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Ecological and Human Health Risk Indicators of Heavy Metals in Soil of Eastern Area of Fayoum, Egypt

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FAO: Food and Agriculture Organization
HI: hazard index
HMs: heavy metals
TCR: total carcinogenic risk
UCES: uncontaminated Egyptian soil
UUC: average composition of the upper continental crust.

ABSTRACT

Soil pollution discusses the contamination of soil with anomalous concentrations of harmful substances. Since it harbors many ecological and health hazards. There is growing concern about the gradual accumulation of heavy metals (HMs) in soils. This paper is conducted to appraise the extent of soil contamination in the Eastern Fayoum region. It examines the associated potential risks due to four HMs: cadmium (Cd), nickel (Ni), lead (Pb), and manganese (Mn). Moreover, non-carcinogenic and carcinogenic health risks resulting from soil exposure were evaluated for adults and children. The result showed that the mean concentration of heavy metals (mg kg^{-1}) in soil was often arranged as follows: Mn (350.35) > Pb (207.39) > Ni (78.48) > Cd (14.25) exceeds the FAO permissible limit. The pollution indices showed that the studied soil experienced high contamination with Cd and Pb, moderate to considerable contamination with Ni, and low Mn contamination. Cd shows very high ecological risk (4156.82), while Pb exhibits moderate ecological risk (51.46) and Ni and Mn show low ecological risk (19.62 and 5.84). The hazard index (HI) values of the four studied HMs signified that there was no adverse non-carcinogenic risk for adults (HI<1). Children have higher HI than adults, and the safe limit (HI>1) indicates that children are expected to be subjected to high non-carcinogenic risks. The carcinogenic risk of Cd, Ni, and Pb was higher than the acceptable values (TCR > 1.00E-04), indicating that Eastern Fayoum residents may suffer from carcinogenic risks. Thus, soil management and regular monitoring of heavy metal levels should be assessed to prevent further soil pollution.

Introduction

Soil contamination poses a severe hazard to ecosystems, particularly in developing countries [1]. Heavy metal pollution of soil is one of the most prevalent issues that can lower agricultural land efficiency and lead to food insecurity [2]. HMs may reach the ecosystem through both natural and anthropogenic activities [3]. Natural sources include accessions from dust storms, volcanic eruptions, and forest fires, as well as pedogenesis processes that result in mineral breakdown and product transfer [4]. Anthropogenic sources include all contributions generated by humans, such as industrial operations that contribute to both terrestrial and atmospheric depositions, mining and metallurgy, urban and industrial wastes, sewage, and fertilizer applications in agricultural areas [5]. HMs are generally major pollutants because of their persistence, toxicity, and non-biodegradability. Thus, due to their inability to break down, heavy metal buildup in agricultural soils can be transferred to air and water via surface runoff and favorable meteorological circumstances, respectively. It threatens human health and increases cancer risks [6]. Agricultural soils often contain several HMs that are poisonous to plants at high concentrations [7]. Among HMs, cadmium (Cd), arsenic (As), chromium (Cr), nickel (Ni), and lead (Pb) are commonly considered toxic to both plants and humans [8]. The primary routes of human exposure to HMs are ingestion, dermal contact, or inhalation of contaminated soil particles, as well as consumption of crops grown in polluted soils [9, 10]. Exposure to cadmium (Cd) can have harmful consequences on health, such as kidney failure, skeletal diseases, and bone fractures [11]. Lead is one of the most hazardous elements in the environment. It can remain in the soil for 1000 to 3000 years. It is an extremely hazardous metal due to its impact on plant productivity and growth [12]. Furthermore, nephrotoxicity, impacts on the central nervous system, cardiovascular disorders in humans, and several types of cancer have all been linked to lead exposure [13]. Nickel can have harmful implications for human health depending on the exposure time and dose. It has been connected to allergic diseases, kidney, lung, and nasal cancer [14]. The numerous physiological functions of manganese have frequently obscured the impression of its possible toxicity. As a result, research on the extremely toxic consequences this element produces in various environments (water, soil) is rare. However, consumption of high manganese concentrations may cause severe adverse health effects such as neurodegenerative disorder, cardiovascular toxicity, and liver damage [15]. Because of

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differing approaches to environmental and public health protection, different countries have varied toxic levels of HMs. So, there is a great deal of variance in environmental and human health regulations around the world [16]. Comprehensive data on heavy metal concentration in soils, source, and risk assessment are essential for managing soil contamination [17]. Several scientific indicators have been established to make it easier to determine the level of contamination of the soil and its relative risk to the environment [18]. At the same time, health risk assessment models quantitatively assess each of the non-carcinogenic and carcinogenic health risks posed by HMs in polluted soil [19].

The information on the level of soil metal contamination and its associated potential ecological and health risks needs more updates and integration. The objectives of this study are to (1) determine the concentrations of four HMs (Cd, Ni, Pb, and Mn) in the East of Fayoum Governorate's agricultural surface soils; (2) assess the surface soil contamination in the area from HMs by calculating the contamination factor and the degree of contamination indices; (3) estimate the ecological risk of the area by calculating the ecological risk and potential ecological risk indices; (4) identify the anthropogenic or natural source of HMs in this area by calculating the enrichment factor; and (5) determine human health (non-carcinogenic and carcinogenic) risks associated with the examined HMs.

Materials and Methods

Study area

Fayoum Governorate is located 90 kilometers southwest of Cairo. It is located between 28º 55' N and 29º 40' N latitudes, 29º 55' E and 31º 5' E longitudes. It's distinguished by a hot and dry summer, little winter precipitation, and bright sunshine throughout the year [20]. The Eastern part of Fayoum Governorate comprises three main Districts: Sinuris, Tamia, and Fayoum Districts (Fig. 1).

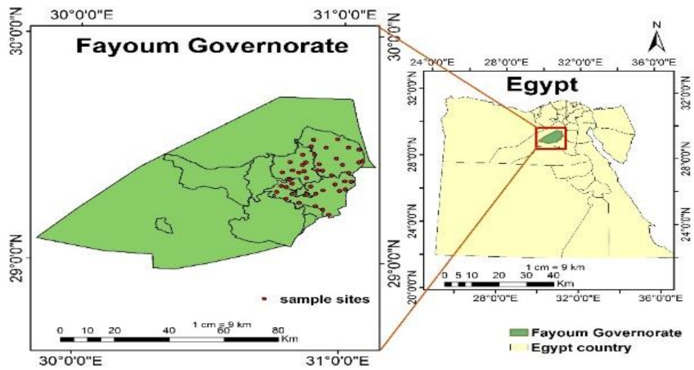

Fig. 1. Study area layout and sampling sites.

Sampling

Forty-five soil samples were collected representing the East of Fayoum Governorate region from November 2022 to April 2024. Locations of the studied sites were identified using GPS (Fig. 1). The samples from the top (0–30 cm) layer of soils were collected using a stainless steel auger sampler. The samples were placed into sealed polyethylene bags and carried to the laboratory until analysis. In the laboratory, samples were air-dried and homogenized with a pestle and mortar. Then they were sieved through a clean sieve of 2 mm mesh size to remove coarse materials, packed in a clean stoppard plastic container, and stored in a cool dry place for further analysis.

Heavy Metals Analysis

For HMs evaluation, one gram of soil was weighed and mixed with 21 ml of 35% conc. Hydrochloric acid and 7 ml of 50% conc. Nitric acid. Soils with an acid mixture were then heated for two hours at 120°C using a heating plate. The wet-digested samples were full volume up to 100 ml using distilled water and then filtered [21]. Atomic spectroscopy was used to analyze the concentration of cadmium (Cd), nickel (Ni), lead (Pb), and manganese (Mn). Results were expressed in terms of mg kg^{-1} dry weight. Blank (mixture of acid solution without soil) and triplicates were measured to control the quality of the analysis.

Soil Contamination Assessment

In order to evaluate the degree of heavy metal contamination in soil with the HMs under investigation (Cd, Ni, Pb, and Mn), single and integrated indices were measured. We use different reference levels in this study, such as the average composition of the upper continental crust and levels of the HMs in uncontaminated Egyptian soils [22].

Contamination factor (CF)

The contamination factor (CF) is utilized for assessing the level of contamination in soil from each metal [23]. It is calculated using the following equation:

$$CF = C_i / B_i.$$

Where C_i and B_i stand for measured metal concentration and background value for a specific metal, respectively. CF was classified into four groups to measure the degree of contamination in the soil as follows: CF <1 (low contamination), 1 ≤ CF < 3 (moderate contamination), 3 ≤ CF <6 (considerable contamination), and 6 ≥ CF (high contamination) [24].

Ecological Risk Factor (Er_i)
The ecological risk factor (Er_i) is a quantitative measure of the possible ecological danger associated with a certain pollutant. It is calculated using the following equation:

$$Er_i = Tr_i \cdot CF_i$$

Where CF_i is the contamination factor and Tr_i is the toxic response factor for a specific metal (Cd = 30, Pb = 5, Mn = 10, and Ni = 5) [25]. (Er_i) was classified into five grades to express the ecological risk from each studied metal as follows: $Er_i < 40$ (low ecological risk), $40 \leq Er_i < 80$ (moderate ecological risk), $80 \leq Er_i < 160$ (considerable ecological risk), $160 \leq Er_i < 320$ (high ecological risk), and $Er_i \geq 320$ (very high ecological risk).

Enrichment Factor (EF)
An effective measure for distinguishing between metals from natural and man-made sources is the enrichment factor. This normalization method compares the element being studied to a reference element [26]. The reference element is an element whose concentration in the environment is slightly variable and is not affected by anthropogenic factors. Elements such as Al, Fe, Mn, Si, and Ti are used as reference elements [27]. In this study, the manganese element was utilized to separate the human component from the natural one. The enrichment factor is calculated using the following equation:

$$EF = \frac{(C_i/C_{ref})_{sample}}{(C_i/C_{ref})_{backgroung}}$$

Where C_i is the concentration of the element of interest and C_{ref} is the concentration of a reference element for normalization purposes. The EF can be divided into five contamination categories as follows: EF < 2 (no enrichment), 2 ≤ EF < 5 (moderate enrichment), 5 ≤ EF < 20 (significant enrichment), 20 ≤ EF < 40 (very high enrichment), and EF ≥ 40 (extremely high enrichment) [28].

Degree of Contamination (DC)
The total of all contamination factors is known as the degree of contamination. It is calculated using the following equation:

$$DC = \sum_{i=1}^{n} (c_f^i)$$

Where c_f^i is the single index of contamination factor, DC is the degree of contamination for soil samples, and n is the count of the heavy metals. Contamination degree can be divided into four grades as follows: DC < 6 (low degree of contamination), 6 < DC < 12 (moderate degree of contamination), 12 < DC < 24 (considerable degree of contamination), and DC > 24 (high degree of contamination) [29].

Potential ecological risk index (RI)
The potential ecological risk index is defined as the sum of the ecological risk factors for each metal, similar to the degree of contamination. It is calculated using the following equation:

$$RI = \sum_{i=1}^{n} (Er_i)$$

Where Er_i is the single index of ecological risk factor and n is the count of the heavy metal species. The terminology used for the potential ecological risk index is as follows: RI<150 (low potential ecological risk), 150 ≤ RI < 300 (moderate potential ecological risk), 300 ≤ RI < 600 (considerable potential ecological risk), and RI > 600 (very high potential ecological risk) [30].

Health Risk Assessment

The risk that pollution poses to humans can be estimated by using an efficient model called the human health risk model. Differences in physiology and behavior of adults compared with children keep them separate. The current study estimated the potential of non-carcinogenic and carcinogenic health risks for the two age groups. Among the studied elements, only Cd, Ni, and Pb are considered carcinogenic elements [31].

Exposure assessment
The primary routes of exposure for children and adults to HMs are through ingestion (ADI_{ing}), inhalation of suspended particles (ADI_{inh}), and dermal contact (ADI_{der}). The dose received through each of the three pathways from agricultural soil was calculated using the following equations [32]. The standard parameters used in the three equations are expressed in Table 1.

$$ADI_{ing} = \frac{C_A * IR * EF * ED * CF}{BW * AT}$$

$$ADI_{inh} = \frac{C_A * InhR * ET * EF * ED}{PEF * BW * AT}$$

$$ADI_{der} = \frac{C_A * SA * AF * ABS * EF * ED * CF}{BW * AT}$$

Where: ADI_{ing} is the average daily intake of HMs ingested from the soil in mg/kg/day. ADI_{inh} is the average daily intake of HMs inhaled from the soil in mg/kg/day. ADI_{der} is the exposure dose via dermal contact in mg/kg/day. C_A is the concentration of HMs available in agricultural soil (mg kg^{-1}). IR is soil ingestion rate. BW is the body weight. EF is the exposure frequency. ED is the exposure duration. ATc is the carcinogenic risk average time. ATnc is the non-carcinogenic risk average time. SA is the skin surface area available for contact. CF is the conversion factor. AF is the soil-to-skin adherence factor. ABS is the absorption factor. InhR is the inhalation rate. ET is the soil exposure time. PEF is the particle emission factor, and ET is the exposure time (h/day).

Table 1. USEPA range for variables used in ADI, HI and Risk indicators calculation [36, 37, 38].

Factor	Adult	Children
soil ingestion rate (IR)	100 mg day^{-1}	200 mg day^{-1}
exposure frequency (EF)	312 Days $year^{-1}$	312 Days $year^{-1}$
exposure duration (ED)	35 Years	6 Years
body weight (BW)	70 Kg	15 Kg
non-carcinogenic risk averaging time (ATnc)	365 × 35 Days	365 × 6 Days
carcinogenic risk averaging time (ATc)	365 × 70 Days	365 × 70 Days
conversion factor (CF)	10^{-6} mg day^{-1}	10^{-6} mg day^{-1}
skin surface area available for contact (SA)	6032 cm^2	2373 cm^2
soil-to-skin adherence factor (AF)	0.07 mg cm^{-2}	0.2 mg cm^{-2}
absorption factor (ABS)	0.001	0.001
inhalation rate (InhR)	1.56 m^3 h^{-1}	1.2 m^3 h^{-1}
soil exposure Time (ET)	8 h day^{-1}	4 h day^{-1}
particle emission factor (PEF)	1.36 × 10^9 m^3 kg^{-1}	1.36 × 10^9 m^3 kg^{-1}
Ingestion reference dose ($RfD_{Ingestion}$)	0.001(Cd), 0.02(Ni), 0.0014(Pb), 0.14(Mn) mg/kg/day	
Inhalation reference dose ($RfD_{Inhalation}$)	0.001(Cd), 0.0206(Ni), 0.00352(Pb), 0.14(Mn) mg/kg/day	
Dermal reference dose (RfD_{Dermal})	0.000025(Cd), 0.0054(Ni), 0.000524(Pb), 0.0018(Mn) mg/kg/day	
Ingestion carcinogenic slope factor ($CSF_{Ingestion}$)	6.3(Cd), 1.7(Ni), 0.0085(Pb) $(mg/kg/day)^{-1}$	
Inhalation carcinogenic slope factor ($CSF_{Inhalation}$)	6.3(Cd), 9.8(Ni), 0.042(Pb) $(mg/kg/day)^{-1}$	
Dermal carcinogenic slope factor (CSF_{Dermal})	6.3(Cd), 40.25(Ni), 0.0085(Pb) $(mg/kg/day)^{-1}$	

Non-carcinogenic risk

The non-carcinogenic health risk of a substance is determined by estimating the likelihood of adverse health effects at a specific dosage within a specific timeframe using the hazard quotient and hazard index. The hazard quotient (HQ) is referred to as the quotient of ADI divided by the chronic reference dose (RfD) of a certain heavy metal in mg/kg/day (Table 1). The potential hazard quotient (HQ) for each metal was calculated by using the following equation [33]:

$$HQ = \frac{ADI}{RfD}$$

If HQ < 1, it means that there are no adverse health consequences, whereas HQ > 1 suggests that there are probably harms [29]. The population's non-carcinogenic response to a certain number of heavy metals is the total of all the HQs caused by each heavy metal. This is regarded as a different word known as the Hazard Index HI [34]. It is calculated as follows:

$$HI = \sum_{i=1}^{n} (HQ)$$

The value of HI≤1 indicates that there is no significant risk of non-carcinogenic effects. On the other hand, there is a chance that non-carcinogenic effects may occur when HI>1, and the probability increases as the value of the HI increases [35].

Carcinogenic risk index

Carcinogen risks are computed as the incremental probability that a person would get cancer during their lifetime as a result of exposure to the probable carcinogen [39]. It is computed as:

$$(CR) = AD\ I * CSF$$

Where (CR) is the unitless probability of an individual contracting cancer during their lifetime. ADI (mg/kg/day) and CSF (mg/kg/day) represent the average daily intake and cancer slope factor (Table 1), respectively. The carcinogenic slope factor (CSF) indicates the maximum probable carcinogenic risk in an individual exposed to a specific carcinogenic substance dose.

A total cancer risk (TCR) was calculated by the sum of CR from all carcinogens in the studied soils as follows:

$$Risk_{(total)}\ (TCR) = Risk_{(ing)} + Risk_{(inh)} + Risk_{(dermal)}$$

Where $Risk_{(ing)}$, $Risk_{(inh)}$, and $Risk_{(dermal)}$ are risk contributions through ingestion, inhalation, and dermal pathways, respectively. The USEPA recommends risk values less than 1.00E-06 are regarded as negligible, whereas a risk exceeding 1.00E-04 is likely to be harmful to human health. If the 1.00E-06 < TCR < 1.00E-04, the cancer risk is acceptable[40].

Data analysis

For statistical analysis, the study used SPSS version 27.0. Descriptive statistics including mean, median, mode, standard deviation, range, minimum, maximum, kurtosis, skewness, and quartiles were calculated. A Pearson correlation coefficient matrix was calculated to identify the strength of relationships among the investigated metals in the soil of the Eastern Fayoum region. The study considered the correlations to be significant at $P < 0.01$ and $P < 0.05$.

Results and discussion

concentrations of heavy metals in soil samples

The descriptive summary statistics (mg kg^{-1}) of the investigated HMs (Cd, Ni, Pb, and Mn) that were analyzed in soil samples collected from the different sites in the East of Fayoum Governorate are presented in Table 2. The results show that the mean concentrations of the examined HMs followed the order: Mn (350.34 mg kg^{-1}) > Pb (207.39 mg kg^{-1}) > Ni (78.48 mg kg^{-1}) > Cd (14.25 mg kg^{-1}). These results were emphasized by the results of El-Bady and Metwally [41] in the Nile Delta of Egypt and Peris et al. [42] in Spain. Mn and Cd recorded the highest and lowest average concentrations in agricultural soils among the studied HMs, respectively. These metals may be enriched in the surface soil for various reasons, including metal deposits, human contamination, and additional natural agricultural sources.

Total Ni concentrations in soil samples ranged from 43.40 to 102.20 mg kg^{-1}. The soils of Fayoum District had total Ni concentrations ranging from 5 to 489.5, with a mean value of 93.51 mg kg^{-1} [43]. Consequently, nickel concentrations in the East of Fayoum Governorate soils are almost similar to the levels of the above-mentioned results. Numerous natural sources and human activity contribute to the distribution of nickel in the environment, including the air, soil, water, sediments, and so on [44].

Total Pb concentrations ranged from 151.00 to 265.00 mg kg^{-1}. Fayoum District soils have total Pb contents ranging from 3 to 45, with a mean value of 17.05 mg kg^{-1} soil [43]. Thus, the concentration of total Pb in the East of Fayoum Governorate soils recently contains greater concentrations of Pb than the previous investigation. Pb concentrations in Egypt's airborne particulate matter generally rose to levels substantially higher than WHO safety standards throughout the 1980s and early 1990s [45]. Through airborne particle attachment and redeposition, lead contamination can have an impact on distant ecosystems [46]. There are several more causes of lead contamination in the environment. The first is the gasoline's lead alkyl additives, which burned and released pollutants into the air that contaminated soil, the road, and the surrounding area. There are additional sources of lead in the atmosphere, such as manufacturing operations, coal combustion, and waste incineration [13].

Total Mn concentrations ranged from 159.27 to 657.87 mg kg^{-1}. The concentrations of Mn in different soils located at the Fayoum Governorate soils ranged between 280 and 840 mg kg^{-1} [47]. The data from the present study indicates that the Mn concentration in the investigated soils is similar to that of the above-mentioned previous investigation.

Table 2. Descriptive statistics of total concentrations (mg kg^{-1}) of the investigated heavy metals in soil samples and their reference values.

Parameters		Cadmium	Nickel	Lead	Manganese
Mean		14.25±0.62	78.48±1.88	207.40±4.22	350.35±21.11
Median		14.46	79.40	208.67	290.00
Mode		11.60 [a]	68.17[a]	151.00[a]	195.07[a]
Std. Deviation		4.22	12.66	28.35	141.62
Skewness		0.92±0.35	- 0.60±0.35	0.13±0.35	0.80±0.35
Kurtosis		1.573	0.21	-0.38	-0.60
Range		19.30	58.80	114.00	498.60
Minimum		6.97	43.40	151.00	159.27
Maximum		26.27	102.20	265.00	657.87
Percentiles	25	11.60	68.87	188.52	245.53
	50	14.46	79.40	208.67	290.00
	75	15.28	88.60	226.80	470.05
Upper continental crust[b]		0.098	20	20	600
Uncontaminated Egyptian soils[c]		0.3	41	18	513
FAO [d]		3	75	100	400

[a]Multiple modes exist. The smallest value is shown, [b] [48], [c] [22, 49], [d] [50]

Correlation analysis

Table 3 depicts Pearson correlation coefficients for Cd, Ni, Pb, and Mn values in the East of Fayoum Governorate agricultural soils. The matrix illustrates the strength and magnitude of the relationship between each metal pair found in the East of Fayoum Governorate's soils. In the present study, Pearson's correlation coefficients of elemental pairs Cd-Ni (0.299), Cd-Pb (0.409), and Ni-Pb (0.385) implied that a significant positive correlation was found among Cd, Ni, and Pb. Like previous research that found a high correlation between metals, it indicated that they probably share the same source [51, 52]. Our results also suggested a similar anthropogenic source for Cd, Ni, and Pb metals. The relationship between HMs in the soil is usually due to parent material, the influence of pedogenic processes, and the effect of human activities [8]. Mn had an inapparent correlation with Cd and Pb, which suggested a great variability among the sources of origin. Conversely, Mn had a positive correlation with Ni (0.587).

Table 3. Pearson's correlation coefficient (P.C) of HMs concentration in studied soil.

HMs	P.C	Cadmium	Nickel	Lead	Manganese
Cadmium	P.C	1			
	Sig. (2-tailed)				
Nickel	P.C	0.30*	1		
	Sig. (2-tailed)	0.05			
Lead	P.C	0.41**	0.39**	1	
	Sig. (2-tailed)	0.01	0.01		
Manganese	P.C	-0.12	0.59**	-0.06	1
	Sig. (2-tailed)	0.44	0.00	0.70	

**Correlation is significant at the 0.01 level (2-tailed). *Correlation is significant at the 0.05 level (2-tailed).

Soil contamination and Risk assessment

Contamination factor (CF); the mean CF values of HMs were recognized in the following order: Cd > Pb > Ni > Mn. According to the concentration of HMs in the upper continental crust (Fig. 2(a)). The mean CF values for Cd (138.56) and Pb (10.29) indicated a very high contamination level (CF > 6). The mean CF values for Mn (0.58) and Ni (3.92) showed a low (CF < 1) and considerable (3 < CF < 6) contamination level, respectively. The contamination factor values for Cd, Ni, and Mn show minor similarity with the soil of Bahr El Baqar in the Eastern Nile Delta [53]. The results of CF according to the concentration of HMs in uncontaminated Egyptian soils are presented in Fig. 2(b). The mean CF values for Cd (45.26) and Pb (11.43) indicated a very high contamination level. Conversely, the mean (CF) values for Mn (0.68) and Ni (1.91) pointed to a low and moderate contamination level, respectively. The soil samples showed very high contamination with Cd and Pb, while they showed moderate contamination with Ni. Nevertheless, most of the studied soil samples showed low contamination of Mn.

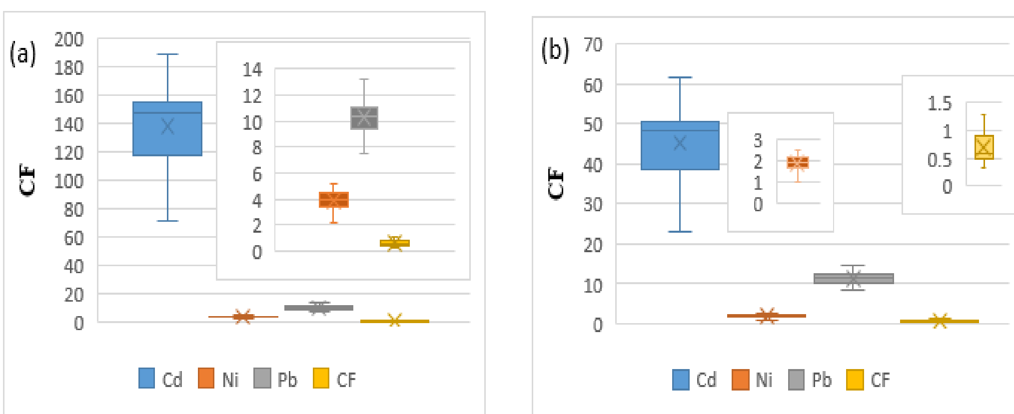

Fig. *2*. (a) Box-plot of contamination factor (CF) for the studied HMs using UCC as reference value; (b) Box-plot of contamination factor (CF) for the studied HMs using UCES as reference value.

Ecological risk factor (Er_i); The ecological risk factor (Er_i) illustrates the risk associated with each heavy metal in an area. Er_i increment for each metal will depend on which site has a higher CF. The mean heavy metal's ecological risk followed the trend as Cd > Pb > Ni > Mn. Fig. 3(a) summarizes the results for Er_i calculation according to the concentration of HMs in the upper continental crust. The mean Er_i values for Pb (51.45) and Cd (4156.81) indicated moderate ($40 \le Er_i < 80$) and very high ($Er_i \ge 320$) ecological risk, respectively. On the other hand, the mean Er_i values for Ni (19.62) and Mn (5.83) pointed to low ecological risk ($Er_i < 40$). According to the concentration of HMs in uncontaminated Egyptian soils, the results of Er_i for studied HMs are presented in Fig. 3(b). The mean Er_i values for Pb (57.17) and Cd (1357.89) indicated moderate and very high ecological risk, respectively. The mean Er_i values for Ni (9.57) and Mn (6.82) pointed to low ecological risk. The soil samples showed very high ecological risk by Cd in all the study sites, while they ranged from low to moderate ecological risk with Pb and had low ecological risk with Ni and Mn. The very high ecological risk of Cd may be due to its very high concentrations compared with its background value and its high toxic-response value.

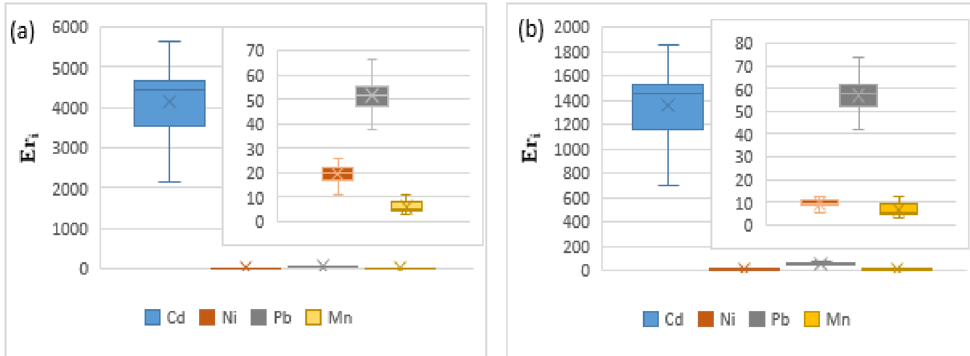

Fig. 3. (a) Box-plot of ecological risk (Er_i) for the studied HMs using UCC as reference value; (b) Box-plot of ecological risk (Er_i) for the studied HMs using UCES as reference value.

Enrichment factor (EF); the enrichment factor is an effective way to identify metals from natural and man-made sources. The mean EF values of HMs decreased in the following order: Cd > Pb > Ni. Fig. 4(a) summarizes the results for EF calculation according to the concentration of HMs in the upper continental crust. The mean EF value for Cd (275.22) indicated an extreme enrichment (EF > 40), while the mean EF value for Pb (20.39) showed a very high enrichment (20≤ EF <40). On the other hand, the mean EF value for Ni (7.52) pointed to significant enrichment (5≤ EF <20). The soil samples show extreme enrichment by Cd in all the study sites. They ranged from significant to very high enrichment with Pb and from moderate to significant enrichment with Ni. Thus, these HMs are possibly derived from anthropogenic activities. In calculating the enrichment factor according to the concentration of HMs in uncontaminated Egyptian soils, the results are presented in Fig. 4(b). The mean EF value for Cd (76.86) indicated an extreme enrichment. The mean EF values for Pb (19.37) showed a significant enrichment. On the other hand, the mean EF value for Ni (3.13) pointed to moderate enrichment. The soil samples fluctuated between very high and extreme enrichment with Cd. They fluctuated between significant and very high with Pb and ranged from depletion (minimal) to moderate with Ni. Consequently, the HMs are possibly derived from anthropogenic activities in general.

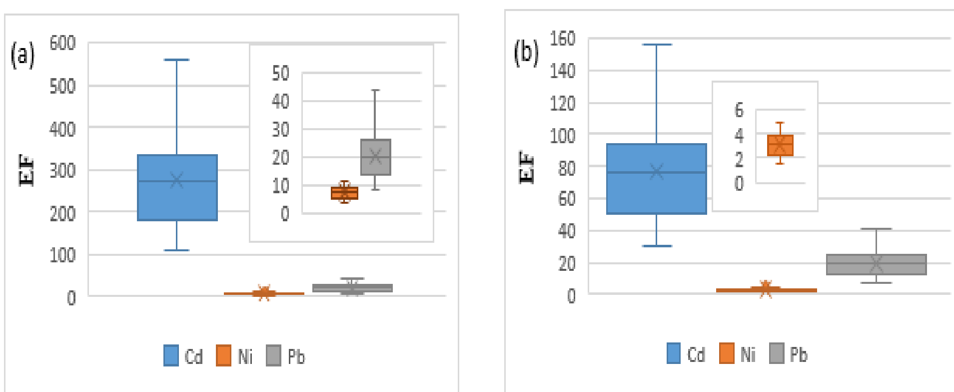

Fig. 4. (a) Box-plot of enrichment factor (EF) for the studied HMs using UCC as reference value; (b) Box-plot of enrichment factor (EF) for the studied HMs using UCES as reference value.

Degree of contamination (DC); Fig. 5(a) shows DC for HMs according to the concentration of HMs in the upper continental crust in the study area. The DC ranged from 68.20 to 232.77 with a mean value of 153.36. While the results of DC for studied HMs according to the concentration of HMs in uncontaminated Egyptian soils are presented in Fig. 5(b). The DC ranged from 37.28 to 82.92 with a mean value of 59.29. The degree of contamination values characterizes high contamination for all of the Eastern part of Fayoum depression soils, reflecting the changes in soil occupation and the intensity of man-made activities. The high degree of contamination comes from the high contamination with Cd and Pb rather than Ni and Mn.

The potential ecological risk index (RI); potential ecological risk index (RI) quantifies and reflects the sensitivity of the environment to combined HMs. The RI values according to the concentration of HMs in the upper continental crust are presented in Fig. 6(a). It varied between 2211.03 and 6694.13 with a mean value of 4233.73. Furthermore, the results of the RI for the studied HMs according to the concentration of HMs in uncontaminated Egyptian soils are presented in Fig. 6(b). It varied between 772.25 and 2223.05 with a mean value of 1431.46. Consequently, the East of Fayoum environment is subjected ecologically to a high risk. This high potential ecological risk was attributed to Cd, followed by Pb pollution.

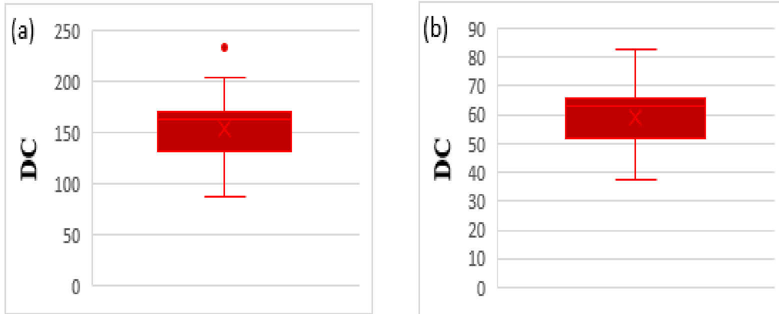

Fig. *5*. (a) Box-plot of degree of contamination for the studied HMs using UCC as reference value; (b) Box-plot of degree of contamination for the studied HMs using UCES as reference value.

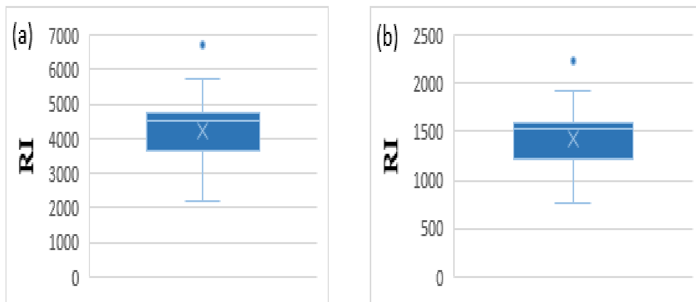

Fig. *6*. (a) Box-plot of potential ecological risk for the studied HMs using UCC as reference value; (b) Box-plot of potential ecological risk for the studied HMs using UCES as reference value.

3.4. Human Health Risk Assessment

In terms of human health risk assessment, investigating potential exposure pathways for HMs is valuable in demonstrating the cumulative impacts of contaminants over a lifetime. Tables (S1, S2, S3, and S4) display the average daily intake (ADI) of the metals under investigation by both adults and children through the three routes under investigation (ingestion, inhalation, and skin contact). The exposure pathways for children and adults were arranged as follows: ingestion > dermal contact > inhalation. These results could relate to the main food consumed in the Fayoum region, such as fish, vegetables, fruits, and bread, being contaminated with ambient dust, water, and soil that contains HMs. This result was in line with the outcomes of Mohammed et al. [36]. In addition, adults were exposed to a lower percentage of average daily doses of metals than children due to eating food with hands contaminated with dust and playing in gardens that may contain large amounts of metals. The other reasons were their behavioral and physiological characteristics, e.g., hand-to-mouth activities with soils, higher respiratory rates per unit body weight, and increased gastrointestinal absorption of some substances [54].

Non-carcinogenic risks; the hazard quotient (HQ) and hazard index (HI) of different exposure pathways for HMs (Cd, Ni, Pb, and Mn) in investigated soil in the study regions were assessed as shown in tables (S5, S6, S7, and S8). It was noticed that the values of HQ_{ing} > HQ_{der} > HQ_{inh} for both adults and children. The mean simulated total HQ for the studied HMs in soils decreased in the following order: Pb > Cd > Ni > Mn for both age groups. The results showed that the HQ values for each heavy metal in soil samples were less than 1 for exposure through inhalation and dermal contact pathways for adults and children, indicating no obvious risk. Also, the HQ values for (Cd, Ni, and Mn) in soil samples were less than 1 for exposure through the ingestion pathway for adults and children and Pb for only adults, indicating no obvious risk [55]. However, the HQ values for ingestion of Pb by children were higher than 1, which indicated a moderate or high risk of adverse effects in children. The maximum values of QH were equal to 2.31E-01 for adults and 2.16E+00 for children resulting from ingestion of Pb in the study area at site 18. The minimum values of QH were equal to 1.27E-07 for adults and 2.29E-07 for children resulting from inhalation of Mn in the study area at site 4. As shown in Fig. 7(a), the total hazard index (HI_{total}) ranged between 1.61E-01 and 2.69E-01 for adults and between 1.49E+00 and 2.48E+00 for children. In turn, the HI_{total} values of soil HMs in each sampling site were lower than 1 for adults, which indicates that there were no non-carcinogenic risks for adults in these sites. On the other hand, the total risk value in children was higher than in adults and the safe limit of one, indicating that children may be exposed to non-carcinogenic risks (HI>1). The HI value of HMs for children is much higher than for adults, and similar observations have been reported in other places [56]. Children are more susceptible to non-carcinogenic risks due to their low toxicity tolerance and inadvertent oral pathway intake of significant amounts of soil [57].

Carcinogenic risks; tables (S9, S10, and S11) summarize the calculated carcinogenic risk values posed by Cd, Ni, and Pb to adults and children from East of Fayoum surface soil samples through soil ingestion, inhalation, and dermal contact. With respect to the pathway, CR values followed the pattern: ingestion > dermal contact > inhalation. Results of the current study showed that, in both adults and children, the calculated carcinogenic risk (CR) values for each metal followed the ranking order of Ni > Cd > Pb via the three pathways. Generally, the CR values of Cd and Pb for adults and children are between 1.00E-04 and 1.00E-06. This finding suggests that the carcinogenic risk of exposure to Cd and Pb in soils may be acceptable. However, the CR values for Ni range between 1.00E-04 and 1.00E-06 for some sites and more than 1.00E-04 for adults and children. Consequently, adults and children may be subjected to an acceptable carcinogenic effect or may pose a more significant carcinogenic threat to human health from Ni. Compared to children, the carcinogenic risk for adults due to heavy metal exposure from soil is lower. Collectively, the total cancer risk ranged between 8.84E-05 and 1.77E-

04 for adults and between 1.38E-04 and 2.75E-04 for children (Fig. 7(b) and Table S12). Hence, TCR values in adults and children were more than 1.00E-04. These values exceeded the safe limit, indicating that East Fayoum residents suffer from carcinogenic risks.

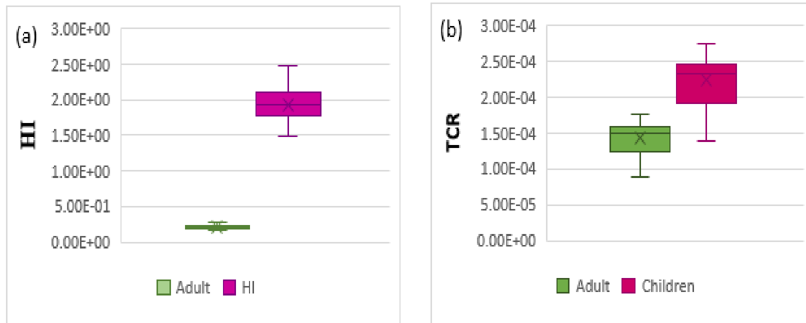

Fig. 7. (a) Box-plot of hazard index HI values for total non-carcinogenic health risk by the studied HMs; (b) Box-plot of total carcinogenic risk values for total carcinogenic health risk by the studied HMs.

4. Conclusions

Heavy metals in agricultural soils can have both geogenic and anthropogenic sources. In this study, the mean concentrations of the studied HMs in soil samples were higher than their corresponding background concentrations. According to the evaluation indices, Cd was found to have the highest levels of pollution and ecological concerns, followed by Pb enrichment. Although Ni fluctuated from moderate to considerable contamination, it showed low potential ecological risk due to the low toxic response value of Ni. On the other hand, Mn exhibited a low degree of contamination and potential ecological risk. The determined EF revealed that Cd, Ni, and Pb were possibly derived from anthropogenic activities. The pollution due to Mn was negligible in the study area, indicating that it had a geogenic origin. The HI values for adults exposed to the four studied HMs ranged between 1.61E-01 and 2.69E-01 (HI < 1), indicating no non-carcinogenic hazard. Conversely, the HI values for children exposed to the four studied HMs ranged between 1.49E+00 and 2.48E+00 (HI > 1), indicating a non-carcinogenic hazard. The carcinogenic risk of Cd, Ni, and Pb metals ranged between 8.84E-05 and 1.77E-04 for adults and between 1.38E-04 and 2.75E-04 for children (TCR > 1.00E-04), expecting significant carcinogenic health risks to adults and children in the study area. The study recommends preventing further Cd and Pb contamination in the Eastern part of Fayoum depression and conducting regular environmental monitoring.

Supplementary Materials

The following supporting information can be downloaded online

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Author Contributions

All authors contributed to this work. N. Reda prepared the samples and completed the experimental measurements. Both S. Amin and N. Rada shared writing and followed the performance of the experiments. A. abdel-Hafeez helped the first author complete the sample preparation. S. Amin with T. Radwan completed the paper writing, analyzing the data, and validation. S. Amin followed the revision and submission of the manuscript for publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendices:

Table S1. Descriptive statistics of average daily intake (ADI) via ingestion, inhalation, and dermal pathways of cadmium and nickel for adults and children [non-carcinogenic risk]

Parameter	Cadmium						Nickel					
	ADI_{ing}		ADI_{inh}		ADI_{der}		ADI_{ing}		ADI_{inh}		ADI_{der}	
	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children
Mean	1.66E-05	1.55E-04	1.52E-09	2.73E-09	6.85E-08	3.67E-07	9.58E-05	8.94E-04	8.79E-09	1.58E-08	4.05E-07	2.12E-06
Median	1.77E-05	1.65E-04	1.62E-09	2.91E-09	7.44E-08	3.91E-07	9.70E-05	9.05E-04	8.90E-09	1.60E-08	4.09E-07	2.15E-06
Mode	1.42E-05 [a]	1.32E-04 [a]	1.30E-09 [a]	2.33E-09 [a]	5.98E-08 [a]	3.14E-07 [a]	8.32E-05 [a]	7.77E-04 [a]	7.64E-09 [a]	1.37E-08 [a]	3.51E-07 [a]	1.84E-06 [a]
Std. deviation	3.70E-06	3.45E-05	3.39E-10	6.09E-10	1.86E-08	8.18E-08	1.55E-05	1.44E-04	1.42E-09	2.55E-09	6.53E-08	3.42E-07
Skewness	-2.23E-01	-2.23E-01	-2.23E-01	-2.23E-01	-1.12E+00	-2.23E-01	-6.04E-01	-6.04E-01	-6.04E-01	-6.04E-01	-6.04E-01	-6.04E-01
Kurtosis	4.64E-01	4.64E-01	4.64E-01	4.64E-01	3.27E+00	4.64E-01	2.07E-01	2.07E-01	2.07E-01	2.07E-01	2.07E-01	2.07E-01
Range	1.80E-05	1.68E-04	1.65E-09	2.96E-09	1.12E-07	3.98E-07	7.18E-05	6.70E-04	6.59E-09	1.18E-08	3.03E-07	1.59E-06
Minimum	8.51E-06	7.94E-05	7.81E-10	1.40E-09	3.59E-08	1.88E-07	5.30E-05	4.95E-04	4.86E-09	8.73E-09	2.24E-07	1.17E-06
Maximum	2.65E-05	2.47E-04	2.43E-09	4.36E-09	1.12E-07	5.86E-07	1.25E-04	1.16E-03	1.15E-08	2.06E-08	5.27E-07	2.76E-06
Percentiles 25	1.42E-05	1.32E-04	1.30E-09	2.33E-09	5.96E-08	3.14E-07	8.41E-05	7.85E-04	7.72E-09	1.39E-08	3.55E-07	1.86E-06
Percentiles 50	1.77E-05	1.65E-04	1.62E-09	2.91E-09	7.44E-08	3.91E-07	9.70E-05	9.05E-04	8.90E-09	1.60E-08	4.09E-07	2.15E-06
Percentiles 75	1.86E-05	1.73E-04	1.70E-09	3.06E-09	7.83E-08	4.11E-07	1.08E-04	1.01E-03	9.93E-09	1.78E-08	4.57E-07	2.40E-06

[a] Multiple modes exist. The smallest value is shown

Table S2. Descriptive statistics of average daily intake (ADI) via ingestion, inhalation, and dermal pathways of lead and manganese for adults and children [non- carcinogenic risk]

Parameter	Lead						Manganese					
	ADI_{ing}		ADI_{inh}		ADI_{der}		ADI_{ing}		ADI_{inh}		ADI_{der}	
	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children
Mean	2.51E-04	2.35E-03	2.31E-08	4.14E-08	1.06E-06	5.57E-06	4.28E-04	3.99E-03	3.93E-08	7.05E-08	1.81E-06	9.48E-06
Median	2.53E-04	2.36E-03	2.32E-08	4.17E-08	1.07E-06	5.61E-06	3.54E-04	3.31E-03	3.25E-08	5.83E-08	1.50E-06	7.84E-06
Mode	1.84E-04 [a]	1.72E-03 [a]	1.69E-08 [a]	3.04E-08 [a]	7.79E-07 [a]	4.08E-06 [a]	2.38E-04 [a]	2.22E-03 [a]	2.19E-08 [a]	3.92E-08 [a]	1.01E-06 [a]	5.28E-06 [a]
Std. deviation	3.37E-05	3.14E-04	3.09E-09	5.55E-09	1.42E-07	7.46E-07	1.73E-04	1.61E-03	1.59E-08	2.85E-08	7.30E-07	3.83E-06
Skewness	1.78E-01	1.78E-01	1.78E-01	1.78E-01	1.78E-01	1.78E-01	7.95E-01	7.95E-01	7.95E-01	7.95E-01	7.95E-01	7.95E-01
Kurtosis	-2.47E-01	-2.47E-01	-2.47E-01	-2.47E-01	-2.47E-01	-2.47E-01	-5.99E-01	-5.99E-01	-5.99E-01	-5.99E-01	-5.99E-01	-5.99E-01
Range	1.39E-04	1.30E-03	1.28E-08	2.29E-08	5.88E-07	3.08E-06	6.09E-04	5.68E-03	5.59E-08	1.00E-07	2.57E-06	1.35E-05
Minimum	1.84E-04	1.72E-03	1.69E-08	3.04E-08	7.79E-07	4.08E-06	1.94E-04	1.82E-03	1.78E-08	3.20E-08	8.21E-07	4.31E-06
Maximum	3.24E-04	3.02E-03	2.97E-08	5.33E-08	1.37E-06	7.17E-06	8.03E-04	7.50E-03	7.37E-08	1.32E-07	3.39E-06	1.78E-05
Percentiles 25	2.29E-04	2.13E-03	2.10E-08	3.76E-08	9.65E-07	5.06E-06	3.00E-04	2.80E-03	2.75E-08	4.94E-08	1.27E-06	6.64E-06
Percentiles 50	2.53E-04	2.36E-03	2.32E-08	4.17E-08	1.07E-06	5.61E-06	3.54E-04	3.31E-03	3.25E-08	5.83E-08	1.50E-06	7.84E-06
Percentiles 75	2.71E-04	2.53E-03	2.49E-08	4.47E-08	1.15E-06	6.01E-06	5.74E-04	5.36E-03	5.27E-08	9.45E-08	2.42E-06	1.27E-05

[a] Multiple modes exist. The smallest value is shown

Table S3. Descriptive statistics of average daily intake (ADI) via ingestion, inhalation, and dermal pathways of cadmium and nickel for adults and children [carcinogenic risk]

Parameter		Cadmium						Nickel					
		ADI ing		ADI inh		ADI der		ADI ing		ADI inh		ADI der	
		Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children
Mean		8.29E-06	1.33E-05	7.61E-10	2.34E-10	3.50E-08	3.15E-08	4.79E-05	7.67E-05	4.40E-09	1.35E-09	2.02E-07	1.82E-07
Median		8.83E-06	1.41E-05	8.10E-10	2.49E-10	3.73E-08	3.35E-08	4.85E-05	7.76E-05	4.45E-09	1.37E-09	2.05E-07	1.84E-07
Mode		7.08E-06 [a]	1.13E-05 [a]	6.50E-10 [a]	2.00E-10 [a]	2.99E-08 [a]	2.69E-08 [a]	4.16E-05 [a]	6.66E-05 [a]	3.82E-09 [a]	1.18E-09 [a]	1.76E-07 [a]	1.58E-07 [a]
Std. deviation		1.85E-06	2.96E-06	1.70E-10	5.22E-11	7.80E-09	7.01E-09	7.73E-06	1.24E-05	7.09E-10	2.18E-10	3.26E-08	2.93E-08
Skewness		-2.23E-01	-2.23E-01	-2.23E-01	-2.23E-01	-2.23E-01	-2.23E-01	-6.04E-01	-6.04E-01	-6.04E-01	-6.04E-01	-6.04E-01	-6.04E-01
Kurtosis		4.64E-01	4.64E-01	4.64E-01	4.64E-01	4.64E-01	4.64E-01	2.07E-01	2.07E-01	2.07E-01	2.07E-01	2.07E-01	2.07E-01
Range		8.98E-06	1.44E-05	8.24E-10	2.53E-10	3.79E-08	3.41E-08	3.59E-05	5.74E-05	3.29E-09	1.01E-09	1.52E-07	1.36E-07
Minimum		4.25E-06	6.81E-06	3.90E-10	1.20E-10	1.80E-08	1.62E-08	2.65E-05	4.24E-05	2.43E-09	7.48E-10	1.12E-07	1.01E-07
Maximum		1.32E-05	2.12E-05	1.21E-09	3.74E-10	5.59E-08	5.02E-08	6.24E-05	9.98E-05	5.73E-09	1.76E-09	2.63E-07	2.37E-07
Percentiles	25	7.08E-06	1.13E-05	6.50E-10	2.00E-10	2.99E-08	2.69E-08	4.20E-05	6.73E-05	3.86E-09	1.19E-09	1.78E-07	1.60E-07
	50	8.83E-06	1.41E-05	8.10E-10	2.49E-10	3.73E-08	3.35E-08	4.85E-05	7.76E-05	4.45E-09	1.37E-09	2.05E-07	1.84E-07
	75	9.28E-06	1.48E-05	8.52E-10	2.62E-10	3.92E-08	3.52E-08	5.41E-05	8.66E-05	4.96E-09	1.53E-09	2.28E-07	2.05E-07

[a] Multiple modes exist. The smallest value is shown

Table S4. Descriptive statistics of average daily intake (ADI) via ingestion, inhalation, and dermal pathways of lead for adults and children [carcinogenic risk]

Parameter		Lead					
		ADI ing		ADI inh		ADI der	
		Adult	Children	Adult	Children	Adult	Children
Mean		1.26E-04	2.01E-04	1.15E-08	3.55E-09	5.31E-07	4.77E-07
Median		1.27E-04	2.03E-04	1.16E-08	3.57E-09	5.35E-07	4.81E-07
Mode		9.22E-05 [a]	1.48E-04 [a]	8.46E-09 [a]	2.60E-09 [a]	3.89E-07 [a]	3.50E-07 [a]
Std. deviation		1.68E-05	2.69E-05	1.55E-09	4.75E-10	7.11E-08	6.39E-08
Skewness		1.78E-01	1.78E-01	1.78E-01	1.78E-01	1.78E-01	1.78E-01
Kurtosis		-2.47E-01	-2.47E-01	-2.47E-01	-2.47E-01	-2.47E-01	-2.47E-01
Range		6.96E-05	1.11E-04	6.39E-09	1.97E-09	2.94E-07	2.64E-07
Minimum		9.22E-05	1.48E-04	8.46E-09	2.60E-09	3.89E-07	3.50E-07
Maximum		1.62E-04	2.59E-04	1.48E-08	4.57E-09	6.83E-07	6.14E-07
Percentiles	25	1.14E-04	1.83E-04	1.05E-08	3.23E-09	4.83E-07	4.34E-07
	50	1.27E-04	2.03E-04	1.16E-08	3.57E-09	5.35E-07	4.81E-07
	75	1.36E-04	2.17E-04	1.24E-08	3.83E-09	5.73E-07	5.15E-07

[a] Multiple modes exist. The smallest value is shown

Table S5. Descriptive statistics of Hazard Quotient via ingestion, inhalation and dermal pathways of Cadmium for adults & children

Parameter		Hazard Quotient$_{ing}$		Hazard Quotient$_{inh}$		Hazard Quotient$_{der}$		Total Hazard Quotient	
		Adult	Children	Adult	Children	Adult	Children	Adult	Children
Mean		1.66E-02	1.55E-01	1.52E-06	2.73E-06	2.80E-03	1.47E-02	1.94E-02	1.69E-01
Median		1.77E-02	1.65E-01	1.62E-06	2.91E-06	2.98E-03	1.56E-02	2.06E-02	1.80E-01
Mode		1.42E-02 [a]	1.32E-01 [a]	1.30E-06 [a]	2.33E-06 [a]	2.39E-03 [a]	1.25E-02 [a]	1.66E-02 [a]	1.45E-01 [a]
Std. deviation		3.70E-03	3.45E-02	3.39E-07	6.09E-07	6.24E-04	3.27E-03	4.32E-03	3.78E-02
Skewness		-2.23E-01	-2.23E-01	-2.23E-01	-2.23E-01	-2.23E-01	-2.23E-01	-2.23E-01	-2.23E-01
Kurtosis		4.64E-01	4.64E-01	4.64E-01	4.64E-01	4.64E-01	4.64E-01	4.64E-01	4.64E-01
Range		1.80E-02	1.68E-01	1.65E-06	2.96E-06	3.03E-03	1.59E-02	2.10E-02	1.83E-01
Minimum		8.51E-03	7.94E-02	7.81E-07	1.40E-06	1.44E-03	7.54E-03	9.95E-03	8.69E-02
Maximum		2.65E-02	2.47E-01	2.43E-06	4.36E-06	4.47E-03	2.34E-02	3.09E-02	2.70E-01
Percentiles	25	1.42E-02	1.32E-01	1.30E-06	2.33E-06	2.39E-03	1.25E-02	1.66E-02	1.45E-01
	50	1.77E-02	1.65E-01	1.62E-06	2.91E-06	2.98E-03	1.56E-02	2.06E-02	1.80E-01
	75	1.86E-02	1.73E-01	1.70E-06	3.06E-06	3.13E-03	1.64E-02	2.17E-02	1.90E-01

[a] Multiple modes exist. The smallest value is shown

Table S6. Descriptive statistics of Hazard Quotient via ingestion, inhalation and dermal pathways of Ni for adults and children

Parameter		Hazard Quotient$_{ing}$		Hazard Quotient$_{inh}$		Hazard Quotient$_{der}$		Total Hazard Quotient	
		Adult	Children	Adult	Children	Adult	Children	Adult	Children
Mean		4.79E-03	4.47E-02	4.27E-07	7.66E-07	7.49E-05	3.93E-04	4.87E-03	4.51E-02
Median		4.85E-03	4.52E-02	4.32E-07	7.75E-07	7.58E-05	3.98E-04	4.92E-03	4.56E-02
Mode		4.16E-03 [a]	3.88E-02 [a]	3.71E-07 [a]	6.66E-07 [a]	6.51E-05 [a]	3.41E-04 [a]	4.23E-03 [a]	3.92E-02 [a]
Std. deviation		7.73E-04	7.21E-03	6.89E-08	1.24E-07	1.21E-05	6.34E-05	7.85E-04	7.28E-03
Skewness		-6.04E-01	-6.04E-01	-6.04E-01	-6.04E-01	-6.04E-01	-6.04E-01	-6.04E-01	-6.04E-01
Kurtosis		2.07E-01	2.07E-01	2.07E-01	2.07E-01	2.07E-01	2.07E-01	2.07E-01	2.07E-01
Range		3.59E-03	3.35E-02	3.20E-07	5.74E-07	5.61E-05	2.94E-04	3.65E-03	3.38E-02
Minimum		2.65E-03	2.47E-02	2.36E-07	4.24E-07	4.14E-05	2.17E-04	2.69E-03	2.49E-02
Maximum		6.24E-03	5.82E-02	5.56E-07	9.98E-07	9.76E-05	5.12E-04	6.34E-03	5.88E-02
Percentiles	25	4.20E-03	3.92E-02	3.75E-07	6.72E-07	6.58E-05	3.45E-04	4.27E-03	3.96E-02
	50	4.85E-03	4.52E-02	4.32E-07	7.75E-07	7.58E-05	3.98E-04	4.92E-03	4.56E-02
	75	5.41E-03	5.05E-02	4.82E-07	8.65E-07	8.46E-05	4.44E-04	5.49E-03	5.09E-02

[a] Multiple modes exist. The smallest value is shown

Table S7. Descriptive statistics of Hazard Quotient via ingestion, inhalation, and dermal pathways of Lead for adults & children

Parameter		Hazard Quotient$_{ing}$		Hazard Quotient$_{inh}$		Hazard Quotient$_{der}$		Total Hazard Quotient	
		Adult	Children	Adult	Children	Adult	Children	Adult	Children
Mean		1.80E-01	1.68E+00	6.55E-06	1.18E-05	2.03E-03	1.06E-02	1.82E-01	1.69E+00
Median		1.81E-01	1.69E+00	6.60E-06	1.18E-05	2.04E-03	1.07E-02	1.83E-01	1.70E+00
Mode		1.32E-01 [a]	1.23E+00 [a]	4.81E-06 [a]	8.63E-06 [a]	1.49E-03 [a]	7.79E-03 [a]	1.33E-01 [a]	1.24E+00 [a]
Std. deviation		2.41E-02	2.25E-01	8.78E-07	1.58E-06	2.71E-04	1.42E-03	2.43E-02	2.26E-01
Skewness		1.78E-01	1.78E-01	1.78E-01	1.78E-01	1.78E-01	1.78E-01	1.78E-01	1.78E-01
Kurtosis		-2.47E-01	-2.47E-01	-2.47E-01	-2.47E-01	-2.47E-01	-2.47E-01	-2.47E-01	-2.47E-01
Range		9.94E-02	9.28E-01	3.63E-06	6.51E-06	1.12E-03	5.88E-03	1.01E-01	9.34E-01
Minimum		1.32E-01	1.23E+00	4.81E-06	8.63E-06	1.49E-03	7.79E-03	1.33E-01	1.24E+00
Maximum		2.31E-01	2.16E+00	8.44E-06	1.51E-05	2.61E-03	1.37E-02	2.34E-01	2.17E+00
Percentiles	25	1.63E-01	1.52E+00	5.96E-06	1.07E-05	1.84E-03	9.66E-03	1.65E-01	1.53E+00
	50	1.81E-01	1.69E+00	6.60E-06	1.18E-05	2.04E-03	1.07E-02	1.83E-01	1.70E+00
	75	1.94E-01	1.81E+00	7.07E-06	1.27E-05	2.19E-03	1.15E-02	1.96E-01	1.82E+00

[a] Multiple modes exist. The smallest value is shown

Table S8. Descriptive statistics of Hazard Quotient via ingestion, inhalation, and dermal pathways of Mn for adults & children

Parameter		Hazard Quotient$_{ing}$		Hazard Quotient$_{inh}$		Hazard Quotient$_{der}$		Total Hazard Quotient	
		Adult	Children	Adult	Children	Adult	Children	Adult	Children
Mean		3.06E-03	2.85E-02	2.80E-07	5.03E-07	1.00E-03	5.26E-03	4.06E-03	3.38E-02
Median		2.53E-03	2.36E-02	2.32E-07	4.17E-07	8.31E-04	4.36E-03	3.36E-03	2.80E-02
Mode		1.70E-03 [a]	1.59E-02 [a]	1.56E-07 [a]	2.80E-07 [a]	5.59E-04 [a]	2.93E-03 [a]	2.26E-03 [a]	1.88E-02 [a]
Std. deviation		1.24E-03	1.15E-02	1.13E-07	2.03E-07	4.06E-04	2.13E-03	1.64E-03	1.37E-02
Skewness		7.95E-01	7.95E-01	7.95E-01	7.95E-01	7.95E-01	7.95E-01	7.95E-01	7.95E-01
Kurtosis		-5.99E-01	-5.99E-01	-5.99E-01	-5.99E-01	-5.99E-01	-5.99E-01	-5.99E-01	-5.99E-01
Range		4.35E-03	4.06E-02	3.99E-07	7.16E-07	1.43E-03	7.49E-03	5.78E-03	4.81E-02
Minimum		1.39E-03	1.30E-02	1.27E-07	2.29E-07	4.56E-04	2.39E-03	1.85E-03	1.54E-02
Maximum		5.74E-03	5.36E-02	5.27E-07	9.45E-07	1.88E-03	9.88E-03	7.62E-03	6.34E-02
Percentiles	25	2.14E-03	2.00E-02	1.97E-07	3.53E-07	7.03E-04	3.69E-03	2.85E-03	2.37E-02
	50	2.53E-03	2.36E-02	2.32E-07	4.17E-07	8.31E-04	4.36E-03	3.36E-03	2.80E-02
	75	4.10E-03	3.83E-02	3.76E-07	6.75E-07	1.35E-03	7.06E-03	5.45E-03	4.53E-02

[a] Multiple modes exist. The smallest value is shown

Table S9. Descriptive statistics of carcinogenic risk via ingestion, inhalation, and dermal pathways of Cd for adults & children

Parameter		Carcinogenic Risk$_{ing}$		Carcinogenic Risk$_{inh}$		Carcinogenic Risk$_{der}$		Total Risk	
		Adult	Children	Adult	Children	Adult	Children	Adult	Children
Mean		5.22E-05	8.36E-05	4.79E-09	1.47E-09	2.21E-07	1.98E-07	5.25E-05	8.38E-05
Median		5.56E-05	8.90E-05	5.10E-09	1.57E-09	2.35E-07	2.11E-07	5.59E-05	8.92E-05
Mode		4.46E-05 [a]	7.14E-05 [a]	4.09E-09 [a]	1.26E-09 [a]	1.88E-07 [a]	1.69E-07 [a]	4.48E-05 [a]	7.16E-05 [a]
Std. deviation		1.16E-05	1.86E-05	1.07E-09	3.29E-10	4.91E-08	4.42E-08	1.17E-05	1.87E-05
Skewness		-2.23E-01	-2.23E-01	-2.23E-01	-2.23E-01	-2.23E-01	-2.23E-01	-2.23E-01	-2.23E-01
Kurtosis		4.64E-01	4.64E-01	4.64E-01	4.64E-01	4.64E-01	4.64E-01	4.64E-01	4.64E-01
Range		5.66E-05	9.05E-05	5.19E-09	1.60E-09	2.39E-07	2.15E-07	5.68E-05	9.07E-05
Minimum		2.68E-05	4.29E-05	2.46E-09	7.57E-10	1.13E-07	1.02E-07	2.69E-05	4.30E-05
Maximum		8.34E-05	1.33E-04	7.65E-09	2.35E-09	3.52E-07	3.16E-07	8.37E-05	1.34E-04
Percentiles	25	4.46E-05	7.14E-05	4.09E-09	1.26E-09	1.88E-07	1.69E-07	4.48E-05	7.16E-05
	50	5.56E-05	8.90E-05	5.10E-09	1.57E-09	2.35E-07	2.11E-07	5.59E-05	8.92E-05
	75	5.85E-05	9.35E-05	5.36E-09	1.65E-09	2.47E-07	2.22E-07	5.87E-05	9.38E-05

[a] Multiple modes exist. The smallest value is shown

Table S10. Descriptive statistics of carcinogenic risk via ingestion, inhalation, and dermal pathways of Ni for adults & children

Parameter		Carcinogenic $Risk_{ing}$		Carcinogenic $Risk_{inh}$		Carcinogenic $Risk_{der}$		Total Risk	
		Adult	Children	Adult	Children	Adult	Children	Adult	Children
Mean		8.15E-05	1.30E-04	4.31E-08	1.33E-08	8.14E-06	7.32E-06	8.96E-05	1.38E-04
Median		8.24E-05	1.32E-04	4.36E-08	1.34E-08	8.24E-06	7.41E-06	9.07E-05	1.39E-04
Mode		7.08E-05 [a]	1.13E-04 [a]	3.74E-08 [a]	1.15E-08 [a]	7.07E-06 [a]	6.36E-06 [a]	7.79E-05 [a]	1.20E-04 [a]
Std. deviation		1.31E-05	2.10E-05	6.95E-09	2.14E-09	1.31E-06	1.18E-06	1.45E-05	2.22E-05
Skewness		-6.04E-01	-6.04E-01	-6.04E-01	-6.04E-01	-6.04E-01	-6.04E-01	-6.04E-01	-6.04E-01
Kurtosis		2.07E-01	2.07E-01	2.07E-01	2.07E-01	2.07E-01	2.07E-01	2.07E-01	2.07E-01
Range		6.10E-05	9.77E-05	3.23E-08	9.93E-09	6.10E-06	5.49E-06	6.72E-05	1.03E-04
Minimum		4.50E-05	7.21E-05	2.38E-08	7.33E-09	4.50E-06	4.05E-06	4.96E-05	7.61E-05
Maximum		1.06E-04	1.70E-04	5.61E-08	1.73E-08	1.06E-05	9.54E-06	1.17E-04	1.79E-04
Percentiles	25	7.15E-05	1.14E-04	3.78E-08	1.16E-08	7.15E-06	6.43E-06	7.87E-05	1.21E-04
	50	8.24E-05	1.32E-04	4.36E-08	1.34E-08	8.24E-06	7.41E-06	9.07E-05	1.39E-04
	75	9.20E-05	1.47E-04	4.86E-08	1.50E-08	9.19E-06	8.27E-06	1.01E-04	1.55E-04

[a] Multiple modes exist. The smallest value is shown

Table S11. Descriptive statistics of carcinogenic risk via ingestion, inhalation, and dermal pathways of Pb for adults & children

Parameter		$Risk_{ing}$		$Risk_{inh}$		$Risk_{der}$		Total Risk	
		Adult	Children	Adult	Children	Adult	Children	Adult	Children
Mean		1.07E-06	1.71E-06	4.84E-10	1.49E-10	4.51E-09	4.06E-09	1.07E-06	1.71E-06
Median		1.08E-06	1.72E-06	4.88E-10	1.50E-10	4.54E-09	4.09E-09	1.08E-06	1.73E-06
Mode		7.84E-07 [a]	1.25E-06 [a]	3.55E-10 [a]	1.09E-10 [a]	3.31E-09 [a]	2.98E-09 [a]	7.87E-07 [a]	1.26E-06 [a]
Std. deviation		1.43E-07	2.29E-07	6.49E-11	2.00E-11	6.04E-10	5.43E-10	1.44E-07	2.30E-07
Skewness		1.78E-01	1.78E-01	1.78E-01	1.78E-01	1.78E-01	1.78E-01	1.78E-01	1.78E-01
Kurtosis		-2.47E-01	-2.47E-01	-2.47E-01	-2.47E-01	-2.47E-01	-2.47E-01	-2.47E-01	-2.47E-01
Range		5.92E-07	9.47E-07	2.68E-10	8.25E-11	2.50E-09	2.25E-09	5.94E-07	9.49E-07
Minimum		7.84E-07	1.25E-06	3.55E-10	1.09E-10	3.31E-09	2.98E-09	7.87E-07	1.26E-06
Maximum		1.38E-06	2.20E-06	6.24E-10	1.92E-10	5.81E-09	5.22E-09	1.38E-06	2.21E-06
Percentiles	25	9.71E-07	1.55E-06	4.40E-10	1.36E-10	4.10E-09	3.69E-09	9.76E-07	1.56E-06
	50	1.08E-06	1.72E-06	4.88E-10	1.50E-10	4.54E-09	4.09E-09	1.08E-06	1.73E-06
	75	1.15E-06	1.84E-06	5.23E-10	1.61E-10	4.87E-09	4.38E-09	1.16E-06	1.85E-06

[a] Multiple modes exist. The smallest value is shown

Table S12. Descriptive statistics of non-carcinogenic risk index [Hazard Index (HI)] and total Carcinogenic risk index (TCR) for adults and children

Parameter		Non-carcinogenic risk index (HI)		Carcinogenic risk index (TCR)	
		Adult	Children	Adult	Children
Mean		2.10E-01	1.93E+00	1.43E-04	2.23E-04
Median		2.08E-01	1.91E+00	1.50E-04	2.33E-04
Mode		1.61E-01 [a]	1.49E+00 [a]	8.84E-05 [a]	1.38E-04 [a]
Std. deviation		2.57E-02	2.38E-01	2.17E-05	3.39E-05
Skewness		3.64E-01	3.56E-01	-9.00E-01	-8.99E-01
Kurtosis		-3.70E-01	-3.71E-01	-2.35E-01	-2.53E-01
Range		1.07E-01	9.93E-01	8.83E-05	1.37E-04
Minimum		1.61E-01	1.49E+00	8.84E-05	1.38E-04
Maximum		2.69E-01	2.48E+00	1.77E-04	2.75E-04
Percentiles	25	1.92E-01	1.77E+00	1.23E-04	1.91E-04
	50	2.08E-01	1.91E+00	1.50E-04	2.33E-04
	75	2.27E-01	2.10E+00	1.57E-04	2.46E-04

[a] Multiple modes exist. The smallest value is shown