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Soil-plant transfer and health risk assessment of potentially toxic elements in wheat grown on calcareous soil in Sulaymaniyah, Iraqi Kurdistan

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ABSTRACT

The accumulation of potentially toxic elements (PTEs) in staple crops poses significant risks to food safety and human health. This study was designed to investigate soil-plant transfer and assess the health risks of arsenic (As), cadmium (Cd), and lead (Pb) in wheat (*Triticum aestivum* L.) grown on calcareous soils in Sulaymaniyah of Iraqi Kurdistan. The analysis involved 120 samples each of soil and grain collected at harvesting in May 2024, using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Soil concentrations ranged from 3.54–14.82 mg kg^{-1} for As, 0.13–0.85 mg kg^{-1} for Cd, and 7.10–20.26 mg kg^{-1} for Pb, whereas grain concentrations were substantially lower (As: 0.001–0.182; Cd: 0.001–0.080; Pb: 0.000–0.013), remaining within FAO/WHO permissible limits. Soil pH and $CaCO_3$ content showed negative correlations with PTE levels, while organic carbon exhibited positive associations, indicating their influence on metal mobility and uptake ($p \leq 0.05$). Chronic daily intake (CDI) values for all PTEs were below reference doses, with higher exposure observed in children. Hazard quotient (HQ < 1) and hazard index (HI ≤ 0.763) values indicated negligible non-carcinogenic risk. Although Cd contributed the highest risk among PTEs, overall exposure remains within safe limits. But, the lifetime cancer risk of the studied PTEs via wheat grain consumption for adults and children is higher than the allowable limit $1x10^{-6}$. Continuous monitoring is recommended given the region's high reliance on wheat in the diet. However, information regarding the soil-to-grain transfer of PTEs and associated dietary risks in calcareous soils of Iraqi Kurdistan remains limited.

Keywords: potentially toxic elements (PTEs), arsenic (As), cadmium (Cd), lead (Pb), chronic daily intake (CDI), health risk assessment.

INTRODUCTION

Winter wheat (*Triticum aestivum* L.) is the primary (Pirhadi et al., 2022; Rasheed, 2022) and staple food for more than 150 countries worldwide (Cotav et al., 2020; Anteneh and Asrat, 2020), accounting for about 26% of global cereal production (Cotav et al., 2020). It covers approximately 15% of the world's cultivated crop area (Anteneh and Asrat, 2020), grown on more than 240 million hectares globally (Khan et al., 2019), with an annual production of 765 million tons (Pequeno et al., 2021; FAOSTAT, 2019) and 3.43 tons per hectare (Le Gouis et al., 2020). This is because grains can be cultivated in areas with various soil types, altitudes, and temperature regimes, ranging from 3 °C to 32 °C (Enghiad et al., 2017).

Wheat plays a crucial role in human life and growth, largely owing to its high nutritional value (Catav et al., 2020; Pirhadi et al., 2022). Globally, it supplies approximately 20% of total calories and proteins (Guarin et al., 2022). In Central Asia and North Africa, wheat accounts for approximately 45% of the daily caloric intake in humans (Le Gouis et a., 2020) and is a source of essential minerals (Salih et al., 2021). The average wheat consumption per capita was approximately 65.6 kg, which amounts of 37% of the mean annual cereal intake of 175 kg worldwide (Erenstein et al., 2022).

Therefore, considering the nutritional value of wheat, the concentrations of metals, particularly PTEs, in wheat products are critical. Previous research has shown that grains can be contaminated by many toxic metals, including Cd, Pb, and As (Fereshteh et al., 2021). This contamination may originate from anthropogenic sources, soil and rainwater inputs, climatic conditions, or anthropogenic activities, including the excessive use of chemical fertilizers (especially phosphate fertilizers), pesticide application, irrigation with wastewater or sewage sludge, and industrial processes (Pirhadi et al., 2022; Erenstein et al., 2022). These activities can increase PTE concentrations in the produced wheat. The intake of high levels of PTEs through wheat grain consumption may cause toxic effects in humans (Catav et al., 2020). Thus, given the high global consumption of wheat, assessing the impact of toxic metals on public health is essential (Fereshteh et al., 2021).

Potentially toxic elements can cause serious environmental problems. The accumulation of PTEs such as Cd, Pb, and As is harmful to biological systems (Karapinar, 2021) and poses a risk to human health (Le Gouis et al., 2020), due to their non-degradable nature (Erenstien et al., 2022). These elements exhibit an abnormal affinity for the sulfhydryl groups in proteins, resulting in their ability to inhibit the function of various enzymes in biological systems (Pompa et a., 2021). They have no biological function in the human body and cause various disorders (Abbas et al., 20217). Continuous intake even at low concentrations, can affect the central nervous system, the musculoskeletal system, cholesterol balance, and kidney dysfunction (Li et al., 2022).

Lead exposure reduces systemic calcium levels and exerts harmful effects on blood enzymes, in addition to impairing the cardiovascular, cellular, and respiratory systems (Collin et al., 2022). In infants and children, prolonged exposure to Pb can lead to growth disorders and reduced intelligence quotient (IQ); whereas, in adults, it may increase blood pressure (Pirhadi et al., 2022). Cadmium is categorized as cancer-causing, allegedly mutagenic, and reprotoxic (Pompa et al., 2021). Excessive Cd intake can cause Itai-Itai painful bone disease as well as prostate, bladder, and lung cancer. Arsenic exposure causes damage to blood vessels, abnormal heart rhythm, reduces red and white blood cell production, causes nausea and sickness, and can lead to cancer (Pirhadi et al., 2022; Wang et al., 2023).

The studied sites are characterized by calcareous soils, which often limit nutrient availability. This is due to high pH value, low organic matter, and high calcite content ($CaCO_3$) (Rasheed, 2022). As a result, farmers tend to apply high rates of NPK fertilizers. However, these fertilizers may contain measurable quantities of PTEs. Continuous application can lead to PTEs accumulation in soil, which may consequently be transferred to humans through the consumption of grains grown in contaminated environments.

Given the region's high wheat production and consumption by people and the detrimental effects of PTEs on human health, it is essential to inform the community about this issue. Therefore, this study aimed to (i) assess PTE contamination (As, Cd, and Pb) in wheat grown on calcareous agricultural soil sites in the region, (ii) determine the concentrations of these elements, and (iii) evaluate the probabilistic health risks for both children and adults.

The first hypothesis is that wheat grain, as a primary staple food, significantly influences the transfer of PTEs from soil to wheat grains. Soil physicochemical properties significantly influence the transfer of PTEs from soil to wheat grains. The second hypothesis is that Wheat consumption in the study region does not pose significant non-carcinogenic health risks. This provides new insights into contamination control and offers a scientific basis for local authorities to protect public health in the long term.

METHODS AND MATERIALS

Study area

The sampling area included five sites in Sulaymaniyah Province, Kurdistan Region, Iraq, located between 34˚32' and 36˚30' N, and 44˚33' to 46˚20' E. The morphology of the area differs considerably, ranging from 758 to 882 m above sea level. It covers an area of about 20,143.91 km^2 and has an estimated population of approximately 2,250,000. The climate of the studied area, Sulaymaniyah Province, is semi-arid to sub-humid, with temperatures typically ranging from 0.0 °C to 45 °C. Annual rainfall is extremely seasonal, ranging from 300 mm in the south to more than 1000 mm in the north of the province. Infrequent snowfall also occurs during the Winter season. Spring and autumn are rainy, whereas summer is dry. Sulaymaniyah Province is one of the largest cities in the Kurdistan Region. The sites were selected based on agricultural activities and geographical differences. According to the FAO/WRB classification system (IUSS, 2022), soils in the study area are classified as Calcic Vertisol in the south and Chernozem in the north. These soils have been cultivated primarily with wheat for more than five decades. Farmers usually apply NPK fertilizers at a rate ranging from 50 to 200 kg annually, based on the information obtained from interviews conducted at the sampling sites. Wheat is grown during a single season extending from October to May. In this study, a total of 120 wheat plant samples were collected at the harvest stage across the five sites within the main wheat-producing area of Sulaymaniyah Province, Kurdistan Region, Iraq (Figure 1).

Sample collection and preparation

A total of 120 wheat-grown fields, along with corresponding wheat grain and soil samples, were collected from five major wheat production sites in Sulaymaniyah Province, Kurdistan Region, Iraq, during May and June 2024. The five representative sites were selected based on agricultural activity, soil characteristics, and geographical diversity. According to a study net of (10 × 10 m plots), the sampling density was 5 points per 100 m^2. Samples were collected following an "X" shaped pattern within each square field. The number of samples collected from each site depended on the site size to ensure adequate spatial representation. Wheat grain samples were collected using a W-transect sampling approach. At each site, samples from five points were combined to form a composite sample. The samples were then sealed in plastic bags for transport to the laboratory. In total, 120 samples in the W-transect, with each sample covering 15–20 wheat heads. Then, the samples were cleaned to remove straw and foreign materials, thoroughly mixed, and a representative subsample (approximately 10 g) was prepared. Before analysis, the grain samples were finely ground using a centrifugal mill (Retsch, Model ZM200) and stored in polyethylene containers. Soil samples were collected from the same sampling points as the wheat grain samples at a depth of 0–15 cm using a stainless-steel trowel. Approximately 1 kg of soil was collected from each location. The soil samples were air-dried at room temperature, kindly disaggregated, and sieved to obtain the <2 mm fraction. A representative subsample (approximately 50 g) was then prepared and finely ground using a planetary ball mill (Retsch, Model PM400) for subsequent analyses. All sampling and sample preparation procedures were carried out in accordance with standardized protocols recommended by the United States Environmental Protection Agency (USEPA) to ensure analytical accuracy, consistency, and reproducibility

Grain analysis

Approximately 200 mg of ground grain samples were individually introduced into a Teflon

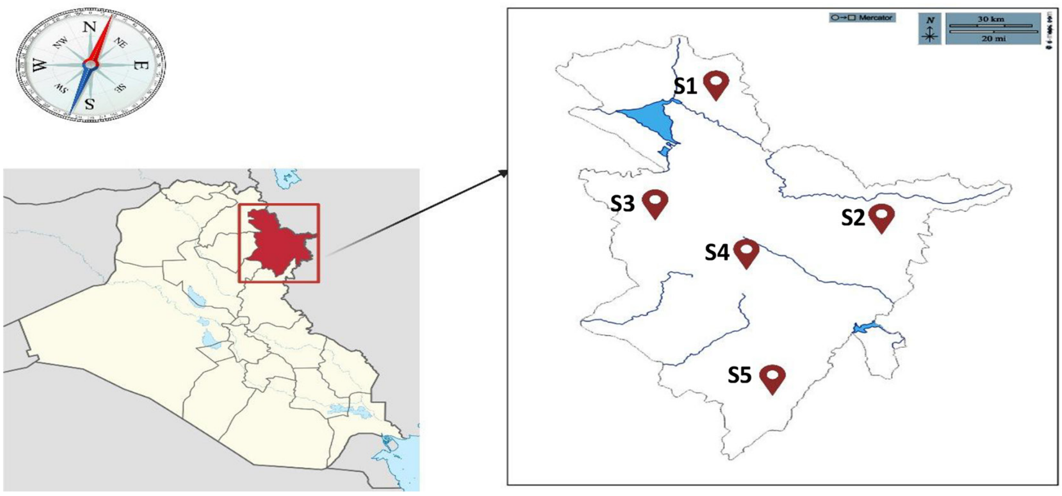

Figure 1. Map of the study area in Sulaymaniyah province, northeastern Iraq. The left map demonstrates the location of the study area within Iraq, while the right map gives the described map of the study region, including sampling five sites with their symbols, including (S1, S2, S3, S4, and S5)

vessel, followed by the addition of 4 mL of 68% HNO_3 and 2 mL of H_2O_2. Samples were digested using an Anton Parr Multiwave 3000 microwave for approximately 45 min at 2 MPa. After digestion, the samples were diluted with Milli-Q water to a final volume of 20 mL and stored in universal plastic tubes for subsequent analysis in triplicate. The concentrations of the analyzed potentially toxic elements were determined using ICP-MS (Thermo Fisher Scientific, ICAP Q, Germany). All reagents were of analytical or trace analysis grade (Fisher Scientific). Each analytical batch included three blanks and three certified reference materials (tomato leaves) for quality assurance, analyzed at the University of Nottingham Laboratory in the UK. The measured concentrations were corrected using the average values of three blank-digested samples and expressed in mg kg^{-1}. Standard reference material, NIST 1573a (tomato leaves), was used for quality control. The average recovery rate was 97±5% for As, 96±6 for Cd, and 95±7% for Pb, indicating adequate analytical accuracy.

Soil analysis

A multiple-element analysis was performed according to the procedure described in (Nazif et al., 2025). Soil pH was determined in a soil-water suspension at a ratio of 1:2.5. The concentrations of potentially toxic elements were measured using ICP-MS. Soil organic carbon was determined using the loss-on-ignition method, as previously described (Hoogsteen et al., 2018). Total calcium carbonate content was determined using the Collin calorimeter method, following the procedure reported in (Zhou et al., 2022). The measured concentrations were corrected using the average of three blank digestions and expressed in mg kg^{-1}. Moreover, standard reference material Montana II soil (NIST 2711a) was used for quality control. The average recovery rates were 98±6% for As, 95±6% for Cd, and 96±6 for Pb, respectively, showing adequate analytical accuracy.

Human health risk evaluation

Given the presence of multiple potentially toxic elements (PTEs), the consumption of wheat grain may lead to non-carcinogenic antagonistic effects. In the present study, chronic daily intake (CDI) was calculated to estimate the possibility of rising non-carcinogenic influences according to Equation 1 (Pirhadi et al., 2022).

$$CDI \; \frac{C \times IR \times ED \times EF}{BW \times AT} \tag{1}$$

In this equation, CDI represents Chronic Daily Intake, C denotes the concentration of PTE in wheat grain (mg kg^{-1}), IR indicates grain consumption (grams per person per day), ED signifies the exposure duration (70 years), EF is the exposure frequency (350 days per year), RfD is the oral reference dose (mg kg^{-1} day^{-1}), BW represents average body weight (70 kg for adults and 30 kg for children), and AT is the average time for non-carcinogens (365 days per year multiplied by ED) (Li et al., 2022).

For this purpose, the hazard quotient (HQ) model was used for each PTE according to the U.S. Environmental Protection Agency (USEPA), according to the following equation:

$$HQ = \frac{CDI}{RfD} \tag{2}$$

where: *CDI* is the daily intake of PTEs in mg/kg body weight per day (mg kg^{-1} day^{-1}), calculated according to Equation 1 (Li et al., 2022).

The oral reference dose for PTEs is shown as the *RfD*. The *RfD* (mg kg^{-1} day^{-1}) for As is 0.003, 0.001, and 0.004 (Li et al., 2022; Kacholi et al., 2028). The total hazard index (THI) was calculated using the following equation:

$$THI = HQ1 + HQ2 + \ldots\ldots\ldots.HQn \tag{3}$$

If HQ or THI values exceed 1, it poses a considerable health risk to humans from non-carcinogenic diseases. However, fewer than one was significantly protected owing to exposure to the detected PTE concentrations (Li et al., 2022; Alam et al., 2023).

Carcinogenic health risk assessment

In this study, carcinogenic health risk assessment was also conducted for PTEs in wheat grain samples. The excessive lifetime cancer risk (ELCR) was used to estimate carcinogenic risk and was calculated according to equation 1 (Pirhadi et al., 2022; Sommer et al., 2025). And just that there is a difference with non-carcinogenic CDI, which were calculated for different age groups. Carcinogenic risk assessment incorporates the cancer slope factor (CSF) of each PTE with known carcinogenic properties. The ELCR was calculated using Equation 4 based on the corresponding CSF values. The CSF values used in this study were 1.5 for As, 6.1 for Cd, and 8.5 for Pb (Pirhadi et al., 2022).

$$ELCR = CDI \cdot CSF \quad (4)$$

The calculated ELCR representing the probability of carcinogenic risk should be equal to the standard risk limits recommended by the World Health Organization (WHO). If the determined ELCR is less than 10^{-6} (at the 95^{th} percentile), it suggests no significant cancer risk from PTEs exposure through wheat grain ingestion and reflects a low priority for further consideration. However, if ELCR falls in the range 10^{-6} to 10^{-4}, it is observed as an acceptable or tolerable risk level. Further assessment may be required before taking action. In contrast, if the ELCR is above 10^{-4}, it indicates a possibly significant carcinogenic risk, and full investigation and risk management actions are required.

Statistical analysis

Statistical analysis of the data was performed using SPSS software (version 26.6) to examine the multivariate relationships among soil properties, soil metal concentrations, and metal concentrations in the grains. The PTEs in soil and wheat grains were analyzed using analysis of variance (ANOVA), and differences between sites were compared using the least significant difference (LSD) test at ($p \leq 0.05$). Relations between variables were assessed using Pearson's correlation coefficients.

RESULTS AND DISCUSSIONS

Soil chemical characteristics and studied toxic metals concentration

Table 1 shows some basic soil characteristics, including pH, organic carbon (OC), total calcium carbonate ($CaCO_3$), and the overall concentrations of the studied PTEs in both wheat grain and soil across all soil sites. A wide variation in pH, loss on ignition (LOI), and $CaCO_3$ content was observed, with values ranging from 7.87 to 8.95, 66.47 to 242.0 g kg^{-1}, and 4.75 to 10.7 g kg^{-1}, respectively. These results indicate that the cultivated soils are calcareous in nature (Rasheed, 2022), which is consistent with the properties described for calcareous soils in a previous study (Taalab et al., 2019). Soil properties, such as pH, OC, and $CaCO_{3,}$ play an important role in managing the availability, mobility, and uptake of PTEs by plants (Bolan et al., 2023).

The mean concentrations of PTE (mg kg^{-1}) across all the cultivated sites followed the order: Pb > As > Cd. The levels of PTEs in the studied soils were similar to those reported for agricultural calcareous soil in China (Liu et al., 2009; Colin et al., 2022), and were below the permissible limit established by FAO (1996) for maximum allowable concentrations in soil (Deng et al., 2024; Angon et al., 2024). This indicates that the soils at the studied sites contain comparatively low levels of PTE and can be considered suitable for agricultural use worldwide. Additionally, the concentrations of all analyzed PTEs fell within the standard range for calcareous soils, suggesting that the soils in the surveyed sites are not contaminated. However, lower concentrations have been reported in other calcareous soils (Rezaei et al., 2019; Zuzolo et a., 2020). Some variability in PTE concentrations was observed between the studied sites.

It has been reported that PTEs at all soil sites originate from both natural (Hoogsteen et al., 2018) and anthropogenic activities (Kubier et al., 2019), including the application of chemical fertilizers (especially NPK), and pesticides used by farmers. High levels of Pb can be attributed to the high use of pesticides and chemical fertilizers, especially phosphorus-based fertilizers. As reported in (Kahn et al., 2019), excessive use of chemical fertilizers can increase the concentration of PTEs in soils. Additionally, Orellana-Mendoza et al. (2024) demonstrated that nitrogen fertilizers can raise soil Cd levels, and phosphate fertilizers often contain PTEs, including As, Cd, and Pb, which can accumulate in the soil and become available for plant uptake. The concentrations of PTEs were higher in soil samples than in the wheat grain, indicating inadequate absorption from the soil compared to the wheat grain. Analysis of variance revealed significant differences ($P \geq 0.05$) in the concentrations of As, Cd, and Pb between the studied sites. The moderately low Cd concentration may be due to the parent rock, especially carbonate stone in the studied soil sites. For example, Kubier et al. (2019) reported that carbonate stones in calcareous regions contain relatively low Cd concentration, approximately 0.012 mg kg^{-1}.

Table 1. A Maximum, minimum, and standard deviation values of soil pH, OC%, $CaCO_3$ (g kg^{-1}), and studied PTEs (mg kg^{-1}) (n=120) in soil and grain. Data originated from the site code

Parameters		Site	S1	S2	S3	S4	S5	p-value
		No. of samples (120)	28	45	12	10	25	
pH		Maximum	8.21	8.19	8.14	8.33	8.67	0.005
		Minimum	7.83	7.58	7.83	7.77	7.46	
		±SD	0.10	0.15	0.08	0.15	0.22	
LOI	%	Maximum	11.97	14.14	20.86	7.56	8.55	0.001
		Minimum	6.123	6.717	6.584	3.927	3.146	
		±SD	1.218	1.535	3.881	1.040	1.263	
$CaCO_3$	g kg^{-1}	Maximum	354.5	296.6	388.4	333.6	341.0	0.001
		Minimum	26.86	16.87	67.82	135.69	65.06	
		±SD	87.40	79.26	89.40	61.86	72.55	
As	Grain	Maximum	0.029	0.010	0.013	0.023	0.056	0.01
		Minimum	0.002	0.001	0.002	0.003	0.002	
		±SD	0.006	0.002	0.003	0.006	0.013	
Cd		Maximum	0.022	0.040	0.019	0.019	0.080	0.001
		Minimum	0.001	0.006	0.002	0.001	0.003	
		±SD	0.005	0.007	0.005	0.005	0.015	
Pb		Maximum	0.034	0.079	0.043	0.019	0.078	0.045
		Minimum	0.000	0.000	0.005	0.004	0.000	
		±SD	0.009	0.014	0.011	0.005	0.021	
As	Soil	Maximum	14.82	12.97	10.57	9.242	8.090	0.001
		Minimum	3.590	5.761	3.540	7.218	5.398	
		±SD	2.778	1.601	2.099	0.693	0.735	
Cd		Maximum	0.578	0.850	0.511	0.374	0.376	0.001
		Minimum	0.310	0.364	0.244	0.161	0.132	
		±SD	0.072	0.107	0.083	0.064	0.065	
Pb		Maximum	19.38	20.26	17.25	13.22	15.51	0.001
		Minimum	8.322	11.08	7.103	9.767	7.494	
		±SD	2.328	2.035	2.547	1.094	2.188	

In the studied soils, correlation analysis showed a negative relationship among soil pH, total $CaCO_3$ content, and PTE concentrations (Figure 2A and B), indicating decreased metal mobility under calcareous and alkaline soil conditions. The distribution and accumulation of PTEs are mainly influenced by the nature of the parent materials, harvested crops, agricultural practices, and atmospheric deposition (Li et al., 2021). In contrast, a positive correlation was observed between the PTEs and the organic carbon content of the soils (Figure 1C), suggesting that organic matter may affect metal accumulation and retention in soils. Soil contains organic matter that acts as a source of metal contamination. Overall, the quality of cultivated soils in the study area can be categorized as having a low level of contamination and related environmental hazard.

Potential toxic elements in wheat grain

The concentrations of the studied PTEs, including As, Cd, and Pb, in wheat grains collected from the five sites in Sulaymaniyah province are shown in (Figure 2). The results showed that the measured ranges were 0.001–0.182 mg kg^{-1} for As, 0.001–0.080 mg kg^{-1} for Cd, and 0.00–0.175 mg kg^{-1} for Pb. Within the grains, the PTE distribution varied among sites, with significant differences observed ($p \geq 0.05$). The observed values were higher than those reported by (Erenstein et al., 2022; Xu et al., 2022), who studied the heavy metal and trace element concentrations in Argentine soil and wheat grain grown in non-contaminated soil, but lower than the results reported for wheat grain from Iraq (Mahdi et al., 2021), and particularly for wheat from Iran (Aibaghi et al.,

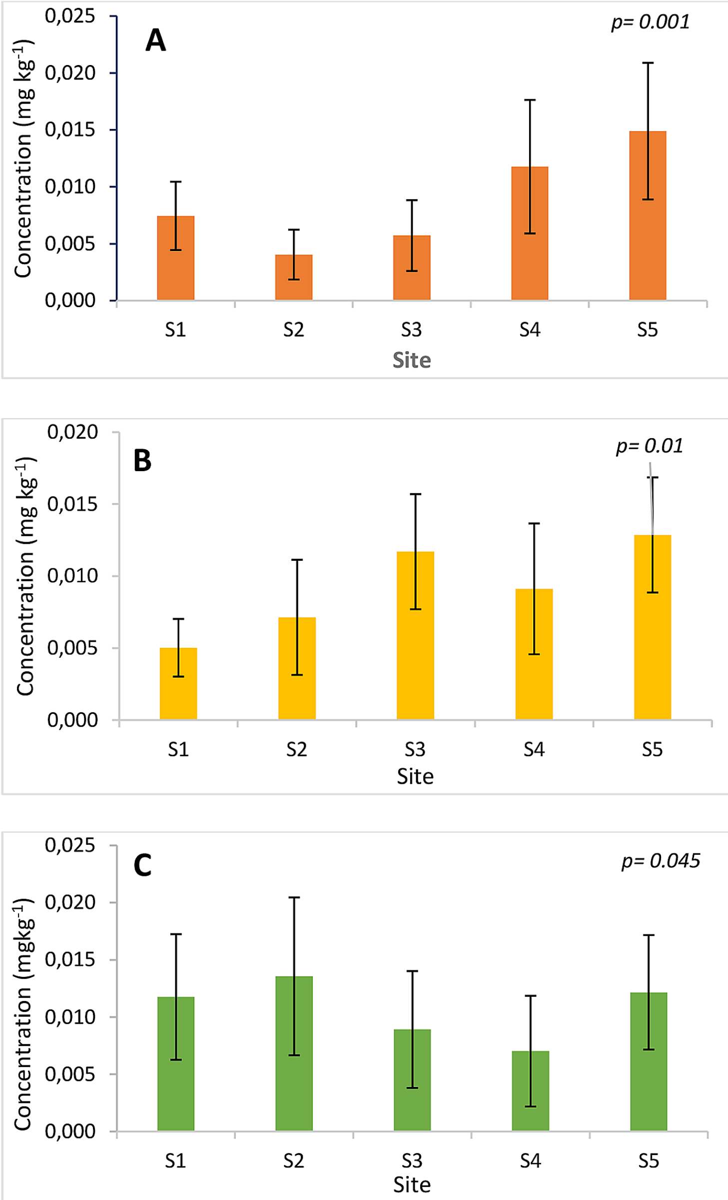

Figure 2. The average of the total concentration (mg kg^{-1}) of (A) As (p=0.001), (B) Cd (p=0.01), and (C) Pb (p=0.045) of the studied PTEs (As, Cd, and Pb) in the 120 wheat grain samples from five sites

2024) in sewage-irrigated soil, and for Chinese wheat grain grown under different farmland use patterns (Xu et al., 2022). Nevertheless, in the study region, only chemical fertilizers were applied to the soil, and wheat growth depended on rainfall, which may have helped maintain the concentrations of the studied PTEs below the established limit. Moreover, according to the international legislation for wheat grains and foodstuffs (Badeeenezhad et al., 2023). The average concentrations of PTE in the grains were below the permissible limits of 0.1, 0.1, and 0.4 g kg^{-1} for As, Cd, and Pb, respectively. Similarly, the values were within the limits suggested by (FAO/WHO, 2002), which recommended a maximum concentration of 0.20 mg kg^{-1} for all the studied PTEs for human intake. Compared with other countries, the measured concentrations of total As (0.001–0.082 mg kg^{-1}), Cd (0.001–0.080 mg kg^{-1}), and Pb (0.00–0.013 mg kg^{-1}) in the studied wheat grains fall within the lower range. The results indicated that the concentrations of these PTEs in the surveyed soils are low. Previous studies have reported that natural PTE concentrations in soil are approximately 5 mg kg^{-1} (Gersztyn et al., 2013) and normally below 10 mg kg^{-1} in uncontaminated soils (Tattibayeva et al., 2016), whereas concentrations in wheat grains are generally below 0.05 mg kg^{-1}. Overall, the results suggest that the low accumulation of PTEs in wheat grains is mainly attributable to cultivation on soils with low levels of contamination.

The highest mean concentrations of As, Cd, and Pb were measured at Site 5 (Figure 2). These raised levels may be attributed to the application of pesticides and chemical fertilizers, as well as anthropogenic activities (Alengebawy et al., 2021), in addition to the initial PTE content in the sampled soils. Tattibayeva et al. (2016) reported that the As in wheat grains originates from pesticide containing high As level, which may be transferred to wheat grains through absorption from the water cycle. Moreover, Cd and Pb are frequently correlated with phosphate fertilizers, pesticides, and other agricultural inputs applied to soils (Alengebawy et al., 2021; Alemu et al., 2022). They also reported that Cd, in particular, is known as a highly toxic contaminant with long-term harmful effects on crop quality and yield. A study by (Mussarat et al., 2021) confirmed the non-significant influence of NPK fertilizer on cumulative PTEs in wheat grains. Furthermore, the source of PTE includes other factors such as soil temperature, cultivation system, soil pH, and organic matter content (Mickovski et al., 2023).

This study investigated the relationships between soil pH, organic carbon (OC), $CaCO_3$, and potentially toxic elements (PTEs) in wheat grains. Regression analyses were performed to explore the association between the PTE concentrations in wheat grains and selected soil characteristics. The results in (Figure 3) showed that As, Cd, and Pb concentrations in wheat grain were negatively correlated with soil pH ($r = 0.42$, 0.22, and 0.19, respectively, respectively; $p \leq 0.002$, 0.0015, and 0.001). Similar findings have been reported in previous studies (Wang et al., 20220). Under alkaline conditions, the availability and mobility of particular elements, such as As and Pb, may vary and be dependent on soil chemical properties (Gersztyn et al., 2013; Wu et al., 2023). The analysis indicates that approximately 40.8% of the variation in Pte concentrations in wheat grains was attributable to soil pH. Furthermore, the concentrations of As, Cd, and Pb in the soil were positively correlated with soil OC ($r = 0.34$, 0.57, and 0.22, $p \leq 0.001$), possibly due to the presence of these metals in soil organic matter. However, other studies have shown that the application of organic amendments can reduce Cd accumulation in wheat grains (Wu et al., 2023). Soil organic matter may reduce the bioavailability of heavy metals by increasing the cation exchange capacity, forming chelate complexes with metal ions, or binding with PTEs to create complexes that are not available for plants to absorb (Kwiatkoska-Malina, 2018; Vasilachi et al., 2023). These findings highlighted that soil pH and organic matter are key factors influencing heavy metal uptake. In addition, As and Cd concentrations in wheat grains were negatively correlated with soil $CaCO_3$ content ($r = 0.35$, 0.51, $p \leq 0.0419$, and 0.001, respectively), but no correlation was observed between Pb in grain and soil $CaCO_3$ content ($r = 0.09$, $p \leq 0.294$). Gao et al. (2022) reported that the application of pig manure and $CaCO_3$ reduced Cd concentration in wheat grains by 51.96% and 45.95%, respectively, at application rates of 3% and 5%. Overall, the uptake of PTEs by wheat grains is managed through a complex interaction between plant-related factors as well as environmental conditions (Xu et al., 2022; Li et al., 2022; Wang et al., 2022).

Human PTEs-estimated chronic daily intake (CDI)

The accumulation of PTE in wheat grain can increase the potential health risk to human lives (Abbas et al., 2016). The calculated CDI values for the studied PTEs at all five sites, for both adults and children, are presented in Table 2 based on wheat grain consumption. The CDI for all studied PTEs was below the individual oral reference dose (RfD) (mg kg^{-1} day^{-1}) of 0.0003 for As, 0.0005 for Cd, and 0.0035 for Pb (Dayananda et al., 2021; de Souza et al., 2021), indicating that exposure to these elements does not pose an extreme potential health risk to the local population. The highest CDI values were observed for As in S5, followed by Pb and Cd; however, the lowest values were found for S2 in the same order. Furthermore, all CDI values for all PTEs in the current survey were below the threshold of 1, which is the safe limit of PTEs in the diet for daily exposure (de Souza et al., 2021). Across all sites, the average CDI values for children were higher than those for adults, revealing the greater susceptibility to non-carcinogenic risk. The qualified influence of PTEs followed the order Cd>As>Pb. These results are in agreement with those obtained for wheat grain in Argentina, Italy, and Ethiopia (Pompa et al., 2021; Alemu et al., 2022), but are higher than those reported

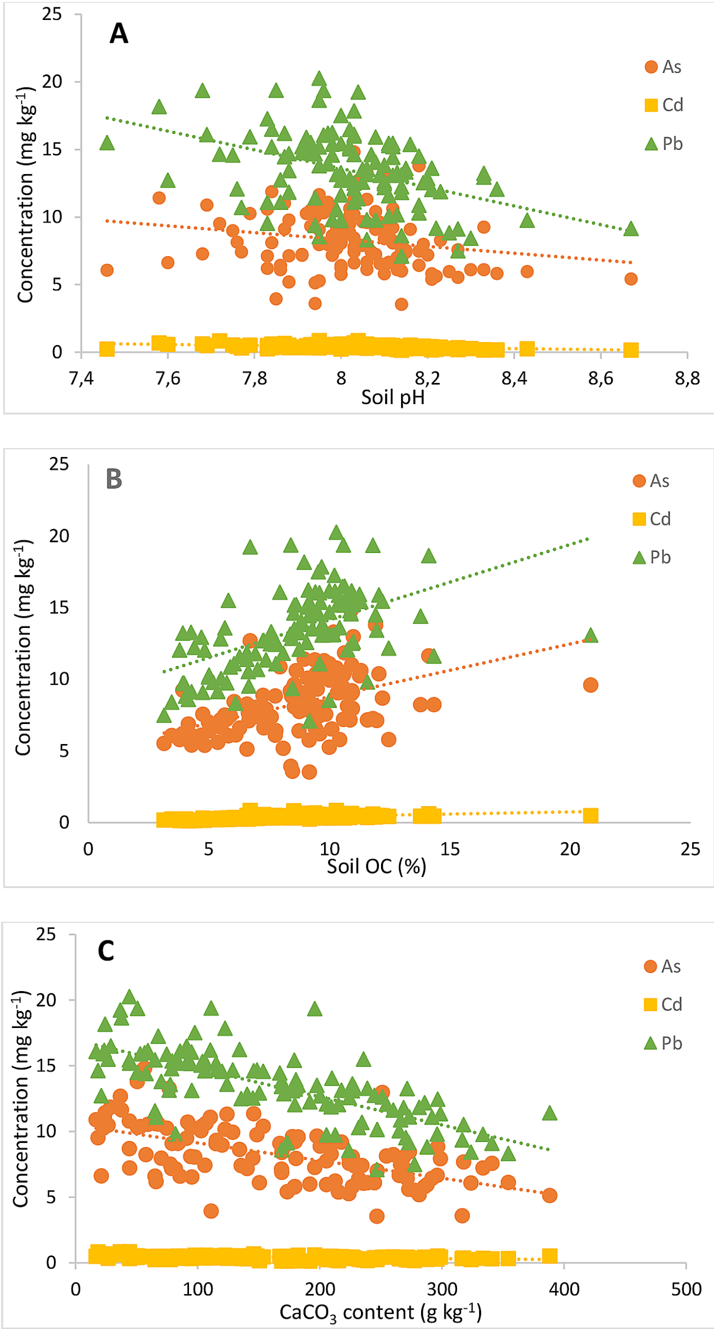

Figure 3. Correlation between soil calcium carbonate content with (Δ) Pb, (○) Cd, and (□) Cd concentrations in the studied soil sites

by Li et al. (2022) for wheat grains grown in southwestern Guizhou, China. The moderately low level of PTE observed in the current study may be attributed to the immobilization effect of calcareous soil, which decreases metal bioavailability. However, the potential health risks may increase when wheat grain is grown in the area influenced by factories and air-transported pollutants from large cities.

To evaluate the overall potential of non-carcinogenic effects from multiple PTEs, the hazard index (HI) method was applied [56], in which the sum of quotients (HQ) represents the combined risk. Potential health risks may arise when the hazard index exceeds 1. Table 3 presents a summary of the HQ and HI values for the five studied sites based on wheat consumption, along with the contribution of each metal HQ to the whole HI. Significant differences in HQ values for As, Cd, and Pb were detected among the five sites; however, the average HQ across all sites remained low, indicating that the chronic daily intake was

Table 2. Average chronic daily intake (CDI) of As, Cd, and Pd metals (mg kg^{-1} day^{-1}) through wheat grain consumption collected in different cities from the Sulaymaniyah region

Soil sites	As		Cd		Pb	
	Adult	Children	Adult	Children	Adult	Children
S1	3.19×10^{-5}	7.45×10^{-5}	5.04×10^{-5}	1.18×10^{-4}	2.15×10^{-5}	5.02×10^{-5}
S2	1.73×10^{-5}	4.04×10^{-5}	5.81×10^{-5}	1.36×10^{-4}	3.07×10^{-5}	7.17×10^{-5}
S3	2.45×10^{-5}	5.72×10^{-5}	3.82×10^{-5}	8.91×10^{-5}	5.01×10^{-5}	1.17×10^{-4}
S4	5.04×10^{-5}	1.18×10^{-4}	3.01×10^{-5}	7.02×10^{-5}	3.91×10^{-5}	9.11×10^{-5}
S5	7.75×10^{-5}	1.81×10^{-4}	5.21×10^{-5}	1.22×10^{-4}	5.51×10^{-5}	1.29×10^{-4}

within safe limits. The HQs for children attributable to wheat consumption exceeded those for adults, indicating a larger susceptibility for the younger population. This observation is consistent with findings reported in the previous study (Liu et al., 2023). The trend of PTEs corresponding to HQ for children was Cd > As > Pb, whereas for adults it was As > Cd > Pb. These values were lower than those reported for wheat grains grown in the sewage-irrigation area of Tianjin, China (Zeng et al., 2015).

In general, the average HI of the studied PTEs was less than 1, indicating a low non-carcinogenic risk. However, long-term attention should be carefully considered, mainly with deference to wheat grain consumption patterns among the population. This is notably essential because wheat is a staple food for the Kurdish population, and increased grain consumption may lead to higher cumulative health risks over time.

The excessive lifetime cancer risk associated with the studied PTEs through wheat grain consumption for adults and children is presented in Table 4. As revealed in this table, the calculated estimated ELCR values for wheat grain for both population groups are above the allowable limit (1×10^{-6}). These results indicate that cancerogenic disease for both adults and children due to PTEs exposure from wheat grain is not within the safe range. Particularly, ELCR values are higher for adults than for children (percentile 95% of ELCR < 10^{-4}, except S1, S2, S3, and S4 for adults ELCR < 10^{-5}. These findings are consistent with those reported by Baghaie and Aghili et al.

Table 3. Average of hazard quotient (HQ) for As, Cd, and Pd metals (mg kg^{-1} day^{-1}) and the total hazard index (HI) for non-cancer risks through wheat grain consumption for different cities from the Sulaymaniyah region

Soil sites	As		Cd		Pb		HQ	HI=∑HQ
	Adult	Children	Adult	Children	Adult	Children	Adult	Children
S1	0.011	0.074	0.050	0.039	0.005	0.013	0.345	0.763
S2	0.006	0.040	0.058	0.045	0.008	0.018		
S3	0.008	0.057	0.038	0.030	0.013	0.029		
S4	0.017	0.118	0.030	0.023	0.010	0.023		
S5	0.026	0.181	0.052	0.041	0.014	0.032		

Table 4. Average excessive lifetime cancer risk (ELCR) assessment of As, Cd, and Pd metals through wheat grain for adults and children in different sites from the Sulaymaniyah region

Soil sites	As		Cd		Pb	
	Adult	Children	Adult	Children	Adult	Children
S1	4.79E-05	1.12E-04	3.07E-04	7.17E-04	1.83E-04	4.27E-04
S2	2.60E-05	6.07E-05	3.54E-04	8.27E-04	2.61E-04	6.09E-04
S3	3.68E-05	8.58E-05	2.33E-04	5.44E-04	4.26E-04	9.94E-04
S4	7.56E-05	1.76E-04	1.84E-04	4.28E-04	3.32E-04	7.75E-04
S5	1.16E-04	2.71E-04	3.18E-04	7.42E-04	4.68E-04	1.09E-03

(2019). Thus, systematic superiority and severe control of wheat processing facilities are essential to ensure the production of safe and healthy bread and to minimize the transfer of PTEs into the food chain. Additionally, future studies should evaluate all stages of flour processing production to improve the understanding of the possible contamination pathway.

CONCLUSIONS

In this study, PTE concentrations were determined in wheat grains cultivated on calcareous soil in the Sulaymaniyah region of Iraqi Kurdistan. The concentrations of the analyzed PTEs in wheat remains were within the limits established by the FAO/WHO and other international legislation for wheat grain and foodstuffs. Also, the PTEs concentrations in the soil were within the average range of agricultural soils and observed with environmental standards. The results of health risk assessment indicated that carcinogenic disease associated with PTEs exposure due to wheat consumption is of concern, as the estimated ELCR exceeds the permissible level (95% percentile, ELCR $> 1 \times 10^{-6}$) for both adults and children. But, the non-carcinogenic disease for both population groups is at a safe limit (HQ, and HI <1). Therefore, continuous monitoring of soil condition and fertilizer application practice should be implemented across the region. While calcareous soils, categorized by alkaline pH and high calcium carbonate content, play a considerable role in immobilizing heavy metals through precipitation and adsorption processes, thereby decreasing their bioavailability, inadequate fertilizer management may remobilize these metals due to changes in the soil chemistry properties. Therefore, nutrient management policies are important to preserve soil condition and prevent hazards to consumers. Additional studies on PTE dynamics in the plant-soil scheme are required to confirm these results and further understand the continuing consequences.

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