</sup>	—	—	—	2.E <sup>-9</sup>	
Cr		2.2E <sup>-8</sup>	4.1E <sup>-8</sup>	2.9E <sup>-8</sup>	4.3E <sup>-8</sup>	3.1E <sup>-8</sup>	3.3E <sup>-8</sup>	2.9E <sup>-8</sup>	3.1E <sup>-6</sup>	3.3E <sup>-8</sup>	4.1E <sup>-8</sup>	3.5E <sup>-8</sup>	3.3E <sup>-8</sup>	4.5E <sup>-8</sup>	4.3E <sup>-8</sup>	4.3E <sup>-8</sup>	6.3E <sup>-9</sup>	
		HI	8.4E <sup>-4</sup>	2.12	2.6E <sup>-3</sup>	0.82	9.3E <sup>-4</sup>	1.20	6.9E <sup>-4</sup>	1.02	1.16	1.03	1.4E <sup>-3</sup>	1.28	1.57	0.85	1.15	0.96

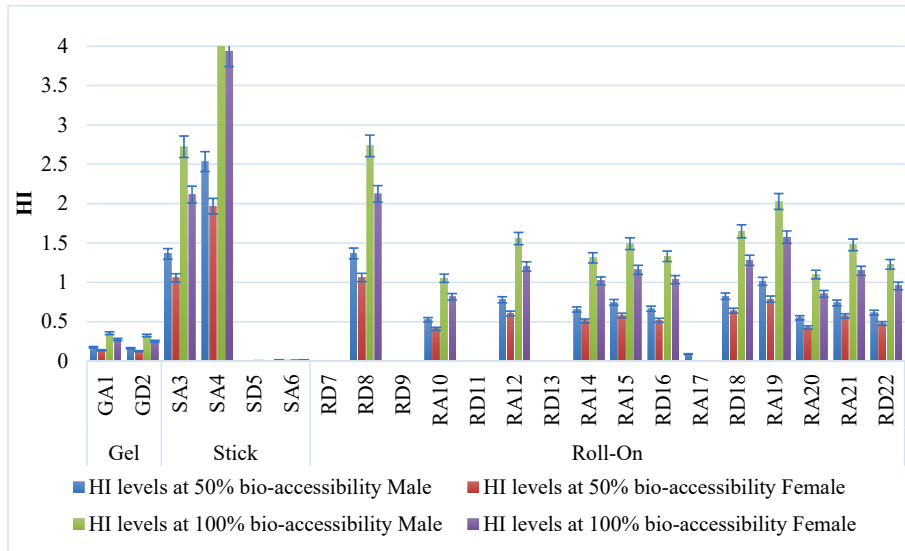


Fig. 9. Hazard Index (HI) values for Gel, Stick, and Roll-On products at BF 50 % and 100 % bioaccessibility.

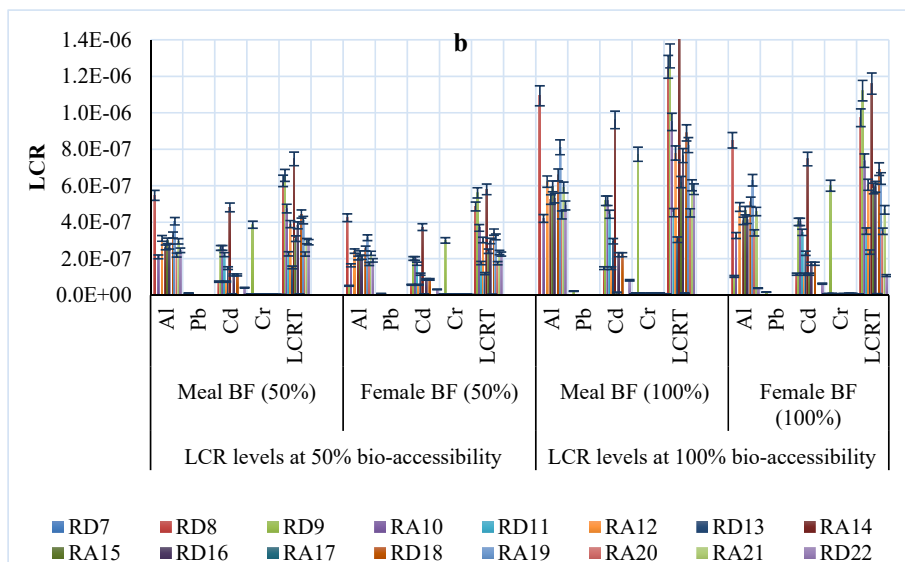
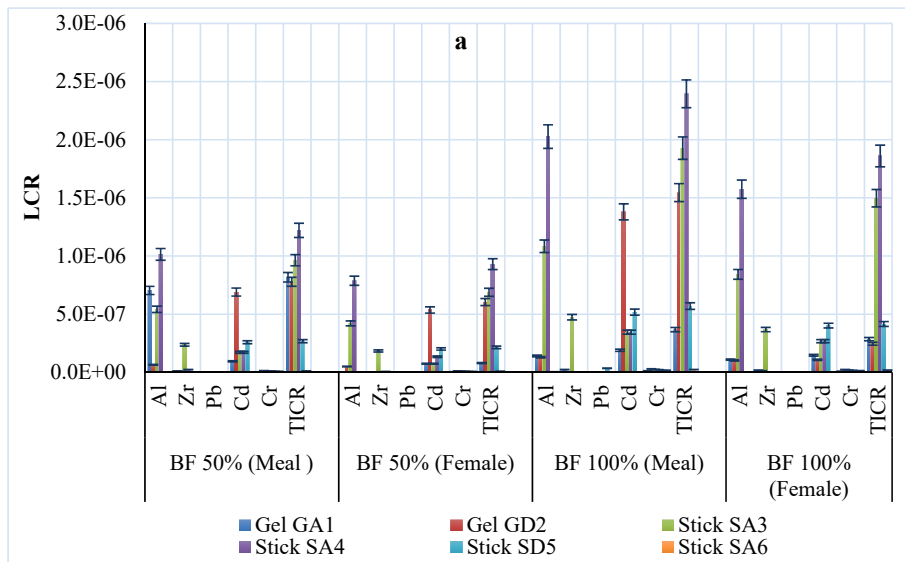


Fig. 10. Lifetime Cancer Risk (LCR) of Al, Pb, Cd, and Cr in (a) Gel and Stick and (b) Roll-On Antiperspirants and Deodorants at BF = 50 % and 100 %, presented separately for males and females.

values for aluminum over 1, especially at 100 % bioaccessibility, indicating localised worry, even if MOS values for all metals surpassed the WHO safety criterion of 100, indicating no considerable non-cancer risk. While few samples marginally above the allowed range ( $1 \times 10^{-6}$  to  $1 \times 10^{-4}$ ), the majority of samples had LCR values below  $1 \times 10^{-6}$  (negligible risk) for carcinogenic risk. According to these findings, aluminum is still the most concerning ingredient in Libyan deodorants and antiperspirants, but generally, there are no serious health hazards.

Our results show both similarities and differences with previous research. The non-cancer risks of Al, Cr, Mn, Ni, and Cd in cosmetics were typically low, according to Lim et al. (2018) [20], with MOS values >100 and HI <1. However, their LCR values were greater than permissible limits (LCR > $10^{-5}$ ), indicating a higher cancer risk than what we saw in our samples. Similar to our study, Arshad et al. (2020) [2] found that Pakistani cosmetics had higher HQ, HI, and LCR values. The cancer risk was greater than allowed limits for the majority of product categories, with the exception of lipsticks. In contrast, Ghaderpoori et al. (2020) [18] found that MOS values in Iranian cosmetics were higher than WHO criteria, and that most metals had HQ values below 1, which is more in line with our data. However, they did discover that Pb contributed the greatest HQ in creams.

More recent studies also offer significant information. While there are no official limitations for Al, Lara-Torres et al. (2021) [31] discovered that the quantities of Cd and Pb in European and Chinese lipsticks were within FDA guidelines but not in compliance with EU rules that completely exclude their presence. In a similar vein, our findings revealed that Al had significantly greater amounts than Cd and Pb, which were both far below safety standards. According to Kicińska and Kowalczyk (2025) [19], internet cosmetics had significant levels of Fe, Zn, Mn, Cr, and Ni, but their MOS, HQ, and HI values showed no significant health risks, which is in keeping with our samples' generally low-risk profile. Last but not least, Mgbemena et al. (2024) [15] evaluated Nigerian cosmetics and discovered Pb, Cd, and Cr concentrations greater than those identified in our investigation; nonetheless, for the majority of metals, HQ values <1 and MOS >100, indicating negligible non-cancer risk. They did, however, draw attention to product-specific hazards not seen in our dataset by highlighting exceedances of the MOS threshold for Cu and Zn in certain items.

According to these comparisons, aluminum levels in Libyan deodorants and antiperspirants are still

quite high, even if Pb, Cd, and Cr levels are lower than those found elsewhere. Our findings imply that the cancer risk from heavy metal exposure through skin absorption is minimal to tolerable for Libyan users, in contrast to a number of other studies where LCR levels surpassed acceptable criteria. However, the frequent finding of aluminum as a major cause of high HQ and HI values emphasises the necessity of more observation and potential regulatory action.

#### 4. Conclusion

The present study offers a thorough, risk-based assessment of heavy metal content in commercially available deodorants and antiperspirants utilized by consumers in Benghazi, Libya. The investigation yielded several key findings:

1. Aluminum was the predominant metal, with concentrations reaching a maximum of 99.10 mg/kg in certain antiperspirant samples. This concentration, while orders of magnitude below regulatory limits for active ingredients, highlighted significant formulation variability. Zirconium presence was strictly limited to gel and stick formulations, aligning with known cosmetic chemistry principles, and was non-detectable in all roll-on products. Crucially, Lead, Cadmium, and Chromium were found at consistently ultra-trace levels, far below international safety thresholds for unavoidable contaminants.
2. Overall, the majority of products pose low carcinogenic and non-carcinogenic hazards. However, the HRA identified a specific subset of samples where non-carcinogenic risk was indicated, with Hazard Quotient HQ and Hazard Index HI values exceeding the threshold of 1. This potential non-carcinogenic risk was primarily driven by the systemic exposure dose SED of aluminum and zirconium under the assumption of 100 % bioaccessibility, warranting heightened caution for long-term users of these specific formulations. Dermal exposure is unlikely to result in major carcinogenic outcomes, as indicated by Lifetime Cancer Risk LCR values that generally remained within the insignificant range ( $<10^{-6}$ ).
3. These results underscore the necessity for ongoing, risk-based monitoring of personal care products in Libya, particularly focusing on the systemic exposure potential of intentionally added ingredients like Al and Zr. We strongly recommend that local regulatory bodies establish or enforce routine testing protocols to

ensure continuous consumer safety. Furthermore, future research should focus on in-vivo bioaccessibility studies to refine the exposure model and provide a more accurate estimation of long-term health risks associated with the daily use of aluminum-rich antiperspirants.

## Source of Funding

This work was not supported by any funding.

## Conflict of Interest

No conflicts of interest are disclosed by the authors.

## Ethical Approval

This study did not use human subjects or animals; instead, it examined commercially available deodorants and antiperspirants. Consequently, an Institutional Ethics Committee's official assessment and approval were not necessary. Standard laboratory safety and research integrity procedures were followed in this work.

## Data Availability

This published article contains all of the data produced or examined during this investigation.

## Author Contributions

Maysson Yaghi: Conceptualization, Methodology, Sample Collection, Data Analysis, and Writing—Original Draft Preparation.

Khaled Elsherif: Conceptualization, Supervision, Formal Analysis, Writing—Review & Editing, and Resources.

## Acknowledgment

The authors gratefully acknowledge the Department of Chemistry, Faculty of Science Al-Abyar, University of Benghazi, Libya, for providing the necessary facilities and support to accomplish this research.

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