Research Article

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Assessment of potentially toxic elements and health risks of agricultural soil in Southwest Riyadh, Saudi Arabia

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Abstract: The rise of emerging pollutants in the environment as a result of economic growth poses a worldwide challenge for the management of environmental and human health. The objective of this study was to assess the presence of potentially toxic elements (PTEs) in the agricultural soil of southwest Riyadh, Saudi Arabia, and to evaluate the potential health risks associated with these elements. Soil samples were collected from 31 farms, and the concentrations of As, Pb, Cu, Ni, Zn, and Fe were analyzed using inductively coupled plasma-atomic emission spectrometry. Various contamination and health risk indices, along with multivariate analyses, were employed in the evaluation. The mean concentrations of PTEs (mg/kg) followed the order: Fe (15,556) > Zn (53.36) > Ni (21.78) > Cu (11.92) > Pb (10.42) > As (2.64). The average PTE concentrations were found to be lower than background levels and the world-soil average. Contamination indices indicated that the studied soil was moderately enriched and contaminated for As, slightly enriched for Zn and Ni, and not enriched for Cu and Pb. This suggests that the PTEs in the soil do not pose a significant threat, although some individual samples exhibited significant enrichment for Zn and Pb. Multivariate analyses suggested a geogenic source for the PTEs, with some contribution from anthropogenic factors for As, Zn, and Pb. The average hazard index values ranged from 0.000293 (Zn) to 0.030561 (Fe) for adults and from 0.002726541 (Zn) to 0.284670158 (Fe) for children, indicating no significant non-carcinogenic risk to the population in the study area. Additionally, the Lifetime Cancer Risk values for adults and children ranged from 6.94×10^{-6} to 6.46×10^{-5} for As and from 7.13×10^{-8} to 6.65×10^{-7} for Pb, suggesting acceptable or tolerable carcinogenic risk and no significant health hazards.

Keywords: potentially toxic elements, health risk assessment, principal component analysis, agriculture soil, Saudi Arabia

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1 Introduction

Potentially toxic elements (PTEs) encompass a group of chemical elements that, even in trace amounts, can pose significant risks to human health and the environment. These elements include As, Pb, Cd, Hg, and Cr, among others [1–3]. Cd, Hg, Pb, and Cr, in particular, demonstrate harmful effects, even in minimal quantities, leading to acute and chronic toxicities in the body [4]. Natural sources of PTEs include the geochemical background in rocks, volcanic eruptions, and windblown mineral dust [5]. Anthropogenic sources of PTEs, on the other hand, encompass airborne sources, coal ash, metals from mining, waste disposal, pesticides, inorganic fertilizers, lead-based paints, petrochemicals, and leaded gasoline, with particular significance [6–8].

Humans can be exposed to PTEs through various means, such as ingesting soil, consuming contaminated water and food crops, inhaling dust and fumes, and direct skin contact with polluted soil and water [9,10]. The toxicity of PTEs is determined by factors like the absorbed dose, exposure route, and duration of exposure [11]. The dissolved forms of PTEs, serving as pollutants in soil, water, and air, enter the food chain and can lead to significant damage to cellular systems, ultimately posing a risk of cancer development. Several PTEs such as Cr, Co, Fe, Ni, Zn, and Mn are known to be nutritionally essential and required in minimal quantities [12,13]. However, overexposure to these elements can be hazardous and lead to various serious illnesses, including kidney disorders, diabetes, irritated and ulcerated skin, neurological abnormalities, cancer, heart disease, and lung fibrosis [14,15]. According

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to reports from the International Agency for Research on Cancer, nonessential PTEs like As, Cd, and Cr are identified as major contributors to cancer [16]. To address these health risks, it is crucial for regulatory bodies, researchers, and the public to be aware of the dangers associated with PTE exposure. Implementing measures to reduce exposure, monitoring environmental pollution, and promoting safe practices in agriculture and industry are essential steps in minimizing the adverse effects of PTEs on human health.

The growing global demand for food due to population expansion has resulted in a notable increase in the consumption of vegetables cultivated in urban and suburban areas [17]. Research studies have pointed out that vegetables grown in these regions tend to accumulate higher levels of various chemical pollutants compared to those cultivated in rural areas [18]. This increased presence of pollutants is attributed to the mobilization of PTEs into the environment caused by human activities, forming a crucial component of the geochemical cycling of these elements. Monitoring and understanding the levels of PTE pollutants in urban soils are essential for assessing the potential risks to human health associated with the consumption of crops grown in these areas.

Most of the soils in Saudi Arabia are considered immature or young, primarily due to the scarcity of moisture [19]. In central region of Saudi Arabia, including the study area, the soil can be categorized into Torriorthents, Torrifluvents, and Torripsamments [20,21]. Torriorthents are shallow soils consisting of loamy sand, fine sandy loam, sandy loam, loam, or clay loam and typically form in residuum or colluvium on actively eroding slopes and in weathering-resistant materials. Torrifluvents, on the other hand, are stratified Entisols that develop in alluvial sediments from intermittent stream flooding. Torripsamments form on well-sorted sandy deposits found on stream terraces, featuring a torrid moisture regime. The objectives of this research are: (i) to quantify the presence of As, Pb, Cu, Ni, Zn, and Fe contamination in the agricultural soils of southwest Riyadh, Saudi Arabia; (ii) to compare the levels of these PTEs in the study area with those found in soils globally and under different environmental backgrounds; and (iii) to evaluate the potential health risks associated with the presence of PTEs in the examined soil.

2 Material and methods

2.1 Study area

Soil samples presently obtained originated from 31 farms situated in the southwestern region of Riyadh, central Saudi Arabia. The sampling encompassed areas such as Al Hariq, Al Mufayger, Naam, and Hawtat Bani Tamim, spanning coordinates between 23°26′11″N–23°37′51″N and 46°46′34″E–46°30′23″E (Figure 1). The examined farms feature diverse crops, including date trees (S1, S2, S5, S9, S15, S17–S19, S21, S23, S24, S26, S28, S29, S31), citrus (S3, S7, S8, S12, S16, S20, S22, S25, S30), rose (S4), clover (S6, S14), maize (S10), sidr (S11), fig (S13), and banana (S27). Groundwater irrigates 28 farms (S3–S20 and S22–S31), while treated water is used for irrigation in three farms (S1, S2, and S21). Geologically, the study area falls within the Arabian shelf, primarily composed of Triassic to Quaternary sedimentary rocks and sediments. These sedimentary facies have undergone extensive previous scrutiny in various studies [22–30].

2.2 Sampling and analytical methods

Materials were gathered from depths of less than 30 cm using a sturdy plastic hand shovel. A representative sample was generated by blending three subsamples to form a composite sample, which was then placed in plastic bags and stored in an icebox. The soil samples underwent air-drying in the laboratory at room temperature for 6 days, with the subsequent removal of large pebbles and organic particles. Physical breakdown was executed using an agate mortar and pestle, followed by size separation utilizing a series of sieves. The resultant mixture was consolidated, diluted to a volume of 12.5 mL with deionized water, and subsequently subjected to analysis.

The analysis of Fe, As, Ni, Zn, Pb, and Cu was carried out using inductively coupled plasma-atomic emission spectrometry (ICP-AES) at the ALS Geochemistry Lab in Jeddah, Saudi Arabia. A 0.50 g portion of the <63 μm fraction underwent digestion with aqua regia (a mixture composed of one mole of nitric acid and three moles of hydrochloric acid) for 45 min, in a graphite heating block. After cooling, the resulting solution is diluted to 12.5 mL with deionized water. For background and certification assessment, the ALS Geochemistry Laboratory employed a standard analytical batch that included a reagent blank. The validation of the ICP-AES method included assessing linearity, limits of detection, limits of quantification, accuracy, and precision. Calibration curves were constructed for each element by plotting the peak area of the optimum emission line against the concentration of standard solutions or spike solutions for standard addition curves. These calibration curves demonstrated excellent linearity across all elements. The relative standard deviations (%)

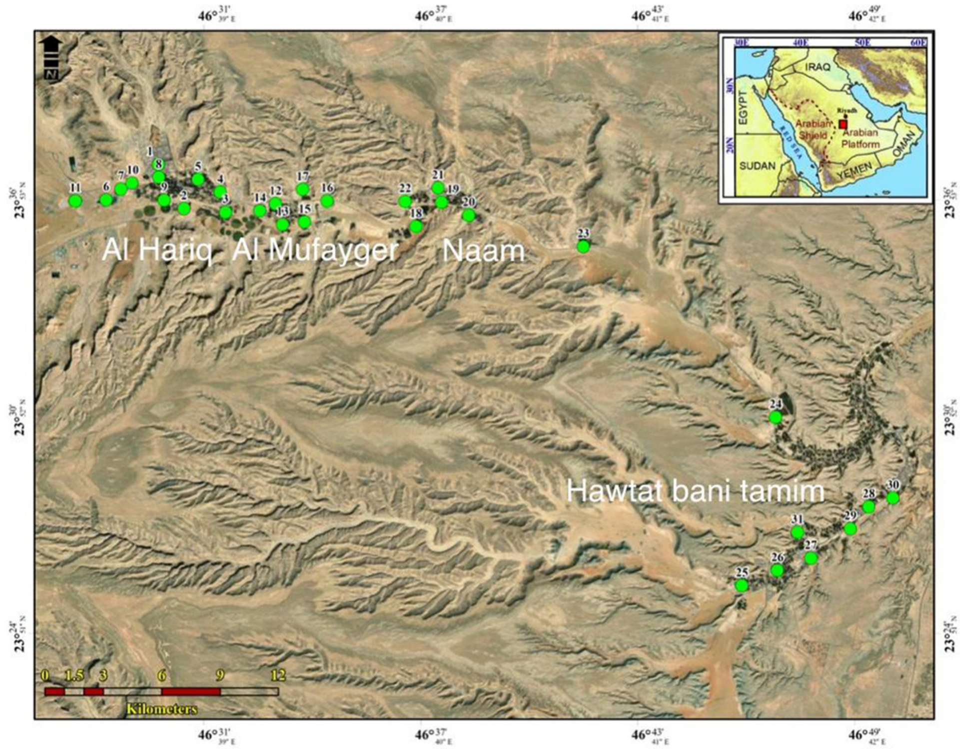

Figure 1: Location map of the study areas and sampling sites.

for all metal(loids) were found to be below 13.5%, indicating satisfactory precision [31]. Moreover, the relative recovery values (R%) fell within the range of 80–120%, confirming the accuracy of the method.

The evaluation of soil samples for PTEs included the application of both single and integrated indices. These indices comprised the enrichment factor (EF), geo-accumulation index (I_{geo}), contamination factor (CF), pollution load index (PLI), and risk index (RI), following the methodologies established by [32–35]. Equations (1)–(6) and Table S1 illustrate the calculation methods and classification of the contamination indices.

$$\text{EF} = (\text{M/Fe})\text{sample}/(\text{M/Fe})\text{background}, \tag{1}$$

$$I_{\text{geo}} = \text{Log}_2(\text{Cn}/(1.5 \times \text{Bn})), \tag{2}$$

$$\text{CF} = C_\text{o}/C_\text{b}, \tag{3}$$

$$\text{PLI} = (\text{CF}_1 \times \text{CF}_2 \times \text{CF}_3 \times \text{CF}_4 \ldots. \times \text{CF}_n)^{1/n}, \tag{4}$$

$$\text{Er}^i = \text{Tr}^i \times \text{CF}^i, \tag{5}$$

$$\text{RI} = \sum(\text{Tr}^i \times \text{CF}^i), \tag{6}$$

where (M/Fe) sample represents the ratio of metal to Fe concentrations in the sample, while (M/Fe) background signifies the ratio of metal to Fe concentrations in the Earth's crust. Cn denotes the measured concentration of metal (n) in the soils, Bn indicates the geochemical background concentration of the metal (n) in shale, and 1.5 is introduced to mitigate the effects of potential variations in the background values. Co stands for the soil metal content in the sample, and Cb represents the normal background value of the metal. CF denotes the contamination factor, Er^i indicates the potential ecological risk factor of an individual element, Tr^i represents the biological toxic response factor of an individual element, and CF^i represents the contamination factor for each single element. The toxic response factor for metals follows the order: Zn = 1, Ni = 6, Cu = Pb = 5, and As = 10.

Additionally, human health assessments were conducted using the hazard index (HI), cancer risk (CR), and total lifetime cancer risk (LCR), accounting for ingestion, dermal contact, and inhalation pathways, for both adults and children, as per guidelines provided in previous literature [36–39]. Equations (7)–(13) and Tables S2 and S3 demonstrate the health risk indices and parameters utilized in this study [36,40–42].

$$\text{CDI}_{\text{ing}} = (C_{\text{soil}} \times \text{Ing}R \times \text{EF} \times \text{ED})/(\text{BW} \times \text{AT}) \times \text{CF}, \tag{7}$$

$$\text{CDI}_{\text{inh}} = (C_{\text{soil}} \times \text{InhR} \times \text{EF}{\times}\text{ED})/(\text{PEF} \times \text{BW} \times \text{AT}), \tag{8}$$

Table 1: Comparison between average PTEs concentration in the study area and other local and world backgrounds

Location and references	Fe	Ni	Zn	Cu	As	Pb
Southwest Riyadh, Saudi Arabia (present study)	15,556	27.82	63.85	12.70	3.64	6.12
Gangetic plain, India [3]	49,297	26.3	188.0	46.1	5.8	32.8
Mashhad city, NE of Iran [43]	—	167.76	166.5	83.08	4.66	112.13
Background value [44]	47,200	68.0	95.0	45.0	13.0	20.0
World-soil average [45]	35,000	29.0	70.0	38.9	6.83	27.0
Frydek-Mistek district, Czech Republic [46]		16.15	85.22	22.54	5.32	33.86
Shandong Province, North China [47]		25.04	51.68	19.4	6.4	25.65
Al-Ammariah soil, northwest Riyadh, Saudi Arabia [48]	11,526	26.94	52.16	11.36	3.78	5.08
Al-Ahsa, Eastern Saudi Arabia [49]	11,891	14.53	54.43	10.83	2.27	5.23
Wadi Jazan, Saudi Arabia [50]	23,811	48.66	75.80	72.85	14.13	19.41
Al Uyaynah soil, Saudi Arabia [51]	35,667	19.25	64.33	10.56	13.8	28.48

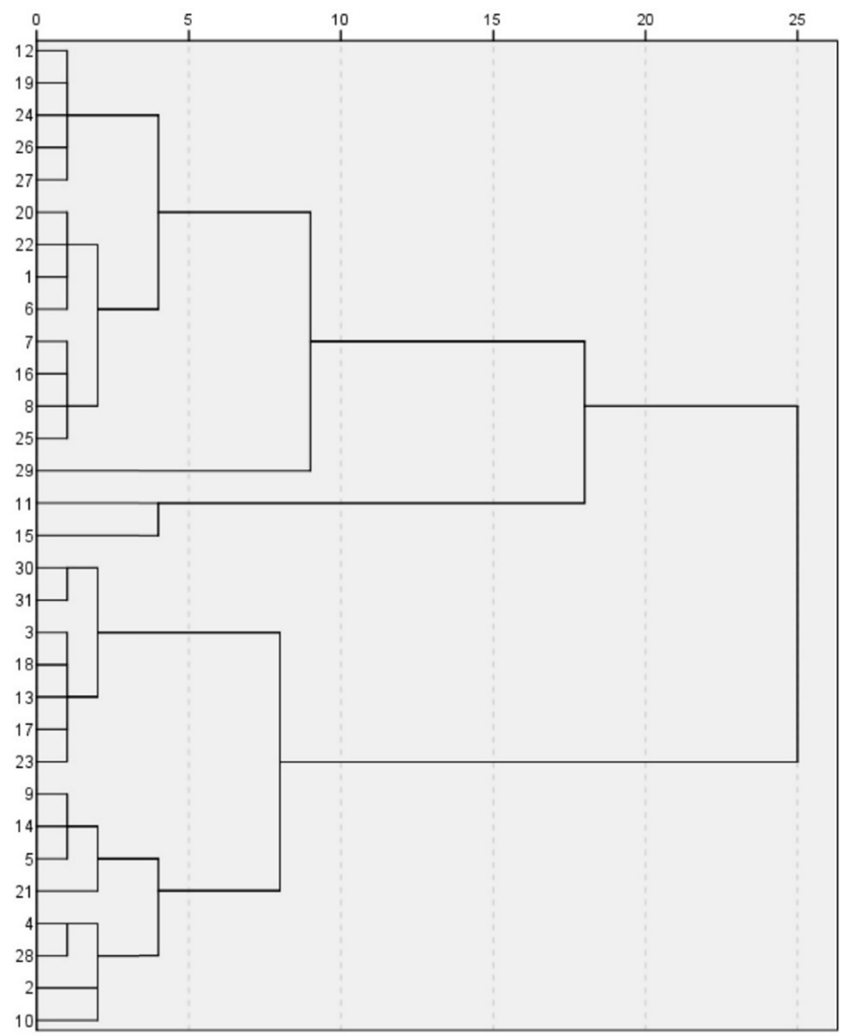

Figure 2: Q-mode HCA of soil samples from southwest Riyadh.

$$CDI_{derm} = (C_{soil} \times SA \times AFsoil \times ABS \times EF \times ED)/(BW \times AT) \times CF, \quad (9)$$

$$HQ = CDI/RfD, \quad (10)$$

$$HI = \Sigma HQ = HQ_{ing} + HQ_{derm} + HQ_{inh}, \quad (11)$$

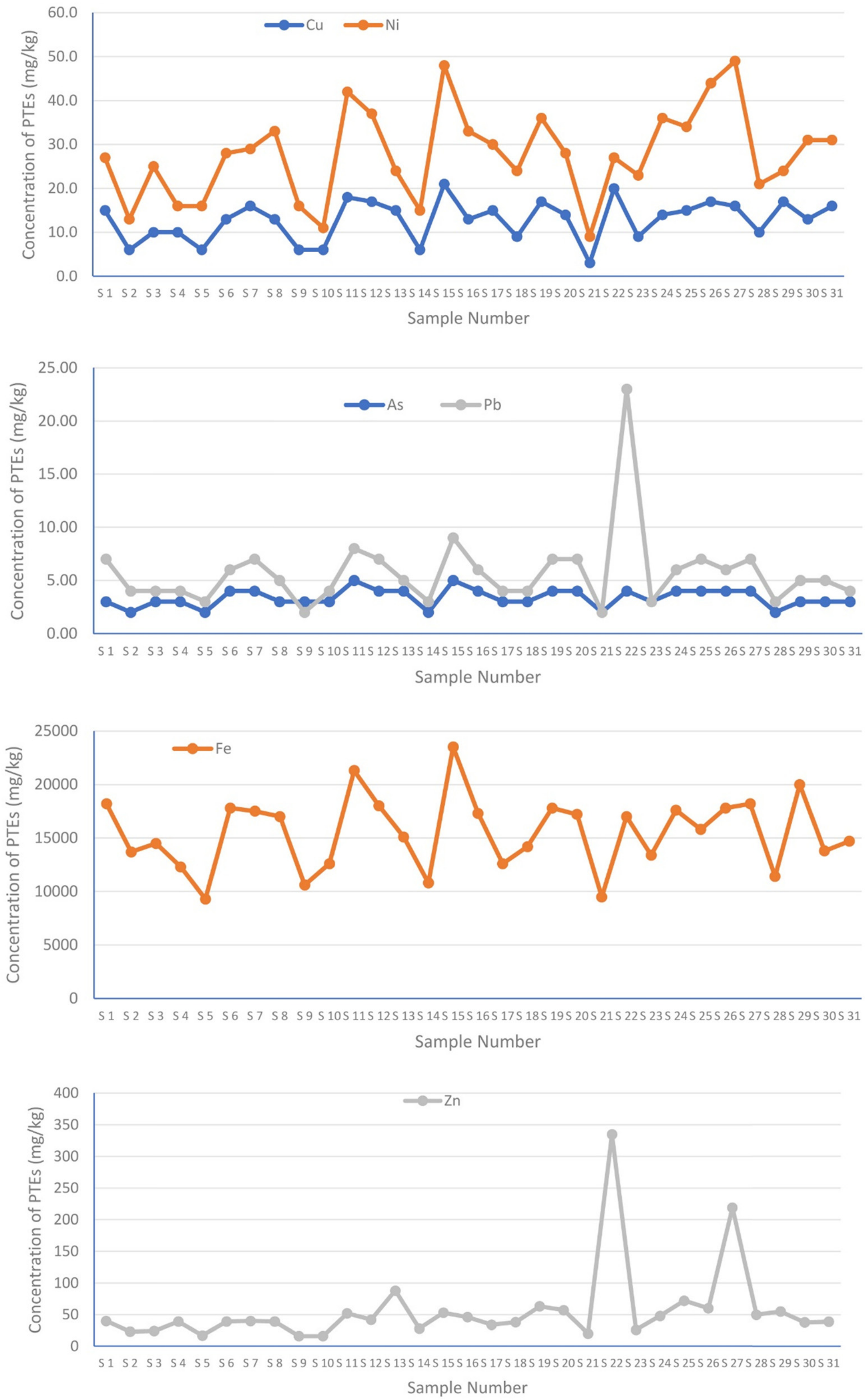

Figure 3: Distribution of the PTEs in soil from southwest Riyadh.

$$\text{Cancer risk} = \text{CDI} \times \text{CSF}, \tag{12}$$

$$\text{LCR} = \sum \text{Cancer risk} = \text{Cancer risk}_{\text{ing}} + \text{Cancer risk}_{\text{derm}} + \text{Cancer risk}_{\text{inh}}. \tag{13}$$

Table S3 does not include a chronic daily intake (CDI) value for Fe because of the lack of RfDinh and RfDderm values for Fe. This absence may stem from discrepancies among published data or unreliable traceability to the original study for the reference value [40]. Additionally, the impact of Pb on humans through dermal contact is uncertain, which is why CSF values for dermal contact of Pb were scarcely mentioned.

3 Results and discussion

3.1 Concentration and distribution of PTEs

The soil concentrations of PTEs in dry weight (mg/kg) are documented in Table S4. The average values are as follows: Fe (15,555), Zn (53.36), Ni (21.78), Cu (11.92), Pb (10.42), and As (2.64). Table 1 shows that the average values of the tested PTEs were lower than those reported from Mashhad city, located in the northeast of Iran [43], the Gangetic plain in India [3], background levels, and the world-soil average [44,45]. For instance, Pb, Ni, Cu, and Zn exceeded in Mashhad city, northeast Iran by 11-, 8-, 7-, and 3-folds compared to the present averages. Moreover, the As, Pb, and Cu average values were lower than those reported from Frydek-Mistek district, Czech Republic [46] and Shandong Province, North China [47]. Notably, the average concentrations of Fe, Cu, and Pb in this study were found to be higher than those reported in the soils of Al-Ammariah and Al-Ahsa in Saudi Arabia [48,49]. In contrast, the values for Fe, Zn, As, and Pb were lower than the average concentrations reported for soils in Wadi Jazan and Al Uyaynah in Saudi Arabia [50,51].

The Q-mode hierarchical cluster analysis (HCA) classified the 31 sampled sites into two groups according to the PTE levels (Figure 2). The first group, comprising S1, S6, S7, S8, S11, S12, S16, S19, S20, S22, S24–S27, and S29, exhibited the highest concentrations of As, Cu, Fe, Pb, Ni, and Zn (5.00, 21.0, 23,500, 23.00, 49.00, and 335.0 mg/kg, respectively). The second group, represented by S2–S5, S9, S10, S13, S14, S17, S18, S21, S23, S28, S30, and S31, demonstrated the lowest concentrations of As, Cu, Fe, Pb, Ni, and Zn (2.00, 3.0, 9,500, 2.00, 9.00, and 16.0 mg/kg, respectively). Figure 3 illustrates the distribution of PTEs across the 31 soil samples, highlighting that S2 and S9 from Al Hariq, and S21 from Naam reported the lowest PTE concentrations, while S15 from Al Mufayger, S22 from Naam, and S27 from Hawtat bani tamim exhibited the highest concentrations among the samples.

3.2 Contamination and risk assessment

PTEs contaminate agricultural soils through the extensive application of both inorganic and organic fertilizers, pesticides, irrigation water, and animal dung [52]. While Cr, As, and Pb pose significant environmental concerns as pollutants, Fe, Ni, Cu, and Zn are essential PTEs vital for various biological activities, albeit in low concentrations [12,53]. To assess PTE contamination in the examined soil, CF, I_{geo}, and EF were utilized (Figure 4, Table S5). The average EF values

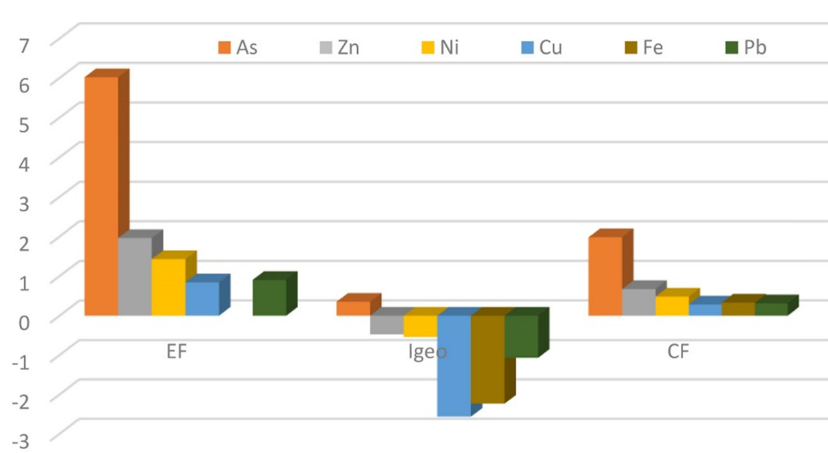

Figure 4: Distribution of the average values of the single contamination indices (EF, I_{geo}, and CF) of soil samples from southwest Riyadh.

for the PTEs were as follows: As (6.05), Zn (1.96), Ni (1.43), Pb (0.90), and Cu (0.84), indicating that the studied soil is moderately enriched with As and deficiency to minimal enrichment for Zn, Ni, Cu, and Pb. The EF analysis results indicate that all soil samples demonstrated deficiency to minimal enrichment levels of Pb and Cu. Among them, 30 soil samples exhibited deficiency to minimal enrichment with Ni, with one sample displaying moderate enrichment with Ni. In terms of Zn, the analysis revealed that 25 samples displayed deficiency to minimal enrichment, while 3 samples showed moderate enrichment, and the remaining 3 samples exhibited significant enrichment. Additionally, 5 samples showed moderate enrichment with As, while the remaining 26 samples displayed significant enrichment with As. The most substantial enrichment was observed in samples such as S9, S13, S22, S25, and S27, located in Al Hariq, Al Mufayger, Naam, and Hawtat Bani Tamim areas.

The average CF values for the PTEs in the investigated soil indicated moderate contamination for As and low contamination with the other PTEs (Table S5). Additionally, certain individual samples exhibited considerable contamination, such as S22 for Zn (CF = 3.53). Zn is highly mobile during weathering processes and tends to accumulate in argillaceous sediments. Anthropogenic sources of Zn include the nonferrous metal industry and agricultural practices [45]. The I_{geo} was employed to assess soil pollution by PTEs [53]. The current average I_{geo} values indicated unpolluted to moderately polluted conditions for As, as they were below zero, while for the rest of the PTEs, the values signified unpolluted soil. However, S22 and S27 showed I_{geo} values for Zn (1.55 and 1.12, respectively), suggesting moderate pollution for Zn in these two samples.

PLI is utilized to indicate the degradation of soil conditions resulting from the accumulation of PTEs [54]. It ranged from 0.16 to 0.59, with an average of 0.38 (Table S4), suggesting relatively clean soil conditions (PLI < 1). The RI, assesses the impact caused by pollutants, including potentially toxic elements (PTEs), in the environment [34]. RI encompasses various environmental effects and can evaluate ecological risks caused by PTEs [55,56]. In the study

Table 2: Correlation matrix for HMs of soil samples from southwest Riyadh

	As	Cu	Fe	Ni	Pb	Zn
As	1					
Cu	**0.799****	1				
Fe	**0.830****	**0.851****	1			
Ni	**0.790****	**0.831****	**0.798****	1		
Pb	**0.542****	**0.648****	**0.513****	0.384*	1	
Zn	0.352	0.487**	0.291	0.327	**0.842****	1

The bold values reveals substantial positive correlations among various pairs of PTEs. ** means correlation is significant at the 0.01 level.

Table 3: Loading matrix of PCs and the total variance explained by each PC

	Component	
	PC1	PC 2
As	**0.902**	0.030
Cu	**0.913**	0.184
Fe	**0.894**	−0.004
Ni	**0.956**	−0.136
Pb	**0.555**	**0.791**
Zn	0.405	**0.863**
% of Variance	73.51	13.12
Cumulative %	73.51	86.64

Bold values indicated notable loadings for PTEs.

Table 4: CDI (mg/kg/day), HQ, and HI for non-carcinogenic risk in adults and children from southwest Riyadh

HMs	CDI_{Ing}	CDI_{Derm}	CDI_{Inh}	HQ_{Ing}	HQ_{Dem}	HQ_{Inh}	HI
Adults							
As	4.608×10^{-6}	1.838×10^{-8}	6.776×10^{-11}	0.015	6.128×10^{-5}	2.259×10^{-7}	0.0152
Pb	8.386×10^{-6}	3.346×10^{-8}	1.233×10^{-10}	0.002	9.559×10^{-6}	3.523×10^{-8}	0.0024
Cu	6.957×10^{-8}	7.607×10^{-8}	2.564×10^{-10}	0.0005	1.875×10^{-6}	6.911×10^{-9}	0.00047
Ni	3.819×10^{-5}	1.520×10^{-7}	5.604×10^{-10}	0.002	7.602×10^{-6}	2.662×10^{-8}	0.0018
Zn	8.746×10^{-5}	3.490×10^{-7}	1.286×10^{-9}	0.00030	1.163×10^{-6}	4.287×10^{-9}	0.00029
Fe	0.021	—	—	0.030	—	—	0.0304
Children							
As	4.301×10^{-5}	8.580×10^{-8}	3.162×10^{-10}	0.143	0.00029	1.05×10^{-6}	0.1436
Pb	7.826×10^{-5}	1.5610×10^{-7}	5.755×10^{-10}	0.0224	4.461×10^{-5}	1.644×10^{-7}	0.022
Cu	0.00016	3.246×10^{-7}	1.196×10^{-9}	0.0044	8.750×10^{-6}	3.225×10^{-8}	0.0044
Ni	0.00036	7.096×10^{-7}	2.615×10^{-9}	0.0178	3.548×10^{-5}	1.308×10^{-7}	0.0178
Zn	0.00082	1.629×10^{-6}	6.002×10^{-9}	0.0027	5.429×10^{-6}	2.0008×10^{-8}	0.0027
Fe	0.1989	—	—	0.284	—	—	0.284

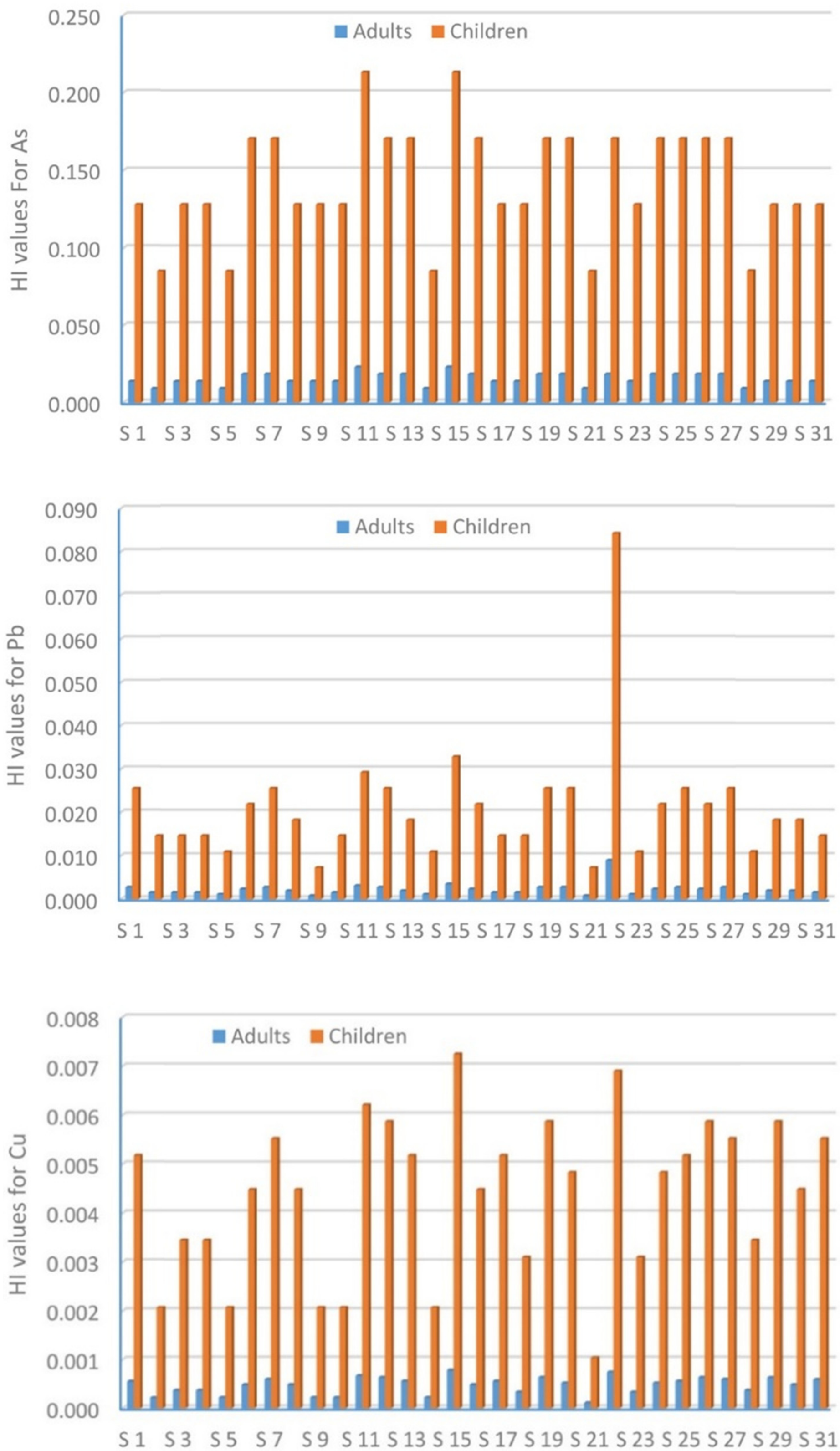

Figure 5: Spatial distribution of HI of PTEs per sampled location from southwest Riyadh.

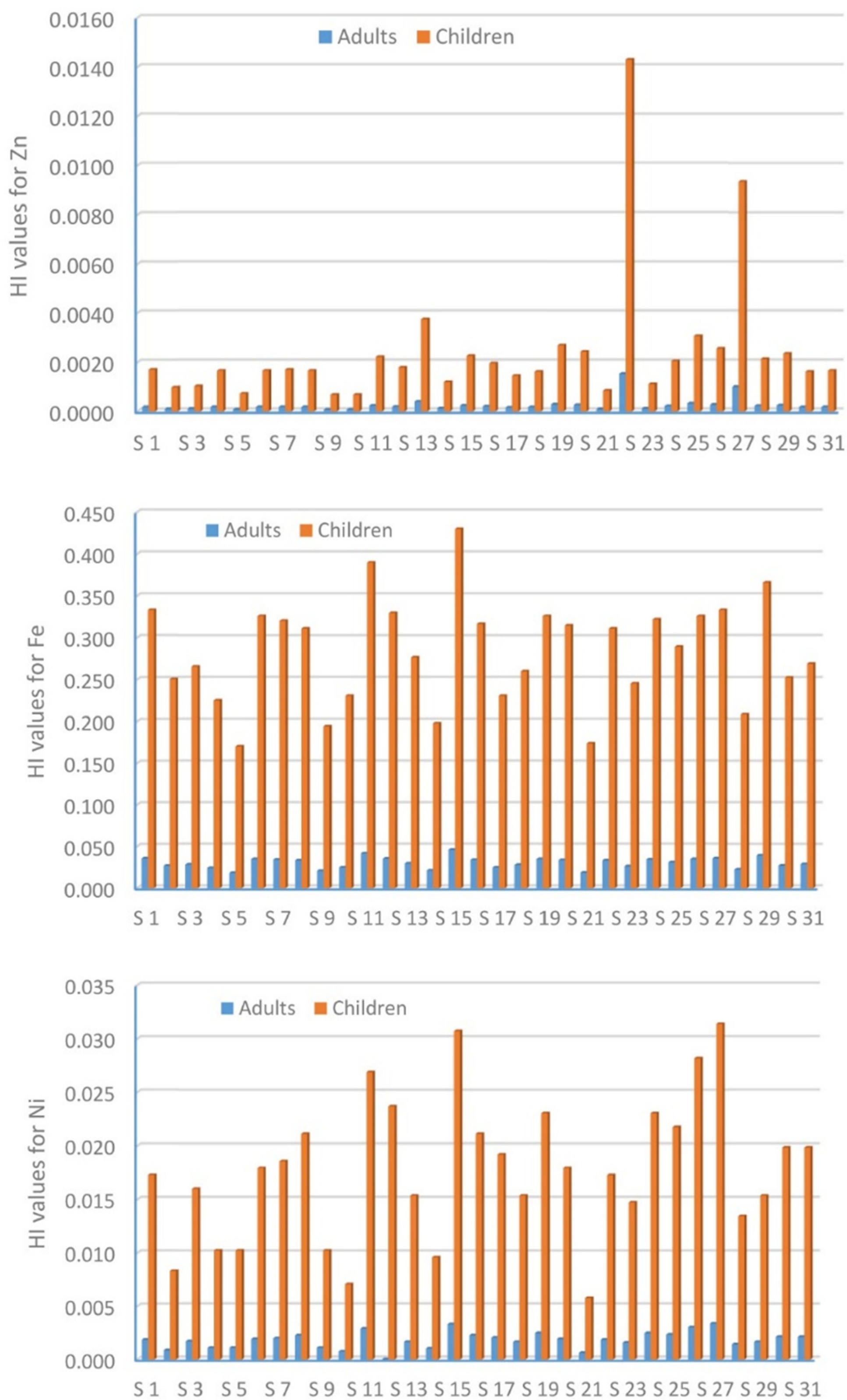

Figure 5: (*Continued*)

Table 5: Average CRs and LCR for PTEs from southwest Riyadh

HMs	CR_{Ing}	CR_{Derm}	CR_{Inh}	LCR
Adults				
As	6.91158×10^{-6}	2.75772×10^{-8}	1.01641×10^{-10}	6.94×10^{-6}
Pb	7.12744×10^{-8}	—	1.04815×10^{-12}	7.13×10^{-8}
Children				
As	6.45081×10^{-5}	1.28694×10^{-7}	4.74324×10^{-10}	6.46×10^{-5}
Pb	6.65228×10^{-7}	—	4.89138×10^{-12}	6.65×10^{-7}

area, RI values follow a similar distribution trend to PLI values, varying from 15.70 to 46.69, with an average of 30.48 (Table S4), indicating no to low risk of the PTEs in the studied soil or the PTEs do not pose a significant threat according to the classification reported by Hakanson [34].

3.3 Multivariate analyses

The correlation matrix presented in Table 2 reveals substantial positive correlations among various pairs of PTEs, such as As with Cu, Fe, Ni, and Pb (with correlation coefficients of 0.799, 0.830, 0.790, and 0.542, respectively). These findings suggest a common origin for these PTEs. The presence of Fe in this positive correlation implies that these elements are attributed to the parent material, from the weathering of nearby sedimentary succession in the study area [3,57–59]. However, the soil's average EF for As is 6.02, suggesting potential human influences, possibly from fertilizers, insecticides, and animal dung, which contain a substantial amount of As [45,60]. In contrast, Zn exhibits a weak correlation with all PTEs except Pb (with a correlation coefficient of 0.842), indicating a shared source for Pb and Zn. Zinc concentrations are likely elevated in argillaceous sediments, calcareous soils, and organic soils in sedimentary rocks, influenced by hydrous oxides and clay minerals. However, notable enrichment was observed in S22 and S27 for Zn and in S22 for Pb, potentially attributed to fertilizer use and other agricultural practices in those specific sites [61,62].

The validity of the correlation analysis findings was strongly supported by principal component analysis (PCA). Two principal components (PCs) were identified, collectively accounting for 73.51 and 13.12% of the overall variation (Table 3). The first PC displayed notable loadings for As, Cu, Fe, Ni, and Pb. The high loadings of these PTEs on the first PC suggested a potential geogenic origin. In contrast, PC2 showed significant loadings for Pb and Zn, implying a minor enrichment possibly originating from both geogenic and human sources. The utilization of phosphate fertilizers and fungicides in agricultural fields to improve yields may contribute to this enrichment, as suggested by the loadings on PC2 [3]. Additionally, animal manure and sewage sludge represent potential human factors introducing Cu, Zn, Pb, and Ni to the soil [63].

3.4 Health risk assessment

Health risk assessment is a widely used method for estimating both non-carcinogenic and carcinogenic risks posed to humans exposed to contaminants found in the air, water, and soil [3]. In this study, health risk assessment is conducted exclusively for agricultural soil samples, considering various exposure pathways. Table 4 presents the average values of the CDI, hazard quotient (HQ), and HI for the non-carcinogenic risk of PTEs on adults and children. For adults, the average CDI values (mg/kg/day) from ingestion, dermal contact, and inhalation pathways ranged from 6.95641×10^{-8} (Cu) to 0.021307597 (Fe), from 7.60651×10^{-8} (Cu) to 3.490×10^{-7} (Zn), and from 6.77606×10^{-11} (As) to 1.286×10^{-9} (Zn), respectively. In children, CDI values ranged from 7.82621×10^{-5} (Pb) to 0.198870901 (Fe), from 8.57958×10^{-8} (As) to 1.629×10^{-6} (Zn), and from 5.75456×10^{-10} (Pb) to 6.002×10^{-9} (Zn), respectively. The results indicate that the average daily dose is highest through ingestion, followed by dermal contact and inhalation routes, regardless of the population group. Moreover, the average CDI values from the ingestion pathway in children for all PTEs showed an increase approximately 9.33 × 10 times, and 4.67 × 10 times for both inhalation and dermal pathways compared to adults. The higher CDI due to the ingestion of soil by children may be attributed to their increased sensitivity to exposure, making them more prone to absorbing toxic PTEs than adults [64,65].

The average HI values ranged from 0.000293 (Zn) to 0.0304 (Fe) for adults and from 0.002726541 (Zn) to 0.284 (Fe) for children (Table 4). The results indicated that the primary exposure route to PTEs in the study area was through ingestion. The HIs for PTEs in the study area were below 1.0, signifying that residents are not at a significantly non-carcinogenic risk [66,67]. However, the average HI value for Fe exceeded 0.2 for children, highlighting the need to protect their health [39]. The spatial distribution of the HI for PTEs at each sample location for both children and adults (Figure 5, Table S6) revealed similar patterns and hotspots in S11 and S15 (As and Fe), S11 and S22 (Cu), S22 (Pb), S15 and S27 (Ni), and S22 and S27 (Zn). These samples were collected from Al Hariq, Al Mufayger, Naam, and Hawtat

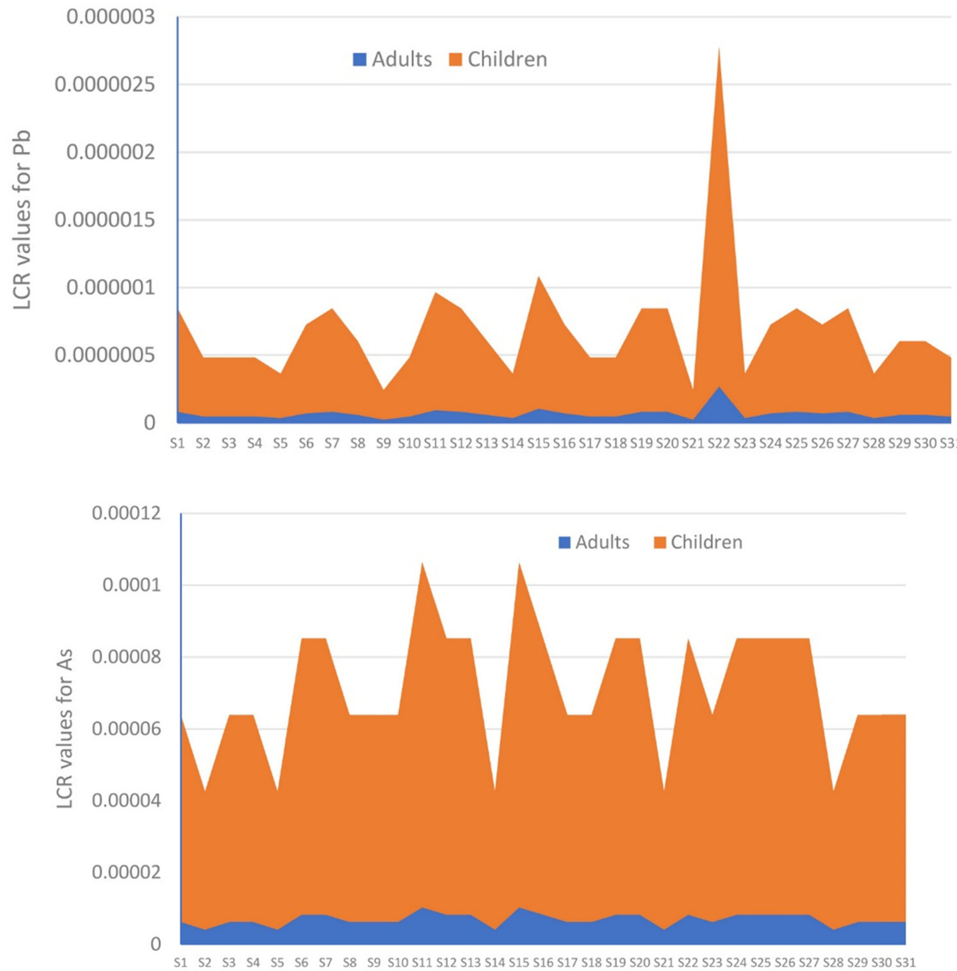

Figure 6: Spatial distribution of LCR for As, and Pb per sampled location from southwest Riyadh.

Bani Tamim areas and from farms irrigated with treated groundwater.

The CRs for As and Pb in children were found to be significantly greater than those in adults (Table 5). The average CR values in ingestion and inhalation pathways for adults ranged from 7.12744×10^{-8} to 6.91158×10^{-6} and from 1.04815×10^{-12} to 1.01641×10^{-10}, respectively. In comparison, for children, the CR values varied from 6.65228×10^{-7} to 6.45081×10^{-5} and from 4.89138×10^{-12} to 4.74324×10^{-10}, respectively. Children's CR values for As and Pb are higher than those for adults, indicating that children are more likely to be exposed to PTEs due to their behavioral habits that increase the likelihood of skin contact, especially with hands [55,68,69].

The values of the total LCR for As and Pb in all studied sites were higher in children than in adults (Table S7). LCR values varied between adults and children from 6.94×10^{-6} to 6.46×10^{-5} (As) and from 7.13×10^{-8} to 6.65×10^{-7} for Pb, respectively. The carcinogenic risk of the ingestion pathway was the principal contributor to the total LCR. The spatial distribution of the LCR for As and Pb per sample location suggested a similar pattern for both children and adults with increased values in children (Figure 6). S11 and S15 showed a hotspot for As, while S22 showed a hotspot for Pb. LCR values for As were between 1×10^{-6} and 1×10^{-4}, while they were lower than 1×10^{-6} for Pb, indicating acceptable or tolerable carcinogenic risk and no significant health hazards, respectively [38,69].

4 Conclusion

The current study shed light on the contamination and associated health risks posed by As, Pb, Cu, Ni, Zn, and Fe in agricultural soil from southwest Riyadh, Saudi Arabia. The tested PTEs exhibited the following ranges: Fe (9,300–23,500 mg/kg), Zn (16.0–335 mg/kg), Ni (9.00–49.00 mg/kg), Cu (3.00–21.0 mg/kg), Pb (2.00–23.00 mg/kg), and As (2.00–5.00 mg/kg). The average values of these PTEs were lower compared to those reported from the northeast of Iran, the Gangetic plain in India, background levels, and the world-soil average. The studied soil is moderately enriched and contaminated with As and deficiency to minimal enrichment and low contaminated with the remaining PTEs. RI values implied that the PTEs in the studied soil do not pose a significant threat. The correlation matrix and principal component analysis identified a geogenic source for the PTEs, while some anthropogenic influences were observed for As, Zn, and Pb, possibly originating from animal manure and fertilizers used in certain farms. Results indicate that the average daily dose is primarily highest through ingestion, followed by dermal contact and inhalation routes, regardless of the population group. The average HI values ranged from 0.000293 (Zn) to 0.0304 (Fe) for adults and from 0.002726541 (Zn) to 0.284 (Fe) for children The HIs for PTEs in the study area were below 1.0, signifying that residents are not at a significantly non-carcinogenic risk. LCR values for As were between 1×10^{-4} and 1×10^{-6}, while they were lower than 1×10^{-6} for Pb, indicating acceptable or tolerable carcinogenic risk and no significant health hazards.

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