Biological Trace Element Research
https://doi.org/10.1007/s12011-024-04182-9

RESEARCH

Tracking the Variations in Trace and Heavy Elements in Smoking Products Marketed in Oman and Egypt: Risk Assessment After Implementation of Constraining Protocols

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Received: 27 February 2024 / Accepted: 9 April 2024

Abstract

Tobacco smoking is becoming one of the major worldwide concerns regarding environmental pollution as well as health threats. In 2005, the World Health Organization (WHO) released the Framework Convention On Tobacco Control (FCTC), which outlined protocols for controlling tobacco products. Oman was one of the leading countries to follow these protocols; however, Egypt has only followed these protocols recently in 2020. One of the main challenges in tobacco product control is the variation in their trace element's types and amounts from country to country owing to differences in agriculture techniques and used chemical additives. Smoking releases different toxic metal ions found in them into the air, and hence, analyzing trace amounts of metals in tobacco smoking products is becoming more critical. The proposed research aims to evaluate the current levels of 11 heavy metals (namely, As, Pb, Cd, Co, Cr, Be, Ba, Mn, Ni, Fe, and Hg) in 22 tobacco products available in Egypt and Oman using inductively coupled plasma optical emission spectroscopy and a direct mercury analyzer. Although some elements such as Be, Co, and Cd were absent, the positive detection of As and Pb and the levels of Ba, Cr, and Ni are still alarming, especially for heavy smokers. The obtained results were then statistically related to previously published data in 2017 to explore the effectiveness of implementing the FCTC protocols within the Egyptian market. The outcomes suggested a positive impact of FCTC protocol implementation in Egypt, besides the lower levels of elemental content for Omani products compared to the Egyptian market.

Keywords Egypt · Framework Convention on Tobacco Control · Heavy metals · Oman · Tobacco products

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Introduction

Tobacco smoking has become one of the leading causes of death and other fatal diseases worldwide. Smoking tobacco products such as cigarettes and shisha (hookah), along with related products like liquid and rolling paper, can have severe health impacts. According to the World Health Organization (WHO), every year, smoking kills up to 8 million people worldwide, of which about 1.3 million are exposed to secondhand smoke (also known as passive smokers) [1]. Moreover, smoking is responsible for over 70% of chronic obstructive pulmonary disease (COPD) cases in high-income countries [2]. The tobacco industry imposes a substantial economic burden, still reported in 2021 to account for 1.8% of the global gross domestic product, equivalent to US$1436 billion [3].

Beyond nicotine, tobacco products contain a mixture of different chemicals, including carcinogens, named tar. Tar represents the total particulate matter, excluding nicotine and water in tobacco. Tar is a thick, sticky residue formed when tobacco is burned at high temperatures and accumulates in smokers' lungs and respiratory tracts. It contains polycyclic aromatic hydrocarbons (PAHs) and other toxic substances, such as benzene, formaldehyde, and acrolein, contributing to various health risks, including respiratory diseases and cancer [4, 5]. On the other hand, tobacco products may also contain harmful toxic metals. Biology refers to toxic metals in living organisms as heavy metals, regardless of their specific gravity, and their general definition is any metal with a specific gravity greater than 5 g/cm³, five times greater than water [6]. Heavy metals such as arsenic (As), cadmium (Cd), lead (Pb), and mercury (Hg) decrease immunity and cause cancer [7]. Some elements have the potential to accumulate in the body over time, leading to death. For instance, Cd has an average half-life of 19 years [8]. Although some metals, like iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu), have beneficial roles in the human body, they can also be toxic in high concentrations [7]. Aluminum (Al), barium (Ba), beryllium (Be), and nickel (Ni) are considered non-essential for the human body and hence have the potential to cause more harm than good [9, 10]. As a result, smoking exposes individuals to tar and heavy metals as the high temperature of these products releases carbon monoxide, PHAs, and metal ions found in them into the air [5, 11].

Although heavy metals are naturally present in the earth's crust, human activities still disrupt the natural balance, affecting our health over prolonged exposure and causing their accumulation in different soils, water, and plants [12]. Twenty percent of the top 40 cancer-risk substances listed by Fowles and Dybing are metals or metalloids [11]. From a human health standpoint, some heavy metals are classified according to the WHO International Agency for Research on Cancer (IARC) as group 1 carcinogens (including As, Cr^{VI}, Ni, Cd, Be, and Fe), group 2 carcinogens (including Co and Pb), and group 3 carcinogens (including Hg) [13]. Group 1 are carcinogenic elements that affect smokers' health and organs, causing lung cancer, high blood pressure, cardiovascular disease, renal damage, and neurological problems, where children's cognitive growth is also impacted even by secondhand smoking [14]. Meanwhile, for group 2 carcinogens, the Centers for Disease Control and Prevention (CDC) advised avoidance of any level Pb, which is considered the second most toxic metal after As, due to neurotoxicity to fetuses, children, and adults [15]. For group 3 carcinogens, Hg toxicity varies according to the exposure chemical form, dose, and rate. Mercury exposure can lead to various health issues, such as arrhythmias, cardiomyopathy, myocardial infarction, high blood pressure, infertility, pneumonitis, and kidney damage, in addition to mental concerns, including memory loss, depression, sudden mood swings, reduced libido, and congenital disabilities [16]. Although Ba and Mn are not listed in the WHO carcinogen groups, excessive Ba inhalation can lead to pulmonary edema, respiratory paralysis, and cardiorenal impacts [17]. Similarly, over the years, Mn may cause neurodegenerative diseases such as Parkinson's, Huntington's, Alzheimer's diseases, and manganism [18].

Another point of concern is the impact of heavy metals on the environment, where Pb and Cr when released into the air, their particles fall back to the ground either by gravity or during rain, polluting the soil and water [19]. Tobacco plants are a clear example of how heavy metals can accumulate in plants due to various factors such as additives, polluted irrigation water, fertilizers, and soil quality [20]. For instance, arsenic is naturally present in the soil and, like any metal, can be transported to the leaves through the tobacco plant's roots [11, 20]. Another recent study showed that there was a negative correlation between the pH value of the soil and the lead content in tobacco leaves, whereas the levels of potassium and phosphorus nutrients were negatively correlated with the copper content [21]. However, pesticides like lead arsenate can increase the level of lead and arsenic in the soil, further increasing their concentration in the leaves [22]. Additionally, fertilizers containing phosphate may increase the amount of these metals in the soil [23]. This variation in heavy metal amounts can be observed from country to country, and even differs depending on the geographic location where the tobacco plant is cultivated in the same country [24]. A previous study showed that cigarette tobacco in Canada contains half the levels of arsenic, lead, and cadmium found in Chinese tobacco [25]. Other studies on smoking products showed that heavy metals are also present in smokeless tobacco products [26], cigarette rolling papers

[20], butts [27], and liquids [28]. Thus, the specific levels of these toxic metals can vary depending on factors such as the region where the tobacco is grown, and the manufacturing processes involved. Hence, analyzing trace amounts of metals in soil, water, air, tobacco plants, and their products is becoming more critical despite the challenges involved.

Some regulations and guidelines were taken to limit the presence of toxic metals in tobacco products. Some organizations and initiatives promote Good Agricultural Practices (GAP) in tobacco farming to minimize contamination. These practices include soil testing, proper fertilizer use, and water management techniques to reduce the uptake of toxic metals by tobacco plants [29]. International organizations such as the WHO have developed strategies, guidelines, and standards related to tobacco products. These strategies aim to regulate the manufacturing, labeling, and testing of tobacco products to ensure consumer safety and minimize health risks, tobacco consumption, and exposure to tobacco smoke. One such strategy is the WHO Framework Convention on Tobacco Control (FCTC), which was adopted in 2003 and came into force in 2005 [30]. The prevalence rate of smoking has started to decline lately within Europe and Asia, with Oman being the lowest consumer of tobacco in the latter region [31]. Nevertheless, the implementation of FCTC policies is challenging, especially in middle- and low-income countries which remain vulnerable. The prevalence of tobacco use in Oman was reported to increase to 33.3% by the year 2025 [31]. The Middle East region has faster-growing rates of smoking prevalence, where the WHO recently reported a significant rise in the number of Egyptian smokers, including young people, highlighting the impact of this market on public health [32]. Therefore, Oman (in 2005) and Egypt (in 2020) adopted the tobacco product control protocols [31, 33] outlined by the FCTC. The challenge remains in organizing explicit ranges for the allowed limits and identifying and quantifying any trace amounts of heavy metals in smoking products, especially given the variations between different countries and brands.

Atomic absorption spectrophotometry (AAS), a direct mercury analyzer (DMA), inductively coupled plasma optical emission spectroscopy (ICP-OES), and ICP-mass spectrometry (ICP-MS) are widely used techniques for elemental analysis in various fields, including pharmaceutical, petrochemical, and environmental. AAS is widely used due to its simplicity, affordability, and feasibility, compared to ICP techniques. However, ICP techniques offer many advantages, such as higher throughput, simultaneous multi-elemental analysis, wide calibration range, and low detection limits, reaching as low as mg/L and ng/L for ICP-OES and ICP-MS, respectively. Although ICP-MS provides enhanced sensitivity and resolution, ICP-OES is more economical and has a faster analysis time [34]. On the other hand, DMA has a higher sensitivity in the nano range, similar to ICP-MS, and does not require the digestion step of solid samples as needed for ICP methods. By skipping the digestion processes, DMA prevents mercury levels from decreasing below detection limits [35], saves time, and offers safer ecological and analysis procedures. Still, the disadvantage of DMA is that it only allows for analyzing a single element.

Reviewing literature, various published research articles had utilized different techniques to analyze the heavy metals in smoking products in different countries. ICP-OES was utilized to investigate products marketed Spain [36] and Pakistan [37], while ICP-MS was employed in the investigation of products marketed in the USA [38] and France [39]. AAS was reported to be used for assessing those products marketed in Ethiopia [40], Saudi Arabia [41, 42], China [43], Nigeria [44], Malaysia [45], and Turkey [46].

After reviewing the available literature, it was found that only a few studies have been reported to examine the heavy metal content in tobacco products sold in Egypt and Oman. In 2017, Abd El-Samad and Hanafi analyzed ten different brands of tobacco products sold in Egypt using the instrumental neutron activation analysis technique [47], noting that this analysis was conducted before the implementation of FCTC in 2020. For Oman, only one study investigated the presence of toxic elements in a smokeless tobacco product [48], leaving plenty to be explored in the Omani market, especially being one of the earliest countries to implement the FCTC protocols since 2005. This research delves into detecting and quantifying heavy metals in various smoking products in Oman and Egypt to provide more insights into their markets and new data for different authorities. Another aim is to assess the impact of implementing FCTC protocols by comparing differences in heavy metal content detected in Egyptian products before and after implementing FCTC protocols. Also, the results in Egypt were assessed in comparison to the Omani tobacco products that have been applying these protocols since their inception. Lastly, explicit ranges for the allowed heavy metal limits in smoking products will be proposed. DMA and ICP-OES methods are employed due to their sensitivity and advantages.

Experimental

Instrumentation and Software

An ICP-OES instrument from PerkinElmer (model Optima 8000) was used to analyze all samples (PerkinElmer, MA, USA). The ICP-OES system was equipped with a Meinhard nebulizer and cyclonic glass spraying chamber. This equipment utilizes a dual backside-illuminated, charge-coupled detector with a wavelength range of 160–900 nm. Syngistix® software (version v2.3) was used to handle the data obtained from the ICP-OES system by PerkinElmer (MA, USA). Before experimentation, samples were digested using Milestone's ultraWAVE® microwave digestion system from Milestone (Sorisole, Italy). A Milestone's direct mercury analyzer model, DMA-80 evo® from Milestone Inc. (Bergamo, Italy), was used for mercury determination, equipped with a silicon UV photodetector and dual spectrophotometer cell. Obtained DMA data were handled using Windows easyDOC® software (version v3.3) by Milestone Inc. (Bergamo, Italy).

Reagents

Analytical grade nitric acid (65%, w/v) was purchased from Merck (Darmstadt, Germany). Stock standard solutions containing the targeted elements were purchased from Merck (Darmstadt, Germany) at 1000 mg/L (ppm) concentration to calibrate and validate the proposed methodology. The mercury Certified Reference Material (CRM) was purchased from the National Institute of Standards and Technology (NIST; MD, USA). Mercury CRM was certified to have a concentration value of 10.004 ± 0.040 mg/g. Ultrapure water used throughout the study (conductivity ≈ 10 μS/cm) was freshly generated by a Millipore water purification system from Merck Millipore (MA, USA).

Sampling of Tobacco Products

A total of 22 different brands of tobacco products marketed as ready-made cigarettes, heated tobacco products, loose tobacco for roll-your-own cigarettes, and flavored shisha (hookah) tobacco were purchased from the Egyptian (11 samples) and Omani (11 samples) markets. Three packs of each branded product were purchased to confirm reproducibility from different governorates of each country. The brands were chosen to represent the most purchased or well-known brands, trying to cover different prices and blend categories. Table 1 shows the details of the studied brands with their average weights. Cigarettes were weighed after filters and rolling papers were removed.

Table 1 List of different tobacco products studied as selected samples

Sample no.	Form	Market	Labeled components	Average product weight (g)
S1	Cigarettes	Egypt	15.0 mg tar/1.0 mg nicotine	0.72
S2	Cigarettes		15.0 mg tar/1.0 mg nicotine	0.77
S3	Cigarettes		8.0 mg tar/0.6 mg nicotine	0.59
S4	Cigarettes		12.0 mg tar/0.9 mg nicotine	0.65
S5	Cigarettes		9.0 mg tar/0.7 mg nicotine	0.62
S6	Cigarettes		11.0 mg tar/0.8 mg nicotine	0.63
S7	Cigarettes		8.0 mg tar/0.6 mg nicotine	0.62
S8	Cigarettes		10.0 mg tar/0.9 mg nicotine	0.64
S9	Cigarettes		7.0 mg tar/0.6 mg nicotine	0.63
S10	Cigarettes		7.0 mg tar/0.6 mg nicotine	0.56
S11	Shisha tobacco		Not labeled	0.75
S12	Cigarettes	Oman	1.0 mg tar/0.1 mg nicotine	0.61
S13	Cigarettes		6.0 mg tar/0.5 mg nicotine	0.54
S14	Cigarettes		5.0 mg tar/0.4 mg nicotine	0.58
S15	Cigarettes		6.0 mg tar/0.5 mg nicotine	0.42
S16	Heated cigarettes		0.2% nicotine	0.28
S17	Loose tobacco		Not labeled	0.61
S18	Loose tobacco		Not labeled	
S19	Loose tobacco		Not labeled	
S20	Loose tobacco		Illegally imported	
S21	Shisha tobacco		0.5% nicotine/molasses/glycerin/flavors	0.78
S22	Shisha tobacco		Not more than 0.5% nicotine/molasses and glycerin	0.77
S23	Shisha water-waste		-	Liquid
S24	Shisha water-waste		-	Liquid
S25	Shisha water-waste		-	Liquid
S26	Roll papers/filters	Egypt	-	-
S27	Roll papers/filters	Oman	-	-

The rationale behind selecting the 22 tobacco product brands for analysis could be clarified according to the proposed research scope. For the Egyptian market, market share and diversity in types were the leading factors. Seven locally manufactured brands (S1 to S7) were chosen besides three imported brands (S8 to S10) of tobacco products. The products (S1 and S2) were two local Egyptian cigarette brands with the highest market share along their category. The following five brands were international brands (S3 to S7) that are manufactured locally under licenses for their production. The five brands were selected at different price categories and were considered for being the best sellers across their price categories as elaborated by the market brief survey. The same was considered for the imported samples (S8 to S10) that were classified into three different price ranges and were considered the best sellers for imported brands of cigarettes. Sample (S11) was a local shisha tobacco commonly sold legally within Egypt.

As for the Omani market, all the samples were imported brands since Oman does not have local tobacco manufacturers. The brands were chosen from the best sellers and highest market share from different price categories. Firstly, samples (S12 to S15) were classic cigarettes representing different price ranges and were selected for being the best sellers among their price categories. Sample (S16) was a new technology of cigarette that is heated by the device provided by its manufacturer. It was chosen to represent a different type of product other than classic cigarettes. Samples (S17 to S20) were locally sold loose blends of tobacco, each with a different composition according to the seller, with no details written on the label except for the blend name and manufacturer. The samples of these very commonly sold loose tobacco were selected to represent both legally (S17 to S19) and illegally (S20) marketed products. Sample S20 was a very common brand known by the Omani smokers but was sold very cautiously by the sellers for being illegally marketed in a plastic bag with no name, label, or information regarding its origin. Samples S21 and S22 were two different brands of imported shisha tobacco. The three shisha wastewater samples (S23 to S25) were obtained from various local Omani bars after shisha tobacco was smoked to calculate the amount of each element retained from different sources of shisha tobacco. Finally, samples S26 and S27 were samples of roll papers and filters that are used in cigarette products.

Element Selection and Standard Calibration Curves

Eleven elements were chosen for the study. Arsenic (As), chromium (Cr), nickel (Ni), cadmium (Cd), cobalt (Co), iron (Fe), mercury (Hg), and lead (Pb) were chosen based on IARC classification and reviewing literature. Beryllium (Be), not typically considered a heavy metal, is a relatively light alkaline earth metal with an atomic number of 4. It was added because it can be toxic, especially in dust or fumes [49], and because its risk limit was set recently [50]. Barium (Ba) was analyzed to help compare with the study conducted in 2017, and manganese (Mn) for having comparable inhalation risk level to Hg. The rationale behind selecting those specific trace elements for evaluation in tobacco products was based on several factors, including their potential health risks, their previously published prevalence in tobacco products, and some regulatory guidelines which are to be mentioned later within the "Discussion" section.

All utilized tools and containers were carefully washed with ultrapure water and then with 5% nitric acid before use. Calibration curves were developed using six working standards for each studied element. The linearity calibration curves for all elements, except iron, were prepared at concentrations of 0.03, 0.05, 0.10, 0.50, 1.00, and 3.00 mg/L by diluting the multi-element standard solution in 5% nitric acid. The Fe calibration curve was prepared at concentrations of 0.50, 1.00, 3.00, 10.00, 15.00, and 20.00 mg/L by diluting the stock standard solution in 5% nitric acid. Mercury was analyzed using DMA, where ten standards were prepared from the mercury stock calibration standard at concentrations 1.00 to 150.00 ng/g (ppb). Mercury was analyzed according to Method 7473, followed by the US Environmental Protection Agency (US-EPA) [51].

Sample Preparation and Analysis Methods

Three individual samples from packs corresponding to each studied tobacco product were analyzed, and the average elemental contents were calculated. Filters and rolling papers of the ready-made cigarettes and heated products were separated from tobacco to be tested individually. These auxiliary filters/rolling papers for the ready-made cigarettes were tested separately, and their average elemental contents were calculated. The results were sorted in the same order as Table 1.

All elements, except mercury, were analyzed using the ICP-OES method. Before microwave digestion, 5.0 mL nitric acid (65%, w/v) was added to about 0.7 g of each sample. The microwave digestion program was performed in modified polytetrafluoroethylene (TFM) tubes, as listed in Table 2.

After digestion, the samples were obtained as clear solutions, filtered, and stoichiometrically set to a volume of 25.0 mL using ultrapure water in polypropylene volumetric flasks. The samples were then injected into the ICP-OES system for analysis of heavy metals.

The sensitivity of ICP-OES measurements has been optimized under specific conditions listed in Table 2. The plasma argon gas was set at a flow rate of 8.00 L/min, while the auxiliary gas was 0.20 L/min. Additionally, the pump flow rate was set at 3.00 mL/min. The emission lines with

Table 2 Microwave digestion and ICP-OES conditions

Microwave digestion conditions				
Step	Power	Temperature	Pressure	Time
1	1500 W	150 °C	80 bars	5 min
2	1500 W	150 °C	80 bars	5 min
3	1500 W	200 °C	100 bars	8 min
4	1500 W	250 °C	100 bars	7 min
ICP-OES				
Rf power (W)			1450	
Injector			Alumina 2 mm internal diameter (I.D.)	
Sample tubing			Standard 1.14 mm I.D.	
Drain tubing			Standard 1.14 mm	
Quartz torch			Single-slot	
Sample capillary			PTFE 1.0 mm internal diameter	
Sample vials			Polypropylene	
Source equilibrium delay			15 s	
Plasma viewing			Axial	
Processing mode			Peak area	
Plasma gas			Argon	
Nebulizer gas flow			0.5 L/min	
Shear gas			Air	

minimal interferences were selected for the studied elements based on previous laboratory studies. These selected emission lines were as follows: Fe 238.204, As 193.696, Cd 228.802, Co 238.892, Pb 220.353, Ba 233.527, Mn 257.610, Cr 267.716, Ni 231.604, and Be 234.861. Lastly, the emission view was axial to enhance the procedure's sensitivity.

An accurately weighed amount of 0.20 g of each sample was directly placed into the quartz boats, which had been washed carefully using nitric acid (5%, w/v) to analyze mercury using DMA. Inside the DMA-80, the samples underwent a drying process at 300 °C for 60 s. Following that, the furnace temperature was raised to 650 °C for 180 s to facilitate sample decomposition in the presence of oxygen as a carrier gas. The resulting Hg vapors were then carried by the carrier gas (at a flow rate of 8 L/h) to the catalyst tube to remove impurities. An atomic absorption spectrophotometer was used to detect Hg, and its absorption intensity was measured at a wavelength of 253.7 nm.

Analytical Method Validation

The International Council for Harmonisation (ICH) guidelines [52] were used to validate the method. Blank experiments were performed to subtract the background signal intensities. Linearity was established across the ranges, which were 0.03–3.00 mg/L for the following elements (As, Cd, Co, Ba, Ni, Cr, Mn, Pb, Be), 0.50–20.00 mg/L for Fe, and 1.00–150.00 ng/g for Hg. Quality control (QC) standard injections were performed to ensure accuracy and precision. The recovery percentages (recovery%) were calculated to confirm the method's accuracy. Precision was calculated in terms of repeatability and intermediate precision and expressed as relative standard deviation percentages (RSD%) of the obtained recovery% results. For accuracy and repeatability, the QC standards were injected six times at a concentration of 3.00 mg/L for the ICP-OES procedure and 20.00 ng/g for the DMA procedure. The same QC standards were injected as duplicates in 3 days to assess intermediate precision.

Results and Discussion

Digestion Optimization for ICP-OES Analysis

Samples are often introduced in ICP-OES as liquids, where this allows better homogeneity and a more efficient extraction and analysis of the target analytes. Microwave-assisted digestion is a method of sample preparation that involves using a microwave in acidic media to digest solid products. It is more advantageous than the open-air digestion technique due to several reasons. Firstly, it saves time as it operates in high temperatures and pressures, and up to 15 samples can be prepared in less than an hour during the same cycle. Secondly, it offers low acid consumption and minimizes exposure to acidic fumes, which benefits the environment and the operator's safety. Also, as a closed system, it reduces the chance of external contamination and loss of volatile elements. Finally, it offers better extraction efficiency and reproducibility [53]. Hence, microwave-assisted digestion was chosen.

The microwave-assisted digestion's effectiveness depends on the solid sample's nature, the acids used, and the device's parameters, including power, temperature, pressure, and time. Three acid mixtures were tested: 5 mL (65%) HNO_3, 3 mL (65%) HNO_3 + 2 mL (37%) HCl, and 2 mL (65%) HNO_3 + 2 mL (37%) HCl + 2 mL (30%) H_2O_2. All three mixtures were effective in digestion, but 5 mL of (65%) HNO_3 was chosen as it minimized the use of several concentrated corrosive reagents for more operator safety. Two methods were tested for the digestion parameters in the early trials. Method 1 [54] was not enough to completely digest filters and the illegally imported tobacco (S20). In contrast, method 2 [20] was successful but was slightly modified to reduce power consumption from 1800 to 1500 Watts (W) without increasing the digestion time. The final program used for different samples is shown in Table 2.

Analytical Method Validation

The analytical methodology was validated according to ICH guidelines and the obtained results are shown in Table 3. Regression coefficients (R^2) were calculated for each

Table 3 Validation data for the determination of elements in smoking products

Element	Range (ppm)	Equation	R^2	Accuracy	Precision (RSD%)*	
				Recovery%	Repeatability	Inter-day precision
As	0.03–3.00	$y=2432.2x-19.985$	0.9995	95.83	0.28	0.30
Cd		$y=241806x-3092.4$	0.9997	101.53	1.07	1.23
Co		$y=279229x-4169.2$	0.9996	101.82	0.70	1.77
Pb		$y=13345x+213.43$	0.9992	99.55	0.53	1.80
Ba		$y=455032x-5974.1$	0.9997	100.93	0.19	0.55
Be		$y=3\mathrm{E}+06x-1.859$	0.9999	93.37	0.30	0.94
Mn		$y=3\mathrm{E}+06x-42{,}191$	0.9996	103.81	0.11	1.75
Cr		$y=386784x-4574.5$	0.9997	102.41	0.49	0.95
Ni		$y=111207x-1359.5$	0.9997	101.56	0.07	0.22
Fe	0.50–20.00	$y=200730x-17{,}049$	0.9999	101.04	0.35	2.13
Hg	1.0–150.0 ppb	$y=0.04808x-0.00279$	0.9996	100.15	0.37	0.52

*Results in relative standard deviation percentage (RSD%) of the obtained recovery%

element and found to be ranged from 0.9992 to 0.9999, indicating good linearity. The estimated mean values for recovery percentages were calculated as follows: arsenic (As) 95.83%, lead (Pb) 99.55%, cadmium (Cd) 95.83%, barium (Ba) 100.93%, chromium (Cr) 102.41%, manganese (Mn) 103.81%, cobalt (Co) 101.82%, nickel (Ni) 101.56%, iron (Fe) 101.04%, mercury (Hg) 100.15%, and beryllium (Be) 93.37%, confirming the closeness of actual and found elemental concentrations. The repeatability and intermediate precision RSD% were less than 2%, indicating the close agreements of all series of measurements.

Updated Exposure Limits for Heavy Metal Regulations for Tobacco Smoking

Over decades, smoking has gained popularity due to different reasons despite its known downsides. Nicotine, its principal constituent, develops dependence, which makes it hard to quit, noting that the WHO stated that it kills half of its users who do not stop [1]. Smoking also increases the risks of cancer, as well as lung and heart disease [55], and can affect pregnant women [55]. Also, it does not only affect the person smoking but also people around him, known as secondhand smokers. The matter is even more alarming, knowing that smoking has become more prevalent among teenagers under 18 years old and is still under development [56]. Most studies classify smokers into light smokers (1–9 cigarettes/day or ≤ 20 packs yearly) and heavy smokers (≥ 20 cigarettes daily or >20 packs yearly) [57, 58]. Heavy metal exposure through ingestion, skin, and inhalation also affects different systems and organs due to many mechanisms, such as apoptosis and necrosis. Therefore, their presence in smoking products can deuterate smokers' health more [59].

Manufacturing smoking products involves numerous variables, including the source of tobacco and rolling paper, fertilizers, agriculture water, and large-scale industrial factories and their production processes. Consequently, smoking products will have varying amounts of trace substances, and it is challenging to organize explicit ranges for the allowed heavy metal limits in smoking products. Table 4 is compiled for this purpose. Table 4 is based on updated minimum inhalation risk levels, which means exceeding these limits risk human health. The data was collected from the Agency for Toxic Substances and Disease Registry (ATSDR) [50], along with updated permissible daily inhalation limits stated by ICH [60] and their cancer group classification by WHO IARC [13].

This research also focused on gathering and tabulating the limits of a range of the commonly studied heavy metals in smoking products. While the ATSDR sets minimum exposure limits (grey zone), the ICH sets maximum limits (red zone). If traces of heavy metals were found in a tobacco product, and the average smoker is exposed to levels within this range, assuming all the amount was inhaled, the product should raise concern, and decisions should be taken accordingly. Another advantage of this approach is that it depends on open-accessed authorized databases updated frequently. For instance, Dahlawi et al. published their investigation on the Saudi tobacco products in 2021 where they relied on literature for permissible daily exposure, which stated cadmium limit to be 2 µg/day [41]. However, this limit was updated the year before (in 2020) to 3 µg/day. Other studies [36, 45, 47] depended on comparing results with other countries' findings or to the WHO bulletin [61], although variations could happen from batch to batch due to many factors affecting tobacco plants, including pesticides [22], fertilizers [23], soils, and water [12, 62]. The inhalation limit for nickel was also updated in 2022 from 5 to 6 µg/day according to the ICH guidelines [60]. Beryllium, which had no minimum inhalation risk levels, was updated during

Table 4 Heavy metals' minimum inhalation risk levels according to the Agency for Toxic Substances and Disease Registry (ATSDR), and permissible daily exposure limits according to ICH, and WHO Cancer group classification

Heavy metal	Type exposure	Minimum inhalation risk levels	Permissible daily exposure limits (µg/day)	Cancer group
	ATSDR [50]		ICH [60]	WHO [13]
Cadmium	Acute*	0.030 µg/m^3	3 (updated December 2020)	1
	Chronic*	0.010 µg/m^3		
Beryllium	Chronic*	0.001 µg/m^3 (updated September 2023)	-	1
Nickel	Intermediate*	0.030 µg/m^3	6 (updated April 2022)	1
	Chronic*	0.010 µg/m^3		
Iron	Chronic*	Not determined by ATSDR and ICH. 1000 µg/m^3 according to the Occupational Safety and Health Administration (OSHA) [63, 64]		1
Arsenic [65]	Toxic but need more studies to determine minimum levels		2	1
Chromium (VI)	Intermediate and chronic*	0.005 µg/m^3	3	1
Chromium (III)	Intermediate*	0.100 µg/m^3		3
Cobalt	Chronic*	0.100 µg/m^3	3	2
Lead [66]	Toxic at very low levels (≤ 5 µg/dL) Also, the CDC declared that no level is safe [15]		5	2
Mercury	Chronic*	0.300 µg/m^3	1	3
Barium [67]	Toxic but need more studies to determine minimum levels		300	Not listed
Manganese	Chronic*	0.300 µg/m^3	-	Not listed

*ATSDR sets acute exposure as (1–14 days), intermediate (15–364 days), and chronic (≥ 365 days)

the past few months (specifically in September 2023). Its amount should be considered in future studies as it was not given importance compared to other popular elemental impurities. Following the same concept of depending on authorized databases, when no limits were found for iron in ATSDR and ICH, the limit of 1000 µg/m^3 set by the Occupational Safety and Health Administration (OSHA) was added [63, 64]. No clear inhalation risk limits (≤ 5 µg/dL) were set for lead exposure, so its presence should be avoided in any inhaled product, as stated by the Centers for Disease Control and Prevention (CDC). Lastly, combining minimum inhalation risk with cancer group classification should help in ordering the restriction priority of heavy metals present in tobacco products.

Elemental Contents in the Studied Tobacco Products

Eleven heavy metals were studied in different smoking products, including cigarettes with their rolling paper/filters, roll-your-own cigarette tobacco, heated cigarette tobacco, shisha tobacco, and shisha water. In the case of ready-made and heated cigarettes, the elements were calculated per the average weight of each cigarette brand (Table 1). In the case of shisha tobacco, the content was calculated based on the average weight of tobacco weighed three times in the shisha bowl/head from each brand. Loose tobacco for roll-your-own cigarettes was calculated by rolling three cigarettes of each product and then calculating the average rolled weight of tobacco (Table 1).

Table 5 shows the quantified amount per unit smoking product. Compared to the other heavy metals studied, Fe was the most abundant. Fe was even found in the filters of ready-made cigarettes, especially in those obtained from the Omani market (sample S27), 339.4 µg, compared to those studied from Egypt (sample S26) and the other types of elements Ba, Mn, Cr, and Hg (Table 5) were found at much lower concentrations per filter compared to the content found in their attached tobacco product. However, they can still contribute to the burden inhaled by smokers. According to Evans-Reeves et al. [68], the European regulations on tobacco packaging and products have not yet addressed the design and innovation of cigarette filters, resulting in tobacco companies taking advantage of these loopholes and developing new filter designs to distinguish their products from those of their competitors. The heated tobacco product (sample S16) had the least Fe content, 60.1 µg, among ready-made cigarettes. It is also worth highlighting that the Fe content of shisha tobacco (samples S11, S21, and S22), ranging from 20.5 to 32.4 µg, was much lower than that of all other studied tobacco products. Meanwhile, the illegally imported loose tobacco in the Omani market (sample S20), which is sold in a plastic bag claimed to be tobacco, had the

Table 5 Elemental impurities quantified in the studied tobacco products as calculated per unit smoking

Sample number	As*	Cd*	Co*	Pb*	Ba*	Mn*	Cr*	Ni*	Be*	Fe*	Hg**
S1	0.0	0.0	0.0	0.0	66.4	100.5	2.1	1.7	0.0	482.9	11.5
S2	0.0	0.0	0.0	0.0	70.3	106.5	4.5	2.9	0.0	422.1	10.9
S3	0.0	0.0	0.0	0.0	54.1	81.9	1.2	1.3	0.0	284.9	8.7
S4	0.0	0.0	0.0	0.0	59.8	90.6	1.2	1.0	0.0	355.0	12.0
S5	0.0	0.0	0.0	0.0	57.1	86.5	2.0	0.0	0.0	269.1	12.2
S6	5.9	1.1	0.0	2.6	57.1	86.5	8.8	1.3	0.0	356.8	12.4
S7	0.0	0.0	0.0	0.0	56.4	85.4	1.2	1.1	0.0	340.4	11.7
S8	4.4	0.0	0.0	2.0	58.8	89.2	6.0	0.0	0.0	201.9	10.8
S9	0.0	0.0	0.0	0.0	57.3	86.8	1.0	1.1	0.0	197.0	11.7
S10	0.0	0.0	0.0	0.0	51.0	77.2	1.1	1.0	0.0	222.6	8.2
S11	0.0	0.0	0.0	1.6	116.4	314.3	0.0	0.0	0.0	20.5	2.7
S12	2.1	0.0	0.0	0.0	56.3	85.3	2.9	0.0	0.0	183.7	11.3
S13	0.0	0.0	0.0	0.0	49.1	74.4	1.2	1.3	0.0	257.2	7.7
S14	0.0	0.0	0.0	0.0	53.0	80.3	1.0	0.0	0.0	193.9	6.8
S15	0.0	0.0	0.0	0.0	38.8	58.7	0.0	0.0	0.0	145.4	4.5
S16	0.0	0.0	0.0	0.0	25.5	38.6	0.0	0.5	0.0	60.1	6.1
S17	0.0	0.0	0.0	0.0	55.4	84.0	1.6	2.4	0.0	163.1	11.7
S18	0.0	0.0	0.0	0.0	55.4	84.0	1.6	2.8	0.0	203.9	12.9
S19	0.0	0.0	0.0	0.0	55.4	84.0	1.3	1.9	0.0	145.2	7.9
S20	0.0	0.0	0.0	0.0	55.4	84.0	3.8	1.4	0.0	3648.1	3.3
S21	2.2	0.0	0.0	1.8	1.0	0.0	0.0	0.0	0.0	26.8	2.4
S22	0.0	0.0	0.0	0.0	116.4	314.3	0.0	0.0	0.0	32.4	2.6
S23	0.0	0.0	0.0	1644.0	100.0	0.0	0.0	182.0	0.0	0.0	0.0
S24	0.0	0.0	0.0	525.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0
S25	0.0	0.0	0.0	564.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0
S26	0.0	0.0	0.0	0.0	4.2	1.2	0.5	0.0	0.0	14.0	0.4
S27	0.0	0.0	0.0	0.0	4.1	1.5	0.5	0.0	0.0	339.4	0.6

Zero means the studied element was not detected

*Results in (µg/cigarette), (µg/ filter), (µg/shisha tobacco sitting), or (µg/L shisha water)

**Results in (ng/cigarette), (ng/ filter), (ng/ shisha tobacco sitting), or (ng/L shisha water)

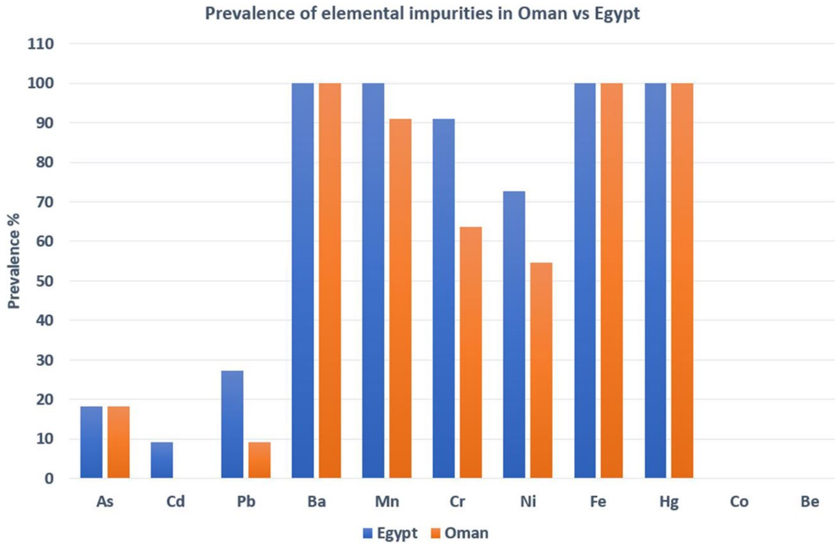
highest level of Fe content of 3648.1 µg, exceeding three times the OSHA limits (Table 4) which impose risk to its users as Fe, a group 1 carcinogen, inhalation was reported to cause hepatic complications, production of reactive oxygen, and neurological disorders [69].

Although As was quantified in only 4 samples (sample S6, sample S8, sample S12, and sample S21) out of 22 studied products, the amount calculated per one cigarette exceeds 2 µg, which is higher than the daily limits stated by ICH (Table 4) threatening all types of smokers. Ni was also quantified in several samples (55.6% prevalence), ranging from 0.5 to 2.9 µg, which exceeded ATSDR minimum risk levels (0.030 µg). Still, even after the ICH daily limit was increased (6 µg), this limit could be exceeded by smoking 12 heated cigarettes (sample S16), which had the lowest amounts. It is worth noting that Cd was not detected in studied samples in the Omani market, yet it was detected in only one sample from the Egyptian market (sample S6); this still imposes some risk on all smokers.

Mercury (Hg), a group 3 carcinogen, was quantified at nano-gram levels by DMA ranging from 0.4 to 12.4 ng. Fortunately, this means that heavy smokers should smoke between 30 and 100 cigarettes from the highest detected product to exceed ATSDR and ICH daily levels, respectively (Table 4). Higher levels of Pb were found in shisha wastewater samples (samples S23, S24, and S25) than in cigarettes. Although shisha water is not inhaled, its danger could come from disposal, as lead impacts the ecosystem, bioaccumulates, and transfers through food chains, including worms, animals, and humans [70]. When discussing Ba levels, as shown in Table 5, it can be concluded that light smokers could easily exceed the Ba daily ICH limit (Table 4). For instance, smoking five cigarettes of sample S2 can serve as an example.

The prevalence of heavy metals in smoking products in both Oman and Egypt was analyzed (Fig. 1) as obtained from the data included in Table 5. The prevalence was calculated as a percentage of the number of samples where

Fig. 1 Comparison between the Omani and Egyptian markets regarding the prevalence of heavy metals



heavy metal was detected in the total number of samples. For Egypt's smoking products (S1–S11; $n = 11$), the most abundant heavy metals were Ba, Mn, Fe, Hg (100.0%) > Cr (90.9%) > Ni (72.7%) > Pb (27.3%) > As (18.2%) > Cd (9.1%) > Co, Be (0.0%). For Oman's smoking products (S12–S22; $n = 11$), the prevalence was found as follows: Ba, Fe, Hg (100.0%) > Mn (90.9%) > Cr (63.6%) > Ni (54.5%) > As (18.2%) > Pb (9.1%) > Cd, Co, Be (0.0%). Figure 1 presents a market comparison between Egypt and Oman regarding the prevalence of heavy metals.

Overall, taking the whole sample set in both countries ($n = 27$), the most abundant was Ba (100.0%) > Fe, Hg (88.9%) > Mn (85.2%) > Cr (70.4%) > Ni (55.6%) > Pb (25.9%) > As (14.8%) > Cd (3.7%) > Co, Be (0.0%). Co and Be were not detected in any of the samples marketed in Oman and Egypt. Most previously published studies had frequently ignored the detection and quantification of Be, which might be attributed to the absence of official minimal risk exposure limits until recently, when the ASTDR updated its limit by the end of 2023 (Table 4). The most abundant heavy metals were Ba, followed by Fe and Hg, although Hg detection limits were in the nanoscale compared to other elements due to DMA sensitivity.

Considering the different types of tobacco products, the assessment of the results obtained (Table 5) indicates that the new heated cigarette systems (sample S16) had the lowest burden of toxic elements in terms of the number of elements detected (only Ba, Mn, Ni, Fe, and Hg) and most of their concentration low levels, when compared to ready-made cigarettes (samples S1–S10 and S12–S15), loose tobacco (samples S17–S20), or shisha tobacco (samples S11, S21, and S22).

As shown by the results, the lowered heavy metal content in tobacco products can have significant public health implications. Reduced health risks and enhanced consumer safety will contribute to a healthier population and a reduction in healthcare costs associated with heavy metal–related illnesses. Furthermore, the obtained results of the study demonstrate the effectiveness of FCTC protocols in reducing heavy metal content and can aid policymakers in developing better tobacco control strategies. Policymakers can use this evidence to strengthen the existing regulations or introduce new measures to further limit heavy metal exposure. This might include stricter monitoring of manufacturing processes, enforcing product quality standards, and implementing comprehensive labeling requirements, which in turn can contribute to a decline in smoking rates. Nevertheless, further studies are needed by researchers to evaluate the long-term health benefits associated with reduced heavy metal exposure. The results of such studies can inform the evidence-based tobacco control strategies, leading to more effective public health interventions.

Market Evaluation

After analysis, the obtained results could be used to evaluate the effectiveness of applying FCTC protocols. Figure 2 shows a comparative graphical representation of Cd and Ba levels reported in Egypt during the year 2017 (before FCTC) and our current results (after FCTC). The proposed study also conducted a statistical analysis for Ba levels after implementing FCTC protocols in Egypt in 2020, compared to those previously reported levels in the study executed in 2017 [47]. A paired *t*-test was conducted between the two groups, and the *p*-value was 9.51×10^{-6} ($p < 0.05$), indicating statistical significance. The *t*-test between the Egyptian and Omani markets, assuming unequal variance between Ba levels detected in this study, was also significant with a *p*-value of 0.034 ($p < 0.05$). Lastly, a one-way ANOVA between the three groups showed an *F*-value of 70.46, higher

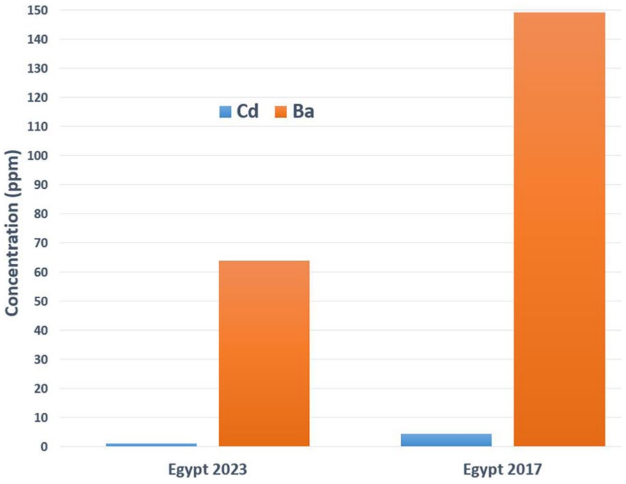


Fig. 2 Comparative diagram showing the levels of Cd and Ba as reported in Egypt in 2017 and current results (before and after implementation of FCTC protocols)

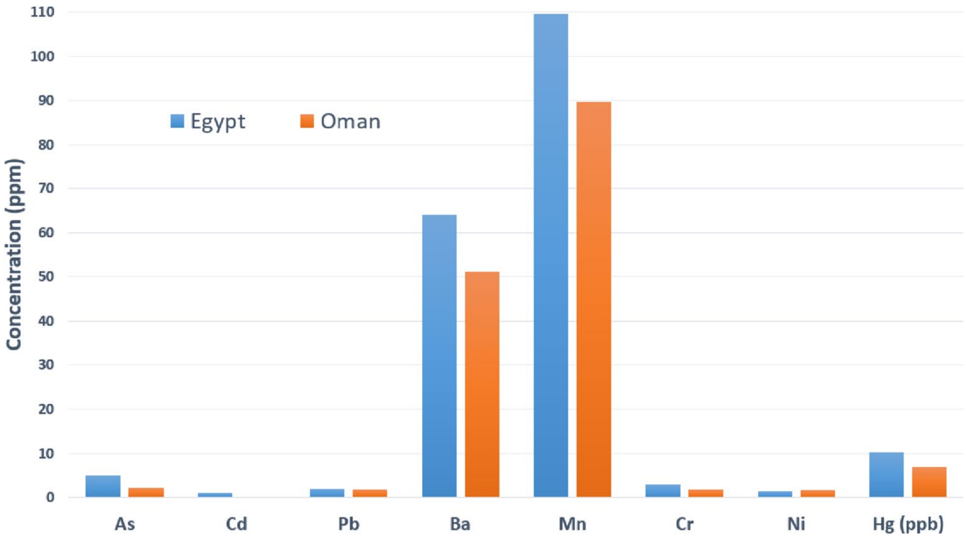
than the F_{crit} value of 3.36, indicating statistical significance. Additionally, the average detected Ba and Cd level order was Oman < Egypt < Egypt in 2017, and the Cd prevalence has become 9.1% (Fig. 1).

When comparing the Egyptian and the Omani markets, it can be concluded that the Omani market has better controls on their marketed tobacco products. Figure 3 compares the averages of some detected elements in the Egyptian and Omani markets. It shows that the Omani market has outperformed the Egyptians in elemental control. Moreover, Oman has stringent measures regarding the cultivation, production, and smoking of tobacco products. Until 2017, Oman only cultivated about 450 acres with tobacco plants for leaves, which produce about 1800 metric tons annually [31]. The stricter tobacco legislation in Oman could also help explain those lower levels. This could be attributed to the FCTC protocol, namely Articles 18 and 20. The protocol highlights the obligation of the countries following their protocols to undertake strict measures regarding the cultivation of tobacco relative to the environmental protection and the exchange of socio-economic data.

Finally, the obtained results also suggest that implementing the FCTC protocols has a role in elemental control. This role can be linked to Articles 9, 10, 11, 15, 21, and 22 in the FCTC. Article 9 requires regulations on tobacco product contents through measurements and tests, while Article 10 mandates manufacturers and importers to provide information about their product's contents and toxic content. Article 11 prohibits any deceptive claims on the package or label of tobacco products, and Article 15 eliminates illegal trade and counterfeiting. Articles 21 and 22 provide technology transfer to strengthen tobacco control strategies and require the parties to provide periodic reports [71]. Also, FCTC Article 12 utilizes all available tools to increase public awareness and education. These campaigns can target countries with a trend of young people starting to smoke, reflecting the meaning behind tar and heavy metals and how even minute amounts found in one cigarette could negatively impact their quality of life and the people around them through second-hand smoke, the ATSDR minimal inhalation risk limits and Table 4 can be utilized for this aim.

Although other practices could have impacted the levels of heavy metals in the source of the studied tobacco products, such as soil composition and agricultural practices, these in turn could be related to the FCTC protocols in one way or another. For instance. in terms of soil composition, the protocols emphasized the importance of sustainable farming practices. Farmers were encouraged to

Fig. 3 Comparative diagram showing the average levels of some of the studied elements in the Egyptian and Omani markets



adopt practices such as crop rotation, organic farming, and integrated pest management. These methods help preserve soil health, reduce the use of chemical inputs, and prevent soil erosion. Moreover, the manufacturing companies could make use of the updated heavy metal limits as reviewed in the proposed manuscript (Table 4) to set up their acceptance criteria for the raw tobacco sources. In brief, future research focusing on the effect of other factors such as soil composition and agricultural practices on the levels of heavy metals in tobacco products holds great significance and should be considered by researchers all over the world. However, the final outcomes investigated in the two countries under study prove the progressive improved impact of applying more restrictive protocols on the overall public health.

Conclusion

Beyond nicotine, several elements contribute to the overall burden of tobacco smoking dangers. The tar being labeled without details and the source from which the tobacco product was derived can impact its potential risk, especially regarding its chemical composition. Different tobacco sources vary in cultivation practices, processing methods, and additives. Additionally, smokers may be in situations where they are exposed to secondhand smoke from others in a group or crowded places. The Framework Convention on Tobacco Control (FCTC) protocols came into force in 2005. Oman was one of the earliest countries to implement these protocols. Lately, after its implementation in Egypt, the concentrations of different toxic heavy metals such as Ba and Cd have been reduced compared to previous results published in 2007, and the Cd prevalence was also reduced to 9.1%. However, some of the obtained results are still alarming to the maximum acceptable limits. The results showed that elemental control within the Omani market was higher than in the Egyptian market. Besides, the statistical analysis conducted ($p < 0.05$) suggests the positive impact of the FCTC protocols. It is essential to keep in mind that smokers typically smoke more than one cigarette per day. Therefore, the levels of heavy metals detected, even at the nano-range level, could still be highly significant for those elements detected within permissible limits, such as mercury. Finally, the proposed study has shown that cigarette consumption serves as an extra avenue for exposure to specific contaminants of toxic earth elements that have received limited or no prior investigation in the Omani and Egyptian markets. In conclusion, Implementing and enforcing regulations on heavy metals in tobacco products should involve regular testing and monitoring in order to avoid their enclosed risks.

Author Contribution Conceptualization, A.I. and A.A.;Methodology, software, and validation, A.I., S.A., M.H., M.O., H.B., and B.S.; Formal analysis, A.I., S.A., M.H., M.O., H.B., and B.S.; Investigation, S.A. and A.I.; Data curation, S.A. and A.I.; writing—review and editing, A.I., S.A., M.H., M.O., H.B., and B.S.; , A. I. and A. A. Resources and Project administration, A.I. and A. A.;

Funding The authors would like to show their appreciation to the Omani Ministry of Higher Education, Research, and Innovation for supporting this research under TRC research grant number BFP/RGP/CBS/22/002.

Data Availability No datasets were generated or analysed during the current study.

Declarations

Informed Consent Not applicable.

Competing interests The authors declare no competing interests.

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