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RESEARCH ARTICLE

Health risk associated with soil and plant contamination in industrial areas

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Abstract
Aims The aim of the study was to assess human health risk stemming from *i)* contact with contaminated soil and *ii)* consumption of plants growing in contaminated soils in allotment gardens and farmlands located in regions heavily affected by the Zn-Pb and steel industries and in hard coal mining areas.
Methods Based on the *pseudo*-total concentration of Potentially Toxic Elements (PTEs) measured in soil and plant samples and using the US EPA methodology, we assessed estimated daily intake (EDI), as well as non-carcinogenic and carcinogenic health risk in two exposure scenarios (recreational and residential), stemming from the contact with soil with varying degrees of PTE contamination, i.e.: $Cr^{(3+,6+)}$, Fe, Mn, Ni, Pb and Zn. In the recreational scenario, we analyzed three exposure pathways (accidental soil ingestion, dermal contact with contaminated soil and inhalation of contaminated soil particles) for a child (0–6 years), an economically active adult (20–40 years), a senior (40–60 years) and a retiree (60–70 years). In the residential scenario, we additionally analyzed an exposure pathway associated with the intake of contaminated lettuce leaves grown in the soils studied for a child and an adult. With respect to non-carcinogenic health risk, we calculated hazard quotient (HQ) values for individual contaminants under each exposure pathway and target hazard quotient (THQ) values for different exposure pathways.
Results and conclusions We found that the proportion of different exposure pathways in the total health risk decreased in the following order: intake of contaminated vegetables > accidental soil ingestion > dermal contact > inhalation of contaminated soil particles. Children are more exposed to toxic effects of potentially toxic elements than seniors and economically active adults.

Keywords Potentially Toxic Elements (PTE) · Impact of industry on human health · Lettuce · Carcinogenic risk · Non-carcinogenic risk · Silesia area

Abbreviations

Location	B-I	Bukowno, site B-I (extraction and processing of Zn-Pb ores)

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B-II		Bukowno, site B-II (extraction and processing of Zn-Pb ores)
SO		Sosnowiec (hard coal mining)
NH		Nowa Huta—Kraków (steel industry, Fe steelworks)
CŁ		Cło (the eastern border of the city of Krakow)
SŁ		Słopnice (control site)
Receptor	C	Child (0–6 y.o.)
E		Employed person (20–40 y.o)
S		Senior (40–70 y.o.)
P		Pensioner (40–60 y.o.)
R		Retiree (60–70 y.o.)
A		Adults (20–70 y.o.)
Parameters	EDI	Estimated daily intake
HQ		Hazard quotient
THQ		Target hazard quotient
HI		Hazard index
TR		Target cancerogenic risk
UL		Tolerable upper daily intake

Introduction

Nearly all Central and Eastern European Countries have witnessed a consistent decrease in farmland, with the process being spatially diverse (EC 2023). In the years 1990–2017, the agricultural area in Poland decreased by 21.1%, including arable land decline by 24.8% (Roszkowska-Mądra 2020). The loss of arable land occurred mainly in areas located next to large cities. The status of these areas was changed from agricultural to residential and the land was subsequently used for such purposes as single-family housing. Furthermore, the condition of agricultural soils has consistently worsened (Delgado-Baquerizo et al. 2013; Hidalgo-Galvez et al. 2023; Kicińska and Dmytrowski 2023). In the entire European Union (EU), deteriorated soils and those that continue to deteriorate comprise 60–70% of all soils (COM 2023). The main sources of contamination include particulate matter immissions (Borbón-Palomares et al. 2023; Kicińska 2019c), municipal and industrial wastewater runoffs (Piatak et al. 2015; Kicińska 2021, 2019b), dispersion of post-mining spoil tips associated with metal ore extraction and processing (Kicińska 2019a) and other erosive processes leading to an increase in the positive balance of noxious substances, including potentially toxic elements (PTEs), in the soil environment (Oliveira et al. 2017; Kicińska 2020, 2016a, b). PTEs have a harmful effect on humans and pets, as they are easily absorbed from the gastrointestinal tract, bioacummulate in various tissues and damage the structure of the nucleic acid chain (Nieć et al. 2013; Jartun et al. 2003; Norska-Borówka et al. 1990). As for plants, the excess of PTEs – those essential for plant growth and development as well as those that do not serve any significant metabolic function – may adversely influence physiological processes, e.g. alter the permeability of cytoplasmic membranes (Islam et al. 2016a, b; Barrow and Hartemink 2023). Apart from their harmful effect on particular groups of living organisms, excessive amounts of PTEs pose a risk of contaminating the human food chain (Diatta and Grzebisz 2011; Guney et al. 2010, WHO 2023).

The impact of PTEs on living organisms has been investigated in numerous scientific works (Islam et al. 2016a, b; Kicińska 2019b; Li et al. 2015; Norska-Borówka et al. 1990; Zheng et al. 2010). However, the monitoring of PTE content in soils has not been the main goal of these studies (Cope et al. 2010; Houghton et al. 2008). The need to assess soil health (meaning the physical, chemical and biological condition of the soil determining its capacity to function as a vital living system and to provide ecosystem service) stems from legal provisions applicable in the EU (Directive 2004). The Soil Strategy adopted by the European Commission sets out to have all soils in the EU regenerated by 2050, increase their resilience and ensure their adequate protection (COM 2023). In light of this legislation, the EU Member States will be required to prepare a list of sites contaminated with hazardous substances which may pose a major threat to the environment or human health and conduct an analysis for the content of substances potentially contaminating soil. The cited document states that: "*Healthy soils form the essential basis for our economy, society and environment as they produce food, increase our resilience to climate change, to extreme weather events, drought and floods and support our well-being*" (COM 2023).

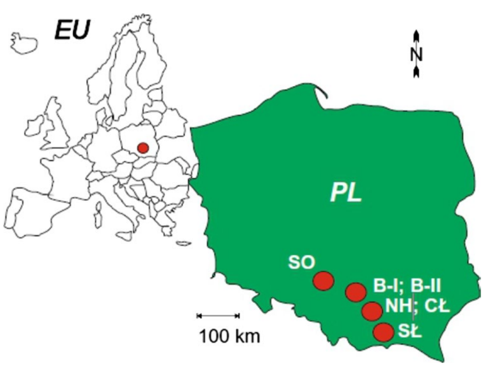
The very identification of contaminated sites or indication of exceeded permissible concentrations does not necessitate remedial actions but, in light of the strategy, points to the need of conducting a risk analysis (Warming et al. 2015; Waterlot et al. 2017; Ugolini et al. 2020). A tool that supports and complements risk analysis is a human health risk assessment. The latter is an analysis of potential negative health effects which might occur following exposure to hazardous substances present in the environment in a given area when no exposure-limiting actions are taken (i.e. remedial actions). Exposure assessment involves the determination of the extent, frequency, duration and pathways of exposure. It seems to be particularly important and necessary in areas subject to long-term impact of various industries (Kicińska and Wikar 2021a,b), where inhabitants currently grow vegetables in backyard vegetable gardens, and in allotment gardens, which additionally serve a recreational function.

In light of the facts listed above and based on extensive studies of inorganic contaminants in soils, the present paper assessed: *i*) estimated daily intake (EDI) for selected PTEs ($Cr_{total}^{(3+,6+)}$, Fe, Mn, Ni, Pb and Zn) and *ii*) total non-carcinogenic and *iii*) carcinogenic health risk in a recreational and residential exposure scenario, stemming from the contact of an individual with soil and plant (lettuce) contaminated with PTEs in an allotment garden or farmland.

Material and research area

Sample collection and processing

The research area included allotment gardens and farmlands located in southern Poland (CEE) with a varying degree of pollution (Fig. 1). These were the regions of: Bukowno (B-I, B-II, Olkusz county), Nowa Huta (NH, Kraków city area), Sosnowiec (SO, city with county rights), Cło (CŁ, eastern part of Kraków) as well as Słopnice (Limanowa county)—a typically rural-agricultural region serving as a control area. Furthermore, Sprinter type lettuce (*Lactuca sativa* L.) was used in the study. Full description of the content of Cr_{total}, Fe, Mn, Ni, Pb and Zn in the soils from the allotment gardens and farmlands analyzed and the content of these elements in the dry matter of lettuce leaves has been provided in previous papers published by Kicińska and Wikar (2021a,b). The content of these elements in the soils and plants analyzed has been presented in Tables S1 and S2. Soil samples from allotment gardens and farmlands were collected in 6 locations. These were: 2 sites in Bukowno (allotment garden B-I and backyard vegetable garden B-II), 1 site in Sosnowiec (allotment



Total concentration of metals in soils and lettuce, at different contaminated areas

Sampling site		Cr soil	Cr lettuce	Fe soil	Fe lettuce	Mn soil	Mn lettuce	Ni soil	Ni lettuce	Pb soil	Pb lettuce	Zn soil	Zn lettuce
		[mg/kg d.m. for soils and fresh mass for lettuce]											
Industrial areas													
Bukowno	B-I	16.0	0.6	11 274	13.6	556	6.5	13.2	0.3	374	0.4	1545	15.5
	B-II	15.6	1.0	10 730	16.9	842	6.8	14.9	0.5	953	0.8	3014	37.3
Sosnowiec	SO	25.3	0.7	14 703	18.4	221	3.7	21.4	0.4	232	0.8	756	15.8
Nowa Huta- Kraków	NH	38.6	0.7	21 431	43.7	573	5.9	28.0	0.4	56	0.3	349	7.6
	CŁ	29.1	0.6	15 881	14.4	643	7.6	23.3	0.3	37	0.1	153	6.0
Control site:													
Słopnice	SŁ	48.6	0.7	16 766	26.9	548	11.6	50.4	0.4	29	0.1	81	7.1

Fig. 1 Sampling sites and total concentration of metals in soils and lettuce samples

garden SO), 2 sites in Kraków (allotment garden NH; farmland CŁ), and 1 control site, namely rural area in Słopnice (farmland SŁ). The control area was chosen due to the lack of industrial impact (both historically and currently) and the possibility to carry out field experiments (lettuce planting).

Soil samples (*n* = *30*) were dried to constant weight and mineralized in aqua regia (65% HNO_3 + 37% HCl, 1:3 ratio) in an SCP Science DigiPREP HT digestion system at 130 °C (for a full description of the method, see Kicińska and Wikar 2021a). Five lettuce seedlings (*n* = *150)* were planted in each of the primary soil samples. The plants grew for 2 months (July–August) in laboratory conditions (temp. 21–23 °C and humidity 60–80%) and were watered with tap water as needed. Once fully grown, lettuce leaves were collected, dried (60 °C), ground and digested with 65% solution of nitric acid (HNO_3) and 30% hydrogen peroxide (H_2O_2) (for a full description of the method, see Kicińska and Wikar 2021b).

Methodology for health risk assessment

In the present study, we used a method based on the US EPA model. Toxicological data for health risk assessment of individual pollutants were taken from the The Risk Assessment Information System (RAIS 2023a), Integrated Risk Information System (IRIS 2023) and California Office of Environmental Health Hazard Assessment (OEHHA 2023) data bases.

The health risk analysis included non-carcinogenic and carcinogenic risk assessment in recreational and residential exposure scenarios. We analyzed two exposure pathways: dermal contact and accidental ingestion, e.g. via hand-to-mouth activity. In the case of the residential exposure scenario, we additionally analyzed an exposure pathway related to ingestion of lettuce leaves contaminated with PTE. We also performed health risk assessment associated with inhalation exposure through inhaling the finest particulate fraction (soil particles) lifted from the ground surface by walking, trampling (friction processes) and by natural air erosion factors (e.g. wind). To assess health risk for both age groups (children and adults), default exposure parameters were adopted as presented in Table 1 (recreational scenario) and Table 2 (residential scenario). To convert the content of PTEs in the dry matter of lettuce leaves into their content in fresh matter, we adopted a conversion factor of K = 0.085 (Latif et al. 2018; Ramteke et al. 2016).

Recreational exposure scenario

Health risk in the recreational exposure scenario was determined for: a child (aged 0–6 years), an economically active adult (including parents, aged 20–40 years) and a senior (pensioner or retiree, aged 40–70 years). The recreational exposure scenario applies when representatives of the above listed age groups spend time in allotment gardens. These individuals are exposed to contaminants through contact

Table 1 Default exposure parameters values adopted in the recreational scenario[1)]

Exposure Parameter	Abbreviation	Unit	Child (C)	Employed person (E)	Senior (S)	
					Pensioner (P)	Retiree (R)
Exposure frequency	EF	days/year	66	66	66	132
Exposure duration	ED	years	6	20	20	10
Body weight	BW	kg	15	70	70	70
Indicator of daily accidental soil consumption	IR_s	mg/day	200	100	100	100
Surface of the skin in contact with soil	SA	cm^2	2800	5700	5700	5700
Soil adhesion to skin	AF	$mg/cm^2•day$	0,2	0,07	0.07	0.07
Dermal-soil absorption value (ABS_d)	ABS_d	unitless	0.05[4)]	0.01[2)]	0.01[2)]	0.01[2)]
Conversion factor	CF	kg/mg	10^{-6}	10^{-6}	10^{-6}	10^{-6}
Averaging time for non-cancerogenic risk (ED·365 days/year)	AT	days	2190	7300	7300	3650
Averaging time for cancerogenic risk (70 years·365 days/year)	AT	days	25 550	25 550	25 550	25 550

Table 2 Default exposure parameters values adopted in the residential scenario

Exposure Parameter		Abbreviation	Unit	Child (C)	Adult (A)
General	Exposure duration	ED	years	6	50
	Body weight	BW	kg	15	70
	Conversion factor	CF	kg/mg	10^{-6}	10^{-6}
	Averaging time for non-cancerogenic risk (ED•365 days/year)	AT	days	2190	7300
	Averaging time for cancerogenic risk (70 years•365 days/year)	AT	days	25 550	25 550
Soil ingestion and dermal absorption	Indicator of daily accidental soil consumption	IR	mg/day	200	100
	Exposure frequency	EF	days/year	365	365
	Surface of the skin in contact with soil	SA	cm^2	2800	5700
	Soil adhesion to skin	AF	mg/cm^2•day	0,2	0,07
	Dermal-soil absorption value (ABS_d)	ABS_d	unitless	0.05[4)]	0.01[2)]
Lettuce ingestion	Exposure frequency	EF	days/year	200	200
	Conversion factor for lettuce [3),5)]	K	unitless	0,085	0,085
	Lettuce intake	FIR	g/day	50	100

[1)]Kubicz (2014), modified,

[2)]www.epa.gov, data,

[3)]Latif et al. (2018),

[4)] Smith et al. (2016),

[5)]Ramteke et al. (2016)

with contaminated soil via three exposure pathways: dermal contact, inhalation of particles of contaminated soil and accidental ingestion (e.g. via hand-to-mouth activity). It was assumed that economically active adults (parents) and their children as well as senior residents spend 1/3 of the plant growing season (i.e. 66 days) in their allotment gardens, whereas retirees spend much more time in their allotments, namely 2/3 of the growing season (132 days). We adopted the following exposure duration: 6 years for children; 20 years for economically active adults and pensioners; 10 years for retirees (Table 1).

Residential exposure scenario

The residential exposure scenario additionally includes the ingestion of lettuce grown in allotment gardens or farmlands in the analyzed areas (Kicińska and Wikar 2021b). Other than that, it comprises the same exposure pathways as the recreational exposure scenario (dermal contact with contaminated soil, inhalation or its accidental ingestion). In the residential exposure scenario, we analyzed two age groups: a child (aged 1–6 years) and an adult (> 20 years, Table 2). The exposure frequency adopted in the study was 365 days (both for children and adults), whereas the exposure duration was 6 years for a child and 50 years for an adult.

Estimated daily intake (EDI)

EDI was calculated using detailed equations for each exposure pathway (ingestion, dermal and inhalation).

To calculate EDI related to the ingestion of contaminated medium (soils and lettuce leaves) we used Eq. (1) and Eq. (2), respectively (Alaba et al. 2018; Li et al. 2015; Sawut et al. 2018; Kubicz 2014; US EPA 2023b).

$$EDI_{ing} = \frac{C_s \times EF \times IngR \times CF}{BW \times AT} \quad (1)$$

$$EDI_{\text{int}} = \frac{C_l \times EF \times ED \times FIR \times CF \times K^*}{BW \times AT} \quad (2)$$

EDI related to dermal contact with contaminated soil was calculated using Eq. (3) (Kubicz 2014; US EPA 2023a):

$$EDI_{derm} = \frac{C_s \times EF \times ED \times SA \times AF \times ABS_d \times CF}{BW \times AT} \quad (3)$$

EDI related to the inhalation of contaminated soil particles was calculated using Eq. (4) (Li et al. 2015):

$$EDI_{inh} = \frac{C_s \times EF \times ED \times ET \times InhR \times \frac{1}{PEF}}{BW \times AT} \quad (4)$$

where:

EDI estimated daily intake:

EDI_{ing} accidental ingestion [mg/day•kg];

EDI_{int} intake of contaminated lettuce leaves [mg/day•kg];

EDI_{derm} dermal contact [mg/day•kg];

EDI_{inh} inhalation [mg/day•kg];

C element concentration in each medium (C_s – in soil, C_l – in lettuce leaves) [mg/kg],

ET exposure time within 24 h [h/day],

EF exposure frequency [days/year];

ED exposure duration [years];

IngR or FIR daily accidental consumption of soil or lettuce [mg/day];

InhR contact volume [m^3/day];

BW body weight [kg];

AT averaging time [ED•365 days/year for non-carcinogenic risk or 70 years •365 days/year for carcinogenic risk];

SA skin surface in contact with the soil [cm^2];

AF soil-to-skin adhesion factor [mg/cm^2•day];

ABS_d dermal absorption factor (ABS_d = 0.01 for adult and ABS_d = 0.05 for child);

CF conversion factor [10^{-6} kg/mg];

PEF soil particle emission factor [m^3/kg];

K^* conversion factor used to convert dry matter content of lettuce to fresh matter (K = 0.085).

According to the established methodology for the assessment of exposure resulting from dermal contact with soil, the range of inorganic substance absorption through the skin falls between 0.1% and 1%. The US EPA recommends adopting 1% as a default value of the ABS_d (absorption factor dermal) for any metal (US EPA 2023a). Given the above consideration, we used the following ABS_d values in the present analysis: 0.01 for adults and 0.05 for children, as their skin is more sensitive to contaminant penetration (Smith et al. 2016).

EDI was estimated as the sum of daily doses of metal intake in individual exposure scenarios. In the case of the residential exposure scenario, this was the sum of four exposure pathways: accidental soil ingestion (EDI_{ing}), dermal contact with contaminated soil (EDI_{derm}), inhalation (EDI_{inh}) and intake of contaminated lettuce leaves (EDI_{int}) analyzed for an adult (> 20 years) and a child (0–6 years). As for the recreational exposure scenario, these were three exposure pathways: dermal contact with contaminated soil, accidental soil ingestion and inhalation. The analysis was performed for a child (0–6 years), an economically active adult (20–40 years) and a retiree (60–70 years)..

Non-carcinogenic risk assessment

When assessing health risk related to the presence of non-carcinogenic substances, their threshold effect is considered. It is assessed based on the target hazard quotient (HQ), which is defined as the ratio of a single substance exposure level in each time interval to a reference dose (RfD) for that substance from a similar exposure period (Islam et al. 2018). It was calculated using Eq. (5):

$$HQ = \frac{EDI_{ing/derm/inh}}{RfD_{ing/derm/inh}} \quad (5)$$

where:

HQ hazard quotient;

EDI (ing/derm/inh) daily dose of metal intake, calculated using a detailed equation for a given exposure pathway [mg/day•kg];

RfD reference dose [mg•(kg/day)$^{-1}$].

The total target hazard quotient (THQ) for a single contaminant under all the exposure pathways in each scenario is calculated as a sum of hazard quotients (HQ) for this substance under individual exposure pathways. In the present study, we adopted the following contaminating substances: Cr^{3+}, Fe, Mn, Ni, Pb, Zn and Cr^{6+}. As for exposure pathways, these were: ing – accidental soil ingestion, derm – dermal contact with contaminated soil, or inh – inhalation of contaminated soil particles or int – intake of contaminated lettuce leaves (in the residential exposure scenario) (Islam et al. 2018). Consequently, in the case of Pb, the total THQ_{Pb} was calculated based on Eq. (6):

$$THQ_{Pb} = HQ_{Pb-ing} + HQ_{Pb-derm} + HQ_{Pb-inh}\left(+HQ_{Pb-int.}\right) \quad (6)$$

The total THQ for a given exposure pathway, on the other hand, was calculated as a sum of HQs for individual contaminating substances under this pathway. For the exposure pathway associated with contaminated soil ingestion (THQ_{ing}), Eq. (7) was used:

$$THQ_{ing} = HQ_{Cr(III)} + HQ_{Fe} + HQ_{Mn} + HQ_{Ni} + HQ_{Pb} + HQ_{Zn} + HQ_{Cr(IV)} \quad (7)$$

The total hazard index (HI) for all the contaminants analyzed in each exposure scenario was calculated as a sum of THQs calculated for individual contaminants under all the exposure pathways (Eq. (8)).

$$HI = THQ_{Cr(III)} + THQ_{Fe} + THQ_{Mn} + THQ_{Ni} + THQ_{Pb} + THQ_{Zn} + THQ_{Cr(IV)} \quad (8)$$

HQ values ≥ 1 indicate a potential risk due to the effect of a toxic substance on the human body. In such cases, adequate preventive and protective actions need to be taken (Islam et al. 2014; 2018; Sawut et al. 2018; Li et al. 2015).

When assessing the level of non-carcinogenic risk, it is assumed that the risk from a single contaminant under a single exposure pathway is considered (Li et al. 2022):

- negligible for $HQ < 0.1$,
- low for $0.1 = HQ < 1$,
- moderate for $1 = HQ < 10$,
- high for $HQ \geq 10$.

In our study, this risk assessment scale was also used to interpret the obtained total THQ and HI values. In accordance with the Regulation of the Minister of the Environment of 1 September 2016 on the method of assessing land surface contamination, the permissible HQ value is < 1 (Regulation of the Minister of the Environment 2016). If $THQ < 1$, there is a low likelihood of evident adverse effects in the exposed population. However, $THQ \geq 1$ is associated with a potential health hazard and measurements should be conducted as part of intervention and protective actions (Islam et al. 2016a, b).

To assess the non-carcinogenic risk, we adopted RfD [mg/kg/d] presented in Table 3. We assumed that Cr^{3+} constitutes 69% of the total Cr content in soil and lettuce leaves (Li et al. 2015).

To assess the non-carcinogenic risk under the exposure pathway associated with dermal contact with the contaminated soil and under the inhalation pathway, we used Eqs. (9–12) to determine RfD and the Cancer Slope Factor (CSF) (RAIS 2023b):

Dermal contact

$$RfD_{absorbed} = \text{Oral RfD} \times \text{GI Absorption Factor} \quad (\;9)$$

$$CSF_{absorbed} = \text{Oral Slope Factor}/\text{GI Absorption Factor} \quad (10)$$

Inhalation pathway

$$RfD_{inhalation}\left[RfC\left(mg/m^3\right) \cdot 20\left(m^3/day\right)\right]/70(kg) \quad (11)$$

Table 3 Hazard quotient (HQ), target hazard quotient (THQ) and hazard index (HI) for analyzed contaminants in different pathways of exposure in the recreational scenario for industrial sites (B-I, B-II, SO, NH, CŁ) and control site (SŁ)

Location	Age Segment	Exposure pathway	HQ of elements							THQ for exposure pathway and HI
			Cr^{3+}	Fe	Mn	Ni	Pb	Zn	Cr^{6+}	
B-I	Employed person	ing	1.90E-06	4.16E-03	1.03E-03	1.70E-04	2.76E-02	1.33E-03	4.26E-04	3.47E-02
		derm	5.82E-06	1.66E-04	4.09E-05	1.70E-04	7.33E-03	2.65E-04	6.80E-04	8.66E-03
		inh	2.39E-08	-	1.21E-04	1.59E-06	3.29E-07	1.59E-08	5.37E-07	1.23E-04
		THQ for element	7.75E-06	4.33E-03	1.19E-03	3.42E-04	3.49E-02	1.60E-03	1.11E-03	**4.35E-02**
	Child	ing	1.77E-05	3.88E-02	9.57E-03	1.59E-03	2.57E-01	1.24E-02	3.98E-03	3.24E-01
		derm	1.91E-04	5.44E-03	1.34E-03	5.56E-03	2.40E-01	8.69E-03	2.23E-02	2.84E-01
		inh	4.24E-08	-	2.14E-04	2.82E-06	5.83E-07	2.83E-08	9.52E-07	2.18E-04
		THQ for element	2.08E-04	4.43E-02	1.11E-02	7.15E-03	4.98E-01	2.11E-02	2.63E-02	**6.08E-01**
	Senior	ing	5.69E-06	1.25E-02	3.08E-03	5.11E-04	8.27E-02	3.99E-03	1.28E-03	1.04E-01
		derm	1.75E-05	4.98E-04	1.23E-04	5.09E-04	2.20E-02	7.96E-04	2.04E-03	2.60E-02
		inh	1.43E-07	-	7.23E-04	9.52E-06	1.97E-06	9.57E-08	3.22E-06	7.38E-04
		THQ for element	2.33E-05	1.30E-02	3.92E-03	1.03E-03	1.05E-01	4.79E-03	3.32E-03	1.31E-01
B-II	Employed person	ing	1.85E-06	3.96E-03	1.55E-03	1.93E-04	7.03E-02	2.60E-03	4.16E-04	7.90E-02
		derm	5.68E-06	1.58E-04	6.20E-05	1.92E-04	1.87E-02	5.18E-04	6.63E-04	2.03E-02
		inh	2.33E-08	-	1.83E-04	1.80E-06	8.38E-07	3.11E-08	5.23E-07	1.86E-04
		THQ for element	7.55E-06	4.12E-03	1.80E-03	3.87E-04	8.90E-02	3.11E-03	1.08E-03	**9.95E-02**
	Child	ing	1.73E-05	3.70E-02	1.45E-02	1.80E-03	6.56E-01	2.42E-02	3.88E-03	7.38E-01
		derm	1.86E-04	5.17E-03	2.03E-03	6.30E-03	6.12E-01	1.70E-02	2.17E-02	6.65E-01
		inh	4.13E-08	-	3.24E-04	3.19E-06	1.49E-06	5.52E-08	9.28E-07	3.30E-04
		THQ for element	2.03E-04	4.21E-02	1.69E-02	8.10E-03	*1.27E+00*	4.12E-02	2.56E-02	***1.40E+00***
	Senior	ing	5.55E-06	1.19E-02	4.66E-03	5.78E-04	2.11E-01	7.79E-03	1.25E-03	2.37E-01
		derm	1.70E-05	4.74E-04	1.86E-04	5.77E-04	5.61E-02	1.55E-03	1.99E-03	6.09E-02
		inh	1.40E-07	-	1.10E-03	1.08E-05	5.03E-06	1.87E-07	3.14E-06	1.12E-03
		THQ for element	2.27E-05	1.24E-02	5.95E-03	1.17E-03	2.67E-01	9.34E-03	3.24E-03	**2.99E-01**

Table 3 (continued)

Location	Age Segment	Exposure pathway	HQ of elements							THQ for exposure pathway and HI
			Cr^{3+}	Fe	Mn	Ni	Pb	Zn	Cr^{6+}	
SO	Employed person	ing	3.00E-06	5.43E-03	4.09E-04	2.76E-04	1.72E-02	6.52E-04	6.74E-04	2.46E-02
		derm	9.21E-06	2.16E-04	1.63E-05	2.76E-04	4.56E-03	1.30E-04	1.08E-03	6.29E-03
		inh	3.78E-08	-	4.80E-05	2.58E-06	2.05E-07	7.82E-09	8.49E-07	5.17E-05
		THQ for element	1.23E-05	5.64E-03	4.73E-04	5.55E-04	2.17E-02	7.83E-04	1.75E-03	**3.09E-02**
	Child	ing	2.80E-05	5.06E-02	3.81E-03	2.58E-03	1.60E-01	6.09E-03	6.29E-03	2.30E-01
		derm	3.02E-04	7.09E-03	5.34E-04	9.03E-03	1.49E-01	4.26E-03	3.52E-02	2.06E-01
		inh	6.70E-08	-	8.51E-05	4.57E-06	3.63E-07	1.39E-08	1.51E-06	9.17E-05
		THQ for element	3.30E-04	5.77E-02	4.43E-03	1.16E-02	3.10E-01	1.04E-02	4.15E-02	**4.36E-01**
	Senior	ing	9.01E-06	1.63E-02	1.23E-03	8.29E-04	5.15E-02	1.96E-03	2.02E-03	7.38E-02
		derm	2.76E-05	6.49E-04	4.89E-05	8.27E-04	1.37E-02	3.90E-04	3.23E-03	1.89E-02
		inh	2.27E-07	-	2.88E-04	1.55E-05	1.23E-06	4.69E-08	5.09E-06	3.10E-04
		THQ for element	3.69E-05	1.69E-02	1.56E-03	1.67E-03	6.51E-02	2.35E-03	5.26E-03	**9.30E-02**
NH	Employed person	ing	4.59E-06	7.91E-03	1.06E-03	3.62E-04	4.16E-03	3.00E-04	1.03E-03	1.48E-02
		derm	1.41E-05	3.16E-04	4.22E-05	3.61E-04	1.11E-03	5.99E-05	1.64E-03	3.55E-03
		inh	5.78E-08	-	1.24E-04	3.38E-06	4.96E-08	3.60E-09	1.30E-06	1.29E-04
		THQ for element	1.87E-05	8.22E-03	1.22E-03	7.27E-04	5.27E-03	3.60E-04	2.68E-03	1.85E-02
	Child	ing	4.28E-05	7.38E-02	9.88E-03	3.38E-03	3.89E-02	2.80E-03	9.62E-03	1.38E-01
		derm	4.61E-04	1.03E-02	1.38E-03	1.18E-02	3.63E-02	1.96E-03	5.39E-02	1.16E-01
		inh	1.02E-07	-	2.20E-04	5.99E-06	8.80E-08	6.39E-09	2.30E-06	2.29E-04
		THQ for element	5.04E-04	8.41E-02	1.15E-02	1.52E-02	7.51E-02	4.77E-03	6.35E-02	**2.55E-01**
	Senior	ing	1.38E-05	2.37E-02	3.17E-03	1.09E-03	1.25E-02	9.01E-04	3.09E-03	4.45E-02
		derm	4.22E-05	9.47E-04	1.27E-04	1.08E-03	3.32E-03	1.80E-04	4.93E-03	1.06E-02
		inh	3.47E-07	-	7.46E-04	2.03E-05	2.98E-07	2.16E-08	7.79E-06	7.75E-04
		THQ for element	5.64E-05	2.47E-02	4.05E-03	2.19E-03	1.58E-02	1.08E-03	8.03E-03	**5.59E-02**

Table 3 (continued)

Location	Age Segment	Exposure pathway	HQ of elements							THQ for exposure pathway and HI
			Cr^{3+}	Fe	Mn	Ni	Pb	Zn	Cr^{6+}	
CŁ	Employed person	ing	3,46E-06	5,86E-03	1,19E-03	3,01E-04	2,77E-03	1,32E-04	7,76E-04	1,10E-02
		derm	1,06E-05	2,34E-04	4,73E-05	3,00E-04	7,36E-04	2,64E-05	1,24E-03	2,59E-03
		inh	4,35E-08	-	1,39E-04	2,81E-06	3,30E-08	1,58E-09	9,77E-07	1,43E-04
		THQ for element	1,41E-05	6,09E-03	1,37E-03	6,04E-04	3,50E-03	1,59E-04	2,02E-03	**1,38E-02**
	Child	ing	3,23E-05	5,47E-02	1,11E-02	2,81E-03	2,58E-02	1,23E-03	7,25E-03	<u>1,03E-01</u>
		derm	3,47E-04	7,66E-03	1,55E-03	9,83E-03	2,41E-02	8,63E-04	4,06E-02	8,49E-02
		inh	7,72E-08	-	2,47E-04	4,98E-06	5,85E-08	2,81E-09	1,73E-06	2,54E-04
		THQ for element	3,80E-04	6,24E-02	1,29E-02	1,26E-02	4,99E-02	2,10E-03	4,78E-02	<u>**1,88E-01**</u>
	Senior	ing	1,04E-05	1,76E-02	3,56E-03	9,03E-04	8,30E-03	3,96E-04	2,33E-03	3,31E-02
		derm	3,18E-05	7,02E-04	1,42E-04	9,01E-04	2,21E-03	7,91E-05	3,72E-03	7,78E-03
		inh	2,61E-07	-	8,36E-04	1,68E-05	1,98E-07	9,51E-09	5,86E-06	8,59E-04
		THQ for element	4,25E-05	1,83E-02	4,54E-03	1,82E-03	1,05E-02	4,76E-04	6,05E-03	**4,17E-02**
SŁ	Employed person	ing	5,77E-06	6,19E-03	1,01E-03	6,52E-04	2,12E-03	6,98E-05	1,30E-03	1,13E-02
		derm	1,77E-05	2,47E-04	4,03E-05	6,50E-04	5,65E-04	1,39E-05	2,07E-03	3,60E-03
		inh	7,26E-08	-	1,19E-04	6,08E-06	2,53E-08	8,37E-10	1,63E-06	1,27E-04
		THQ for element	2,36E-05	6,43E-03	1,17E-03	1,31E-03	2,69E-03	8,37E-05	3,37E-03	**1,51E-02**
	Child	ing	5,39E-05	5,77E-02	9,43E-03	6,08E-03	1,98E-02	6,51E-04	1,21E-02	<u>1,06E-01</u>
		derm	5,80E-04	8,08E-03	1,32E-03	2,13E-02	1,85E-02	4,56E-04	6,77E-02	<u>1,18E-01</u>
		inh	1,29E-07	-	2,11E-04	1,08E-05	4,49E-08	1,48E-09	2,89E-06	2,24E-04
		THQ for element	6,34E-04	6,58E-02	1,10E-02	2,74E-02	3,83E-02	1,11E-03	7,98E-02	<u>**2,24E-01**</u>
	Senior	ing	1,73E-05	1,86E-02	3,03E-03	1,95E-03	6,37E-03	2,09E-04	3,89E-03	3,40E-02
		derm	5,31E-05	7,41E-04	1,21E-04	1,95E-03	1,69E-03	4,18E-05	6,21E-03	1,08E-02
		inh	4,36E-07	-	7,12E-04	3,65E-05	1,52E-07	5,02E-09	9,79E-06	7,59E-04
		THQ for element	7,09E-05	1,93E-02	3,86E-03	3,94E-03	8,06E-03	2,51E-04	1,01E-02	**4,56E-02**

*__bold__ – HI value, <u>underline</u> – low risk; *italics* – medium risk

$$CSF_{inhalation} = \text{Unitrisk}\left(\mu g/m^3\right)^{-1} \cdot 70(kg) \cdot 20\left(m^3/day\right)^{-1} \cdot 1000(\mu g/mg) \quad (12)$$

where:

RfC Reference Concentration [mg/m^3],

GI Gastrointestinal absorption factor (GIAF).

Carcinogenic risk assessment

The effect of carcinogens has no threshold. This means that even a small amount of these substances can cause cancerous lesions. Thus, it is difficult to determine the exact dose of a carcinogen that would pose a risk of such lesions. It is only possible to estimate the probability value. The risk that is deemed acceptable falls in the range of 10E-04 and 10 E-06 (US EPA 2023a). According to the US EPA regulations, the risk of 10 E-06 means that 1 in 1 000 000 individuals in a given population will develop cancer.

The carcinogenic target risk (TR) for any element under a given exposure pathway was calculated using Eq. (13):

$$TR = EDI \times CSF \quad (13)$$

It is assumed that the risk is (Islam et al. 2016a, b):

- negligible for TR < 1.0E-06,
- acceptable for 1.0E-04 < TR = 1.0E-06,
- unacceptable for TR ≥ 1.0E-04.

Carcinogenic TR higher than 1.0E-03 necessitates taking preventive and protective actions. The risk of 1.0E-04 < TR < 1.0E-03 is not acceptable, yet it does not require taking preventive action (Gworek et al. 2002).

When assessing chemically degraded areas in Poland, TR = 1.0E-06 was usually adopted as an acceptable carcinogenic risk level for a single substance, whereas the range from TR = 1.0E-06 to TR = 1.0E-04 was treated as a permissible total carcinogenic risk level in the area studied (Wcisło et al. 2016). In accordance with the Regulation of the Minister of the Environment of 1 September 2016 on the method of assessing land surface contamination, the permissible TR value is < 1.0E-05 (Regulation of the Minister of the Environment 2016). In the present analysis we adopted TR = 1.0E-05 as a permissible carcinogenic risk level for a single substance and TR = 1.0E-04 as a permissible total carcinogenic risk level in the studied area (Wcisło et al. 2016). To assess the carcinogenic risk, we adopted cancer potency factors presented in Table 3. We assumed that Cr^{6+} constitutes 31% of the total Cr content in soil and lettuce leaves (Li et al. 2015).

Results

Health risk assessment—recreational exposure scenario

Non-carcinogenic risk

The total non-carcinogenic health risk HI calculated in the recreational scenario ranged from 2.55E-03 to 1.40E + 00 for a child, from 1.51E-02 to 9.95E-02 for an economically active adult and from 4.17E-02 to 2.99E-01 for a senior (Table 3). Calculation results for three exposure pathways are presented below.

Accidental soil ingestion

When analyzing HQ under the accidental soil ingestion exposure pathway, we observed the highest values for Pb (samples from Bukowno and Sosnowiec) and for Fe (samples from Słopnice, Nowa Huta and Cło). The highest HQ value was obtained for a child (6.56E-01) and was associated with accidental ingestion of soil contaminated with Pb in Bukowno (B–II), which points to a low risk (1.0E-01 < HQ < 1.0E + 00). For this age group, the same risk level was also found in the other site in Bukowno (B–I, HQ = 2.57E-01) and in Sosnowiec (HQ = 1.60E-01). A low risk from Pb HQ = 2.11E-01) was also found in B-II for seniors (> 40 years). In the case of the other sites and metals, the non-carcinogenic risk was negligible (HQ < 1.0E-01).

When comparing the estimated HQ values for individual metals with the permissible HQ value set out in the Regulation of the Minister of the Environment of 1 September 2016 on the method of assessing land surface contamination (Regulation of the Minister of the Environment 2016), we found that the health risk was acceptable, as the value did not exceed HQ = 1 in any of the cases.

Under the exposure pathway analyzed, the highest THQ_{ing} value was found in the region of extraction and processing of Zn-Pb ores, i.e. in Bukowno, and more specifically in site B-II. THQ_{ing} in this location was 7.38E-01 (child), 2.37E-01 (senior) and 7.90E-02 (economically active adult). These parameters point to a low health risk in the case of children and seniors, and a negligible risk in the case of economically active adults. The total THQ_{ing} values estimated for the other sites also indicate a low risk for children and seniors exposed to accidental soil ingestion in Bukowno (sites B-I and B-II). As for the other groups and locations, the obtained THQ_{ing} values point to a negligible risk (Table 3, Fig. 2).

Dermal contact with contaminated soil

Under the exposure pathway associated with dermal contact with contaminated soil, the calculated HQ values point to:

- a low health risk of Pb for children in Bukowno and Sosnowiec. In these locations, HQ was 2.40E-01 (B-I), 6.12E-01 (B-II) and 1.49E-01 (SO).
- a negligible risk for children in the other locations and for the other age groups (Table 3).

Given the permissible HQ level of 1, the estimated values of this indicator for the metals analyzed in all the age groups and all the locations are acceptable.

As for THQ_{derm}, we found the highest values for children in Bukowno (2.84E-01 and 6.65E-01). These results point to a low risk, as was the case with nearly all the other locations (Table 3; Fig. 3). The exception was Cło, where the risk was negligible (THQ_{derm} = 8.49E-02). For all the other locations and age groups, the health risk was negligible.

Inhalation of contaminated soil particles (inhalation pathway)

The level of non-carcinogenic health risk stemming from the inhalation of contaminated soil particles was found to be negligible for the age groups located in all the locations. The highest THQ_{inh} value (3.30E-03) under this exposure pathway was found for a child and the lowest (1.27E-04) for an economically active adult in the control area of Słopnice (Table 3).

The THQ_{inh} values constitute an insignificant share (0.04–0.56%) in the level of the total non-carcinogenic health risk in the recreational exposure scenario. Thus, they could be omitted when estimating HI.

The HI values obtained indicate that accidental soil ingestion calculated in accordance with the default exposure parameters presented in Table 1 (as a sum of HQs for all the exposure pathways analyzed) for all the contaminants (Cr^{3+}, Fe, Mn, Ni, Pb, Zn and Cr^{6+}) had the highest share in the recreational exposure scenario. As for individual contaminants, two metals had the highest share in health risk: Pb (in the region of Zn-Pb ore mining and processing) and Fe (in the other areas).

The analyzed HIs for individual elements contaminating the industrial areas studied, we found that these values descended in the following order:

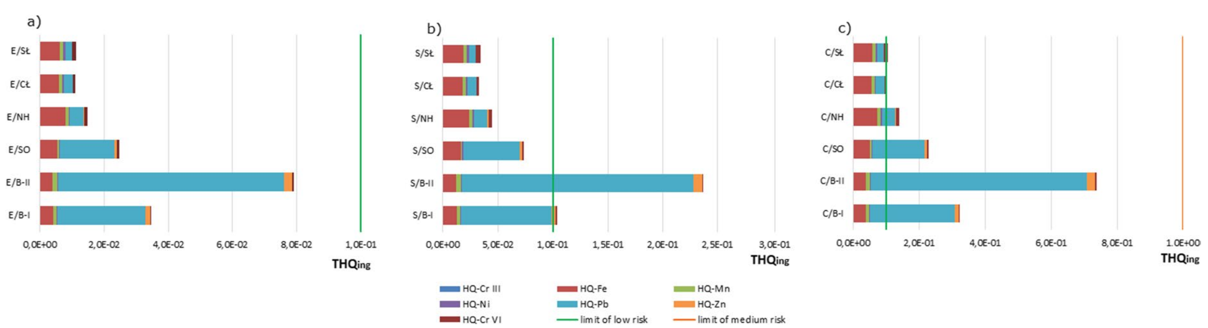


Fig. 2 Target hazard quotient (THQ_{ing}) for analyzed contaminants in the pathway of exposure: *accidental soil ingestion* [**a**) employed person; **b**) senior **c**) child]

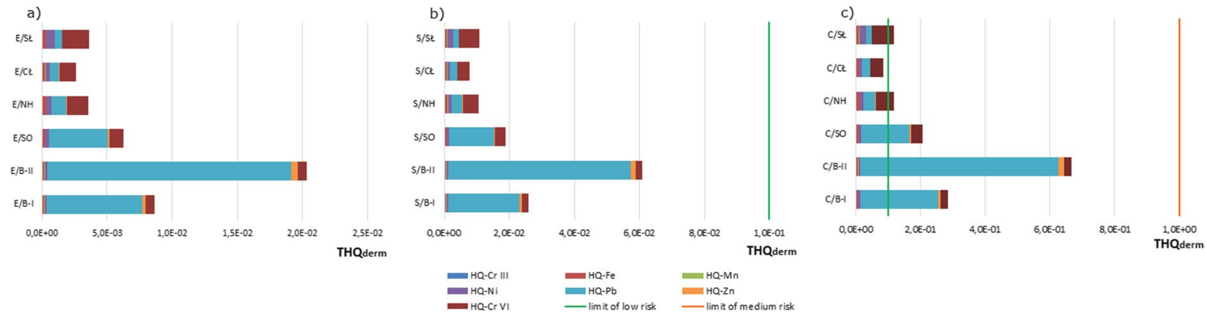


Fig. 3 Target hazard quotient (THQ_{derm}) for analyzed contaminants in the pathway of exposure: *dermal contact with contaminated soil* [**a**) employed person; **b**) senior **c**) child]

– **Pb** > Fe > **Zn** > Mn > Cr^{6+} > Ni > Cr^{3+} in the region of Zn-Pb ore mining and processing (Bukowno, sites B-I and B-II),
– Pb > **Fe** > Cr^{6+} > Zn > Ni > Mn > Cr^{3+} in the region of hard coal mining and steel processing (Sosnowiec SO),
– **Fe** > Pb > Cr^{6+} > Mn > Ni > Zn > Cr^{3+} in Kraków metropolitan area and the region of steel processing (NH and CŁ) (Table 3).

These sequences reflect the impact of industrial activity in the analyzed areas: mining and processing of Zn and Pb ores in Bukowno, hard coal mining in Sosnowiec and a metalworking conglomerate in Nowa Huta in the Kraków region, which has been demonstrated in the previous studies by Kicińska and Wikar (2021a).

As regards Słopnice (SŁ), which represents a typical rural-agricultural region, HI values descended in the following order: Fe > Cr^{6+} > Pb > Ni > Mn > Zn > Cr^{3+} (Table 3), with a relatively high share of Cr^{6+}.

Carcinogenic risk

We found an acceptable level of health risk caused by the presence of carcinogens: Cr^{6+} and Pb in soils, for both a child and a senior as well as for an economically active adult (TR < 1.0E-05). A similar relationship was also observed in the case of the total carcinogenic risk estimated for dermal contact with contaminated soil and accidental soil ingestion. The obtained TR values were below 1.0E-04. Importantly, an analysis performed for a child in the Słopnice region showed that the TR value was close to the permissible carcinogenic risk level for a single substance (TR = 1.00E-05). Under this exposure pathway, the acceptable risk level was exceeded for a senior in Nowa Huta, Cło and Słopnice (TR = 1.41E-06, 1.06E-06 and 1.77E-06, respectively).

In the case of accidental soil ingestion, the risk level (TR = 1.00E-06) was exceeded for a child in Słopnice and Nowa Huta (TR_{Cr6+} = 1.56E-06 and TR_{Cr6+} = 1.24E-06, respectively) and for a senior in Słopnice (TR_{Cr6+} = 1.11E-06). However, it did not exceed the acceptable level for carcinogenic risk (TR = 1.00E-05). In the other cases, carcinogenic risk stemming from exposure to Cr^{6+} was negligible.

As for carcinogenic risk related to exposure to Pb in soils, we found it to be negligible in all the locations (TR_{Pb} < 1.00E-05).

Health risk assessment – residential exposure scenario

Non-carcinogenic risk

In the residential exposure scenario, the calculated risk level was similar to that observed in the recreational scenario. The total HI for a child in all the locations was below 1.00E + 00, which points to a moderate health risk. Importantly, the HI value for a child in Bukowno (site B-II) was close to the borderline high-risk level (HI = 8.81E + 00). This value was to the greatest extent determined by the content of Pb in soil (HQ_{Pb} = 7.47E + 00). In the case of adults, the highest HI value was found for Bukowno (HI = 1.00E + 00) and the lowest for Cło (HI = 2.38E-01), which points to a low risk at the analyzed areas (Table 4).

In the residential scenario, the risk stemming from the presence of individual metals in soils was found to be low for a child living in:

- Bukowno due to the THQ values obtained for Fe (2.80E-01 and 2.77E-01), Zn (2.11E-01 and 4.55E-01), Cr^{6+} (2.55E-01 and 3.36E-01), and Mn (1.82E-01),
- Sosnowiec (SO) due to the THQ values obtained for Fe (3.67E-01), Zn (1.54E-01) and Cr^{6+} (3.71E-01) and Nowa Huta (NH), Cło (CŁ) and Słopnice (SŁ) due to the THQ values for Fe, Mn, Ni, Pb, Cr^{6+} (Table 4).

A low health risk stemming from the presence of Pb in soils was also found for an adult living in Bukowno (THQ_{Pb} = 2.91E-01 and THQ_{Pb} = 6.87E-01) and Sosnowiec (THQ_{Pb} = 2.92E-01). A similar risk level associated with exposure to Zn was also observed in site B-II in Bukowno (THQ_{Zn} = 1.15E-01).

Accidental soil ingestion

The HQ values calculated for individual metals under the accidental soil ingestion exposure pathway (Table 4) point to a low health risk for an adult living in Bukowno only for Pb exposure (HQ_{Pb} = 1.52E-01 for site B-I and HQ_{Pb} = 3.89E-01 for site B-II). As for all the other analyzed metals and in all the locations, the level of health risk for an adult was deemed negligible. The total THQ_{ing} calculated for an adult confirmed that the risk posed by accidental soil ingestion is low for adults living in Bukowno (1.92E-01, 4.37E-01) and Sosnowiec (1.36E-01)(Fig. 4a).

In the case of a child, the risk level was moderate for Bukowno due to the HQ values calculated for Pb (HQ_{Pb} = 1.42E + 00 in B-I and HQ_{Pb} = 3.63E + 00 in B-II). In the remaining locations, the health risk was low (Sosnowiec: HQ_{Pb} = 8.85E-01, Nowa Huta: HQ_{Pb} = 2.15E-01, Cło: HQ_{Pb} = 1.43E-01 and Słopnice: HQ_{Pb} = 1.10E-01). HQ calculated for the content of Zn in soil collected in Bukowno also pointed to a low risk (1.34E-01). In the remaining cases, the risk was negligible (Fig. 4b).

In both age groups, the HI value was predominantly determined by Pb content in the soils from Bukowno and Sosnowiec. Otherwise, in Nowa Huta, Cło and Słopnice the health risk was associated with a considerable amount of Fe.

Dermal contact with contaminated soil

The HQ values calculated for individual elements in soils under the dermal contact exposure pathway for a child and an adult living in the regions analyzed point to (Table 4):

- a moderate risk for a child living in Bukowno, caused by Pb content (site B-I: HQ_{Pb} = 1.33E + 00; site B-II: HQ_{Pb} = 3.39E + 00),
- a low risk for a child living in any other location, caused by Cr^{6+} content (1.0E-01 < HQ_{Cr6+} < 1.0E + 00),
- a low risk for a child, caused by Pb content of in Sosnowiec (HQ_{Pb} = 8.26E-01), Nowa Huta (HQ_{Pb} = 2.01E-01), Cło (HQ_{Pb} = 1.33E-01) and Słopnice (HQ_{Pb} = 1.02E-01),
- a low risk caused by the Ni content in Słopnice (HQ_{Ni} = 1.18E-01).

To conclude, the THQ_{derm} values point to a moderate health risk for a child living in Bukowno (1.57E + 00 and 3.68E + 00*)* and Sosnowiec (1.14E + 00), and a low risk for children living in the other locations (Table 4; Fig. 5b). A low risk was also found for an adult living in Bukowno due to Pb soil content (HQ_{Pb} = 1.03E-01, THQ_{derm} = 1.12E-01) (Fig. 5a).

Contaminated lettuce intake The residential exposure scenario included one more exposure pathway, namely the intake of contaminated lettuce leaves growing in the soils analyzed. The HQ values obtained revealed a different relationship from what we observed when analyzing the other exposure pathways. Proportions between individual metals changed.

In the case of an adult, low risk pertained to the inhabitants of Bukowno and Sosnowiec (HQ_{Pb} = 1.72E-01) who consumed lettuce leaves contaminated with Pb (HQ_{Pb} = 1.95E-01). As for the other PTEs, health risk for an adult consuming lettuce growing in the areas analyzed was found to be negligible. When analyzing the THQ_{int} values, we found that low risk applied to an adult living in any of the

Table 4 Hazard quotient (HQ), target hazard index (THQ) and hazard index (HI) for analyzed contaminants on the pathways of exposure in the residential scenario for industrial sites (B-I, B-II, SO, NH, CŁ) and control site (SŁ)

Location	Age segment	Exposure pathway	HQ							THQ for exposure pathway And HI
			Cr^{3+}	Fe	Mn	Ni	Pb	Zn	Cr^{6+}	
B-I	Adult	Ing	1.05E-05	2.30E-02	5.67E-03	9.41E-04	1.52E-01	7.36E-03	2.36E-03	1.92E-01
		Derm	3.22E-05	9.18E-04	2.26E-04	9.39E-04	4.06E-02	1.47E-03	3.76E-03	4.79E-02
		Inh	1.32E-07	-	6.66E-04	8.78E-06	1.82E-06	8.82E-08	2.97E-06	6.80E-04
		Int	2.10E-04	1.52E-02	3.61E-02	1.16E-02	9.83E-02	4.04E-02	4.71E-02	2.49E-01
		THQ for element	2.52E-04	3.92E-02	4.27E-02	1.35E-02	2.91E-01	4.92E-02	5.32E-02	**4.89E-01**
	Child	Ing	9.79E-05	2.15E-01	5.29E-02	8.79E-03	*1.42E+00*	6.87E-02	2.20E-02	*1.79E+00*
		Derm	1.05E-03	3.01E-02	7.41E-03	3.08E-02	*1.33E+00*	4.81E-02	1.23E-01	*1.57E+00*
		Inh	2.34E-07	-	1.18E-03	1.56E-05	3.22E-06	1.56E-07	5.26E-06	1.21E-03
		Int	4.89E-04	3.55E-02	8.43E-02	2.71E-02	2.29E-01	9.43E-02	1.10E-01	5.81E-01
		THQ for element	1.64E-03	2.80E-01	1.46E-01	6.67E-02	*2.98E+00*	2.11E-01	2.55E-01	***3.94E+00***
B-II	Adult	Ing	1.02E-05	2.19E-02	8.60E-03	1.07E-03	3.89E-01	1.44E-02	2.30E-03	4.37E-01
		Derm	3.14E-05	8.74E-04	3.43E-04	1.06E-03	1.03E-01	2.86E-03	3.67E-03	1.12E-01
		Inh	1.29E-07	-	1.01E-03	9.94E-06	4.64E-06	1.72E-07	2.89E-06	1.03E-03
		Int	3.70E-04	1.90E-02	3.82E-02	2.00E-02	1.95E-01	9.74E-02	8.31E-02	4.53E-01
		THQ for element	4.12E-04	4.17E-02	4.81E-02	2.21E-02	6.87E-01	1.15E-01	8.91E-02	**1.00E+00**
	Child	Ing	9.55E-05	2.04E-01	8.02E-02	9.95E-03	*3.63E+00*	1.34E-01	2.15E-02	*4.08E+00*
		Derm	1.03E-03	2.86E-02	1.12E-02	3.48E-02	*3.39E+00*	9.38E-02	1.20E-01	*3.68E+00*
		Inh	2.28E-07	-	1.79E-03	1.76E-05	8.22E-06	3.05E-07	5.13E-06	1.82E-03
		Int	8.63E-04	4.42E-02	8.91E-02	4.66E-02	4.54E-01	2.27E-01	1.94E-01	*1.06E+00*
		THQ for element	1.99E-03	2.77E-01	1.82E-01	9.14E-02	7.47E+00	4.55E-01	3.36E-01	***8.81E+00***
SO	Adult	Ing	1.66E-05	3.00E-02	2.26E-03	1.53E-03	9.49E-02	3.61E-03	3.73E-03	1.36E-01
		Derm	5.10E-05	1.20E-03	9.01E-05	1.52E-03	2.52E-02	7.20E-04	5.95E-03	3.48E-02
		Inh	2.09E-07	-	2.65E-04	1.43E-05	1.13E-06	4.33E-08	4.70E-06	2.86E-04
		Int	2.69E-04	2.06E-02	2.09E-02	1.45E-02	1.72E-01	4.13E-02	6.04E-02	3.30E-01
		THQ form element	3.36E-04	5.18E-02	2.35E-02	1.76E-02	2.92E-01	4.57E-02	7.01E-02	**5.01E-01**
	Child	Ing	1.55E-04	2.80E-01	2.11E-02	1.43E-02	8.85E-01	3.37E-02	3.48E-02	*1.27E+00*
		Derm	1.67E-03	3.92E-02	2.95E-03	4.99E-02	8.26E-01	2.36E-02	1.95E-01	*1.14E+00*
		Inh	3.71E-07	-	4.71E-04	2.53E-05	2.01E-06	7.67E-08	8.33E-06	5.07E-04
		Int	6.27E-04	4.81E-02	4.87E-02	3.38E-02	4.01E-01	9.64E-02	1.41E-01	7.70E-01
		THQ for element	2.45E-03	3.67E-01	7.32E-02	9.80E-02	*2.11E+00*	1.54E-01	3.71E-01	***3.18E+00***

Table 4 (continued)

Location	Age segment	Exposure pathway	HQ							THQ for exposure pathway And HI
			Cr^{3+}	Fe	Mn	Ni	Pb	Zn	Cr^{6+}	
NH	Adult	Ing	2.54E-05	4.37E-02	5.85E-03	2.00E-03	2.30E-02	1.66E-03	5.70E-03	8.20E-02
		Derm	7.79E-05	1.75E-03	2.33E-04	2.00E-03	6.13E-03	3.31E-04	9.10E-03	1.96E-02
		Inh	3.19E-07	-	6.88E-04	1.87E-05	2.75E-07	1.99E-08	7.18E-06	7.14E-04
		Int	2.62E-04	4.88E-02	3.33E-02	1.55E-02	6.79E-02	1.98E-02	5.88E-02	2.44E-01
		THQ for element	3.65E-04	9.43E-02	4.00E-02	1.95E-02	9.70E-02	2.18E-02	7.36E-02	**3.47E-01**
	Child	Ing	2.37E-04	4.08E-01	5.46E-02	1.87E-02	2.15E-01	1.55E-02	5.32E-02	7.65E-01
		Derm	2.55E-03	5.72E-02	7.65E-03	6.54E-02	2.01E-01	1.09E-02	2.98E-01	6.42E-01
		Inh	5.66E-07	-	1.22E-03	3.31E-05	4.87E-07	3.53E-08	1.27E-05	1.27E-03
		Int	6.11E-04	1.14E-01	7.76E-02	3.61E-02	1.58E-01	4.63E-02	1.37E-01	5.70E-01
		THQ for element	3.40E-03	5.79E-01	1.41E-01	1.20E-01	5.74E-01	7.27E-02	4.88E-01	***1.98E+00***
CŁ	Adult	Ing	1.91E-05	3.24E-02	6.56E-03	1.66E-03	1.53E-02	7.31E-04	4.29E-03	6.10E-02
		Derm	5.87E-05	1.29E-03	2.62E-04	1.66E-03	4.07E-03	1.46E-04	6.85E-03	1.43E-02
		Inh	2.41E-07	-	7.71E-04	1.55E-05	1.82E-07	8.76E-09	5.41E-06	7.92E-04
		Int	2.26E-04	1.61E-02	4.24E-02	1.34E-02	2.31E-02	1.56E-02	5.08E-02	1.62E-01
		THQ for element	3.04E-04	4.98E-02	5.00E-02	1.68E-02	4.25E-02	1.65E-02	6.19E-02	**2.38E-01**
	Child	Ing	1.78E-04	3.03E-01	6.12E-02	1.55E-02	1.43E-01	6.82E-03	4.01E-02	5.69E-01
		Derm	1.92E-03	4.24E-02	8.57E-03	5.44E-02	1.33E-01	4.78E-03	2.24E-01	4.70E-01
		Inh	4.27E-07	-	1.37E-03	2.75E-05	3.23E-07	1.55E-08	9.59E-06	1.40E-03
		Int	5.27E-04	3.76E-02	9.90E-02	3.13E-02	5.39E-02	3.65E-02	1.18E-01	3.77E-01
		THQ for element	2.63E-03	3.82E-01	1.70E-01	1.01E-01	3.30E-01	4.81E-02	3.83E-01	***1.42E+00***

Table 4 (continued)

Location	Age segment	Exposure pathway	HQ Cr^{3+}	Fe	Mn	Ni	Pb	Zn	Cr^{6+}	THQ for exposure pathway And HI
SŁ	Adult	Ing	3.19E-05	3.42E-02	5.59E-03	3.60E-03	1.17E-02	3.86E-04	7.17E-03	6.27E-02
		Derm	9.79E-05	1.37E-03	2.23E-04	3.59E-03	3.12E-03	7.70E-05	1.14E-02	1.99E-02
		Inh	4.02E-07	-	6.57E-04	3.36E-05	1.40E-07	4.63E-09	9.02E-06	7.00E-04
		Int	2.61E-04	3.01E-02	6.47E-02	1.72E-02	2.25E-02	1.84E-02	5.87E-02	2.12E-01
		THQ for element	3.91E-04	6.57E-02	7.11E-02	2.45E-02	3.74E-02	1.89E-02	7.73E-02	**2.95E-01**
	Child	Ing	2.98E-04	3.19E-01	5.22E-02	3.36E-02	1.10E-01	3.60E-03	6.69E-02	5.85E-01
		Derm	3.21E-03	4.47E-02	7.30E-03	1.18E-01	1.02E-01	2.52E-03	3.75E-01	6.52E-01
		Inh	7.12E-07	-	1.16E-03	5.96E-05	2.48E-07	8.21E-09	1.60E-05	1.24E-03
		Int	6.09E-04	7.02E-02	1.51E-01	4.02E-02	5.25E-02	4.30E-02	1.37E-01	4.94E-01
		THQ for element	4.12E-03	4.34E-01	2.11E-01	1.92E-01	2.64E-01	4.91E-02	5.78E-01	***1.73E+00***

* **bold** –HI value, underline – low risk; *italics* – medium risk

locations studied, with the highest value recorded for an inhabitant of Bukowno (4.52E-01) and the lowest for a person living in Cło (1.62E-01) (Table 4; Fig. 6a).

Human health risk calculated for a child living in Bukowno (B-I, B-II), Sosnowiec and Nowa Huta were low due to Pb soil content (HQ_{Pb} = 1.10E-01, HQ_{Pb} = 4.54E-01, HQ_{Pb} = 4.01E-01 and HQ_{Pb} = 1.58E-01, respectively). The same health risk level was also obtained for a child living in Nowa Huta and Słopnice due to the contamination of lettuce leaves with Fe (HQ_{Fe} = 1.14E-01), Mn (HQ_{Mn} = 1.51E-01) and Cr^{6+} (for every location). The highest HQ_{Cr6+} value was found for a backyard vegetable garden in Bukowno (1.94E-01) and the lowest for an allotment garden, also in Bukowno (1.10E-01). The total THQ_{int} values suggest a moderate health risk for a child living in Bukowno (1.14E + 00 and 1.06E + 00) and a low risk for a child living in the other areas (7.70E-01 for Sosnowiec, 5.70E-01 for Nowa Huta, 3.77E-01 for Cło and 4.94E-01 for Słopnice) (Table 4; Fig. 6b).

Carcinogenic risk

Under the exposure pathway associated with the ingestion of lettuce grown in the analyzed areas, we found that the level of carcinogenic health risk for an adult should be unacceptable due to the contamination of lettuce leaves with Cr^{6+} (TR > 1.0E-05), with the highest TR value obtained for site B-II in the region of Bukowno (TR_{Cr6+} = 9.97E-05). The level of carcinogenic health risk caused by the content of Pb in soil was acceptable for an adult in all the locations. Nevertheless, the TR value exceeded the TR = 1.00E-06 threshold in Bukowno (site B-II) and Sosnowiec (Figs. 7, 8, 9 and 10).

When analyzing the obtained values of carcinogenic health risk for a child living in the locations studied, we found an acceptable risk level for Cr^{6+} and Pb under the accidental soil ingestion pathway, with the TR value for Cr^{6+} exceeding the TR = 1.00E-06 threshold. Under the exposure pathway associated with dermal contact with contaminated soil, the level of carcinogenic health risk was unacceptable for Cr^{6+} (TR_{Cr6+} > 1.00E-05). The highest TR value was obtained for a child in Słopnice (TR_{Cr6+} = 4.82E-05) and the lowest in Bukowno (TR_{Cr6+} = 1.54E-05). As for the intake of contaminated lettuce leaves, the level

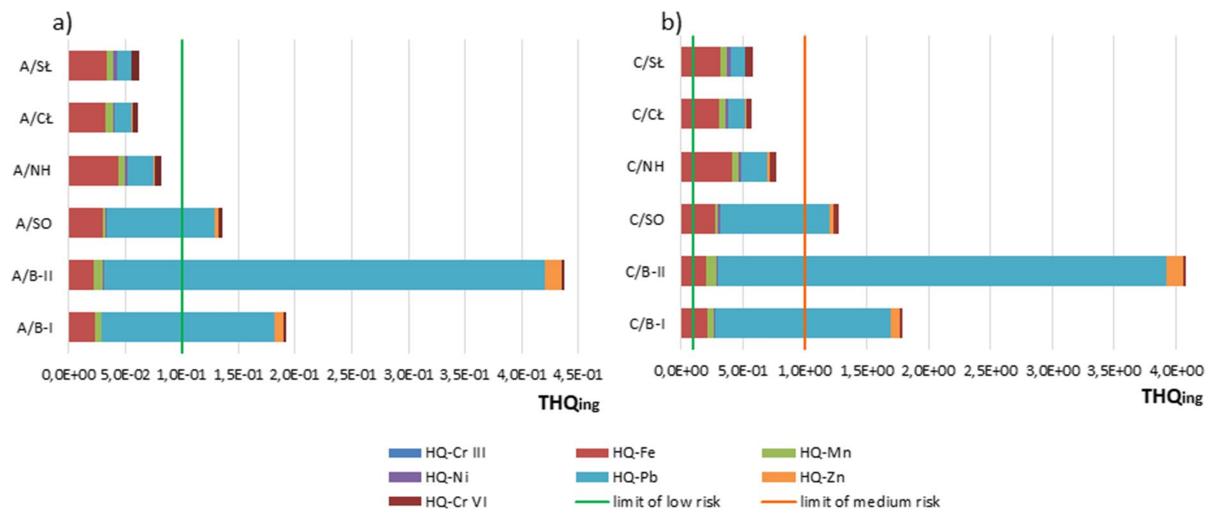


Fig. 4 Target hazard quotient (THQ_{ing}) for analyzed contaminants in the pathway of exposure: *accidental soil ingestion* in the **residencial scenario**: [**a**) adult; **b**) child]

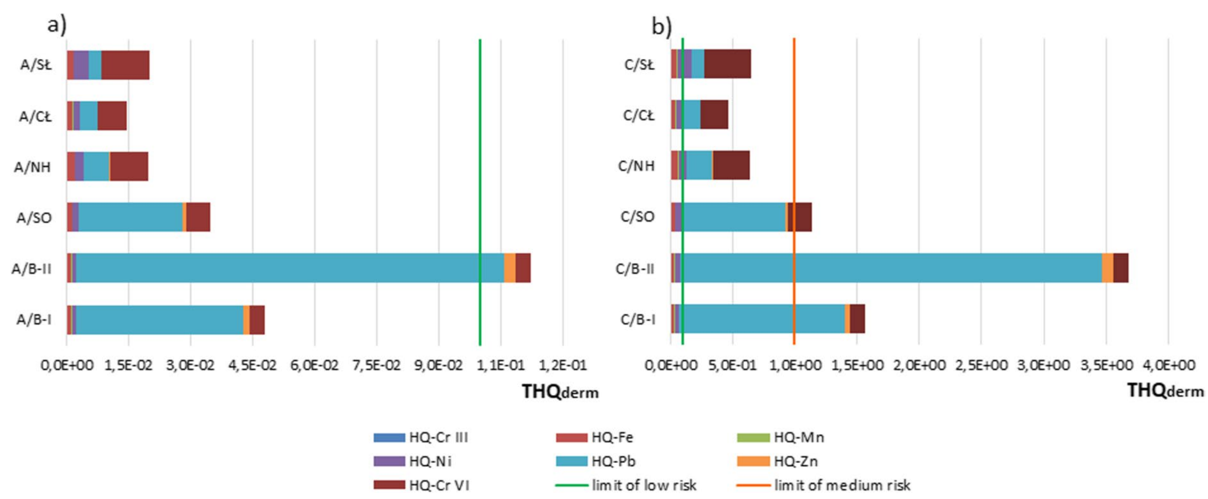


Fig. 5 Target hazard quotient (THQ_{derm}) for analyzed contaminants in the pathway of exposure: *dermal contact with contaminated soil* in the residencial scenario [**a**) adult; **b**) child]

of carcinogenic health risk resulting from exposure to Cr^{6+} was unacceptable, with the highest TR_{Cr6+} value observed for Bukowno (TR_{Cr6+} = 2.49E-05).

The total carcinogenic health risk in this exposure scenario showed an unacceptable level for an adult living in Bukowno, site B-II (TR = 1.07E-04). In the other areas, the level of carcinogenic health risk was acceptable for both a child and an adult.

Estimated daily intake

The minimum and maximum EDI values under individual exposure pathways are presented in Tables 5 and 6. In both the recreational and residential exposure scenarios, these values did not exceed the upper intake level (UL) for individual metals (Table 7). We observed that the different exposure pathways in the

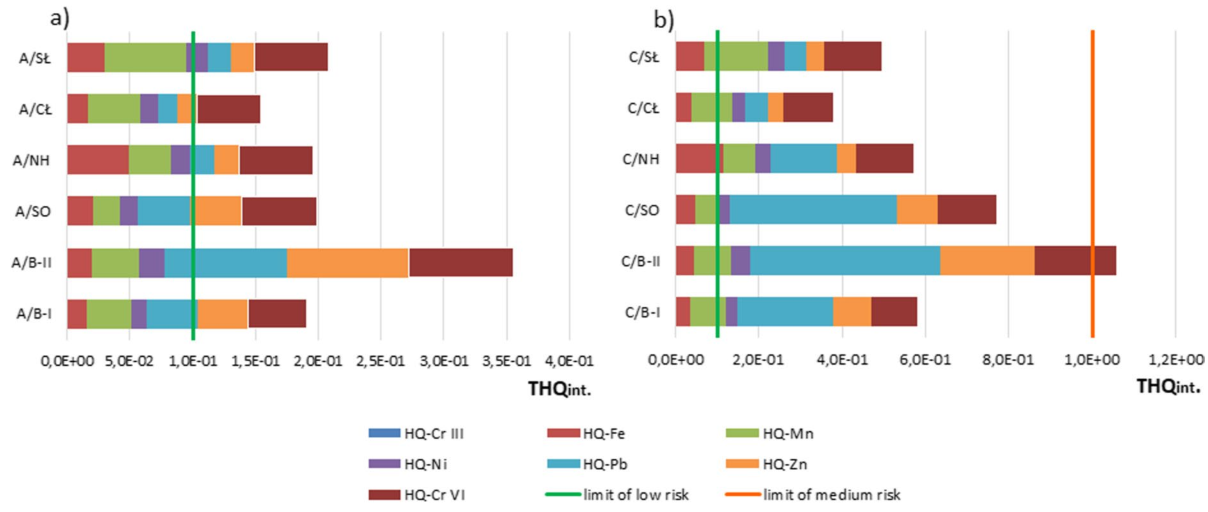


Fig. 6 Target hazard quotient ($THQ_{int.}$) for analyzed contaminants in the pathway of exposure: *intake of polluted lettuce* in the residencial scenario [**a**) adult; **b**) child]

total EDI varied and decreased in the following order: intake of contaminated vegetables > accidental soil ingestion > dermal contact > inhalation.

Higher EDI values were observed for children as compared to adults (senior > economically active adult). The values also differed depending on the industrial activity. The highest risk stemmed from the presence of Ni, Cr and Pb in the samples analyzed. The values of EDI increased in the order:

– for the Zn-Pb ore mining and processing industry: $Ni < Cr_{Total} < Pb < Mn < Zn < Fe$ and $Ni < Cr_{Total} < Pb < Mn < Fe < Zn$;
– for the coal mining and steel industries: $Ni < Cr_{Total} < Pb < Mn < Zn < Fe$ and $Pb < Ni < Cr_{Total} < Mn < Zn < Fe$;
– for the agricultural and control areas: $Pb < Ni < Cr_{Total} < Zn < Mn < Fe$.

Discussion

The food products contaminated with PTEs are a relevant source of exposure to harmful effects (e.g. Chang et al. 2014; Edogbo et al. 2020; Manea et al. 2020). Importantly, human health risk stemming from the exposure to PTEs may differ depending on their bioavailability which, in turn, may be affected by the type of soil or various environmental factors (Qureshi et al. 2016, Zhou et al. 2016). Potentially Toxic Elements behavior in soil and ecosystems should be considered when assessing population health risk (e.g. Kicińska et al. 2019; Nkosi and Msimango 2022; Yu et al. 2021). Liu et al. (2021), found that differences in PTE accumulation, including Pb and Zn, may occur in the same vegetable species, which stems from the fact that Zn is an element essential to vegetable growth and easily transported to the aerial plant parts, whereas Pb is toxic to plants and not essential to their growth, thus its transport is limited. Lead is excluded from plant metabolism and accumulated in roots.

To compare human health risk caused by the intake of contaminated lettuce leaves, we could use the results obtained for the residential exposure scenario (Table 3). The results obtained for children indicate that this age group is more susceptible to the effects of metals contained in lettuce leaves than adults. This stems from the fact that children have lower body weight and higher skin sensitivity. Undoubtedly, age is a factor that determines greater susceptibility of growing or aging individuals to toxic substances (Cavatorta and Pieroni 2013). Under exposure scenarios associated with accidental soil ingestion and dermal contact with contaminated soil, the HI value was predominantly determined by Pb in the case of industrial areas and by Fe in the control area. As for the values of HQ for individual metals (comprising the total THQ),

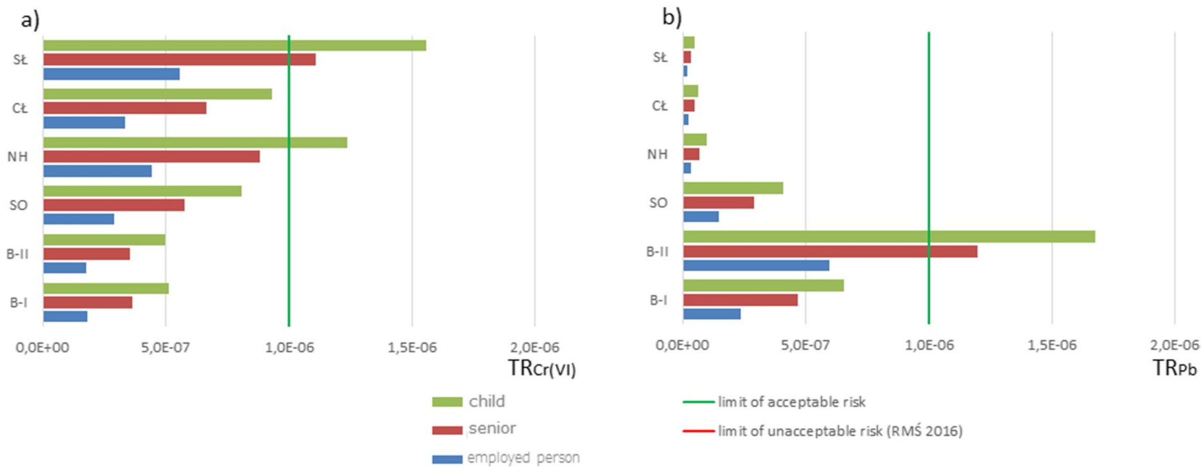


Fig. 7 Target carcinogenic risk (TR_{CI}) in the pathway of exposure *accidental soil ingestion (AD)* in the recreational scenario for: **a**) Cr (VI) and **b**) Pb

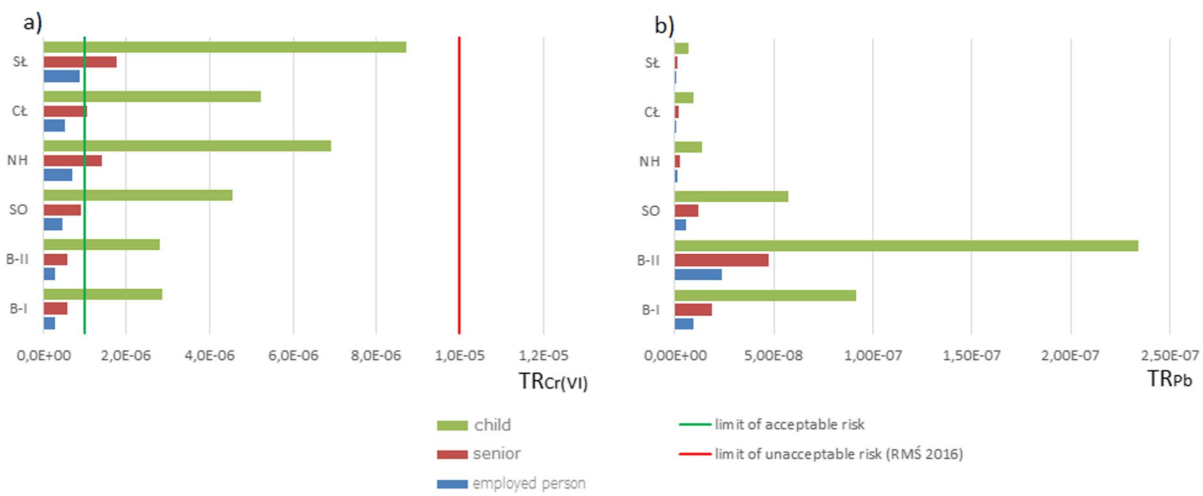


Fig. 8 Target carcinogenic risk (TR_{AD}) in the pathway of exposure *dermal contact with contaminated soil (AD)* in the recreational scenario for: **a**) Cr (VI) and **b**) Pb

we found an increased proportion of such elements as Fe, Mn, Zn, as well as Cr^{3+}, i.e. elements that are essential to plant growth, under the exposure pathway associated with the intake of contaminated lettuce leaves. These results show that the most important factors affecting the assimilation of elements by plants (vegetables) that are subsequently consumed by people include the concentration of elements in soil and their mutual quantitative proportions (Waterlot et al. 2017, Wierzbowska et al. 2018).

The present study revealed that the most significant exposure pathway through which PTEs from soil enter into the human body, in the case of both children and adults, is accidental soil ingestion together with food consumed with soiled hands because of poor hygiene habits. Additionally, in the case of children, this happened because of sucking on a thumb or palm and PICA behaviors, recurring or repeated ingestion of non-food substances such as dirt or paint chips (www.epa.gov).

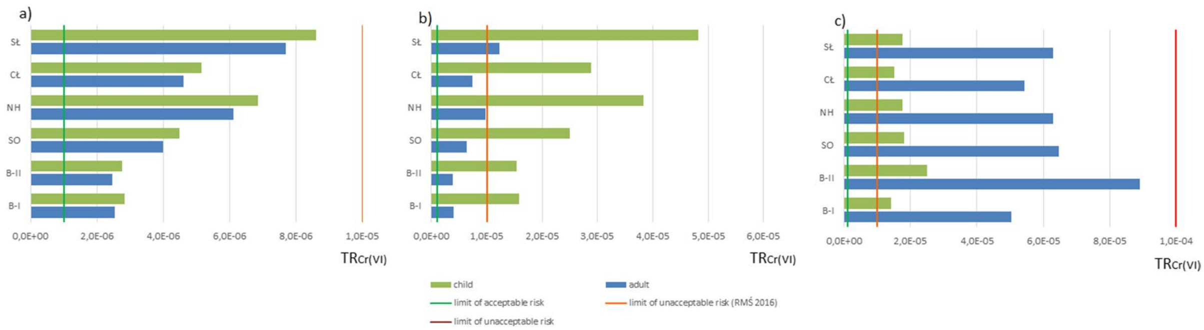


Fig. 9 Target carcinogenic risk (TR) for Cr(VI) in the residential scenario in the pathway of exposure: **a**) accidental soil ingestion, **b**) dermal contact with contaminated soil and **c**) contaminated lettuce intake

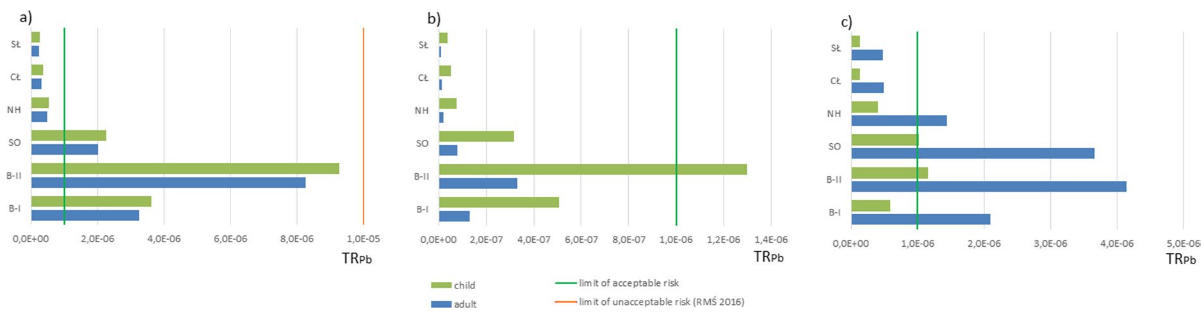


Fig. 10 Target carcinogenic risk (TR) for Pb in the residential scenario in the pathway of exposure: **a**) accidental soil ingestion, **b**) dermal contact with contaminated soil and **c**) contaminated lettuce intake

We found that the proportion of individual exposure pathways in the total non-carcinogenic risk was similar for children and adults, decreasing in the following order: ingestion > dermal contact > inhalation. Importantly, both carcinogenic and non-carcinogenic risks were higher for children than for adults (as also described by e.g. Yu et al. 2021, Gong et al. 2022, Li et al.2022). To compare the results obtained for the dermal and accidental soil ingestion exposure pathways, we used HQ values from the recreational exposure scenario (Table 5). In the present analysis, Cr and Ni were the exception to the relationship observed, which may stem from the difference in the RfD value adopted for the dermal contact exposure pathway. A similar observation was made by Jiang et al. (2017) for Cr in the case of an adult and by Li et al. (2015) in the case of an adult and a child.

The value of EDI for the metals analyzed under individual exposure pathways demonstrated the same decreasing tendency as in the case of non-carcinogenic risk, i.e., ingestion > dermal contact > inhalation.

We believe that in the case of children, a higher soil ingestion rate, a higher rate of dermal absorption of contaminants from soil and a lower body weight contributed to higher HQ values obtained for the exposure pathways associated with contaminated soil ingestion and dermal contact with contaminated soil. HQ values are determined by various factors, including the dose absorbed, exposure time, body weight and oral reference dose. The significantly different HQ values obtained for adults and children stemmed from the differences in metal ingestion, exposure time and body weight. The present study showed that the potential health risk was higher for children than for adults.

One of the goals of human health risk assessment is to determine the potential, harmful health effects to a given individual based on one's knowledge about population exposure to harmful substances in the environment and prevent these effects whenever

Table 5 Comparison of estimated daily intake (EDI) and hazard quotient (HQ) estimated for adult and child exposure with contact of contaminated soil obtained in this study and other ones

References	Exposure pathway	Receptor	Cr		Ni		Pb		Zn	
			EDI*	HQ	EDI*	HQ	EDI*	HQ	EDI*	HQ
own study*	ing	E	2.78E-06–8.65E-06	1.85–06–5.77E-06	3.40E-06–1.30E-05	1.70 E-04–6.52E-04	7.43E-06–2.46E-04	2.12E-0–7.03E-02	2.09E-05–7.79E-04	6.98E-05–2.60E-03
		C	2.59E-05–8.08E-05	1.73E-05–5.39E-05	3.18E-05–1.22E-04	1.59E-03–6.08E-03	6.93E-05–2.30E-03	1.98E-02–6.51E-01	1.95E-05–7.27E-03	6.51E-04–2.42E-02
	derm	E	1.11E-07–3.45E-07	5.68E-06–1.77E-05	1.36E-07–5.20E-07	1.70E-04–6.50E-04	2.96E-07–	5.65E-04–1.87E-02	8.35E-07–3.11E-05	1.39E-05–5.18E-04
		C	3.63E-06–1.13E-05	1.86E-04–5.80E-04	4.45E-06–1.70E-05	5.56E-03–2.13E-02	9.71E-06–3.22E-04	1.85E-02–6.12E-01	2.74E-05–1.02E-03	4.56E-04–1.70E-02
	inh	E	3.33E-11–1.04E-10	2.33E-08–7.26E-08	4.08E-11–1.56E-10	1.59E-06–6.08E-06	8.91E-11–2.95E-09	2.53E-08–8.38E-07	2.51E-10–9.34E-09	8.37E-10–3.11E-08
		C	5.90E-11–1.84E-10	4.13E-08–1.29E-07	7.24E-11–2.77E-10	2.82E-06–1.08E-05	1.58E-10–5.23E-09	4.49E-08–1.49E-06	4.45E-10–1.66E-08	1.48E-09–5.52E-08
Li et al. (2015)	ing	A	na	2.70E-02	na	1.0E-03–2.2E-02	na	7.40E-02–8.90E-02	na	na
	derm		na	1.8E-02–1.1E-01	na	1.0E-03–6.0E-03	na	3.50E-02–1.25E-01	na	na
	ing	C	na	6.0E-03–5.4E-02	na	4.0E-03–1.2E-02	na	9.30E-02–2.00E-01	na	na
	derm		na	2.4E-02–3.6E-02	na	1.6E-03–1.4E-02	na	5.00E-03–2.05E-01	na	na
	ing	A	na	2.0E-03–9.0E-03	na	1.0E-03–7.0E-03	na	1.50E-02–2.70E-02	na	na
	derm		na	1.6E-02–5.6E-02	na	1.0E-03–2.0E-03	na	1.40E-02–6.70E-02	na	na
	ing	C	na	3.0E-03–5.0E-03	na	2.0E-03–1.30E-02	na	5.00E-03–4.70E-02	na	na
	derm		na	1.0E-03–1.0E-02	na	3.00E-03–8.90E-03	na	6.00E-03–5.40E-02	na	na
Yu et al. (2021)	ing	A	1.3E-04	1.4E-02	1.4E-04	2.3E-03	6.4E-05	1.8E-02	2.1E-04	7.0E-04
	derm		4.8E-07	2.6E-03	5.1E-07	3.0E-05	2.3E-07	4.4E-04	7.5E-07	1.3E-05
	inh		1.55E-08	1.74E-04	1.65E-08	2.57E-07	7.00E-09	2.00E-06	2.27E-08	7.57E-08
	ing	C	9.3E-04	4.8E-02	9.9E-04	7.6E-03	4.5E-04	1.4E-01	1.4E-03	5.3E-03
	derm		3.1E-06	1.4E-02	3.3E-06	1.7E-04	1.5E-06	2.2E-03	4.8E-06	6.4E-05
	inh		3.46E-08	3.35E-04	3.68E-08	4.94E-07	1.66E-08	3.86E-06	5.37E-08	1.46E-07

Table 5 (continued)

References	Exposure pathway	Receptor	Cr		Ni		Pb		Zn	
			EDI*	HQ	EDI*	HQ	EDI*	HQ	EDI*	HQ
Gong et al. (2022)	ing	A	na	5.2E-02	na	3.13E-03	na	1.56E-02	na	6.12E-04
	derm		na	3.0E-02	na	1.32E-04	na	1.18E-02	na	3.49E-05
	inh			5.78E-04		3.24E-06		1.65E-04		6.53E-08
	ing	C	na	3.7E-01	na	2.24E-02	na	1.11E-01	na	4.37E-03
	derm		na	5.2E-02	na	2.32E-04	na	2.07E-02	na	6.12E-05
	inh		na	1.07E-03	na	5.99E-06	na	3.05E-04	na	1.21E-07
Li et al. (2022)	ing	A	na	na	na	na	na	8.34E-01	na	8.46E-03
	derm		na	na	na	na	na	2.22E-02	na	1.69E-04
	inh		na	na	na	na	na	1.22E-04	na	1.24E-06
	ing	C	na	na	na	na	na	3.7E+00	na	3.67E-02
	derm		na	na	na	na	na	6.77E-02	na	5.14E-04
	inh		na	na	na	na	na	1.01E-04	na	1.03E-06
Jiang et al. (2017)	ing	A	na	8.8E-03	na	5.3E-04	na	2.7E-03	na	6.2E-05
	derm		na	2.50E-02	na	1.1E-04	na	1.0E-03	na	1.8E-05
	inh		na	5.41E-04	na	6.95E-05	na	na	na	na
Aluko et al. (2018)	ing	A	5.2E-04	1.7E-01	na	na	4.5E-04	1.2E-01	1.0E-04	3.4E-04
	derm		1.3E-04	na	na	na	1.1E-04	na	2.5E-05	3.4E-04
	ing	C	4.9E-03	1.6E+00	na	na	4.2E-03	1.6E+00	9.5E-04	3.2E-03
	derm		6.3E-04	na	na	na	1.1E-04	na	1.2E-04	5.1E-03
	ing	A	8.5E-04	2.8E-01	na	na	4.3E-04	1.2E-01	8.2E-05	2.7E-04
	derm		2.1E-04	na	na	na	1.1E-04	na	2.0E-05	2.7E-04
	ing	C	7.9E-03	2.6E+00	na	na	4.0E-03	1.1E+00	7.6E-04	2.5E-03
	derm		1.0E-03	na	na	na	5.1E-04	na	9.7E-05	1.3E-03

n.a. – not analyzed; C – child (0–6 y.o.); E – employed person (20–40 y.o); A – adults (20–70 y.o.)

they are at an unacceptable level. So, it is important to encourage society to get into good hygiene habits, wash hands before meals, wash fruit and vegetables before consumption and remind children of proper behaviors during games, among others. These measures may help to limit the intake dose and protect children against health hazards.

When comparing the obtained results with data from the Main Statistical Office (GUS 2023) on the mortality of various diseases in the years 2009–2018 in the countries where the areas analyzed are located, it is difficult to obtain clear relationship between individual locations. With respect to cancer diseases, Sosnowiec county (27.25%) and Limanowa county (Słopnice 26.68%) had the highest share of cancer incidence in the total disease incidence among the areas under analysis. The lowest cancer incidence was observed in Kraków county (Cło 25.59%). The highest incidence of cardio-vascular diseases was recorded in Kraków county (~51%) and Olkusz county (Bukowno ~ 50%), and the lowest in Limanowa county (~43.23%). The highest mortality caused by respiratory diseases was found in Słopnice (~7.96%) and the lowest in Olkusz county (3.98%) and the city of Sosnowiec (3.97%). The comparison between mortality rates due to cancers, cardio-vascular diseases and respiratory diseases calculated for the analyzed locations (data from the Main Statistical Office for the years 2009–2018) and the mean mortality rate for Poland (26.07%, 44.54% and 5.75%, respectively) showed that cancer mortality rates in Kraków (29.12%), Sosnowiec county (27.07%), Olkusz county (26.27%) and Limanowa county (26.47%) were higher in the years analyzed.

These data may correspond to the results we obtained in the present study, especially in the context of carcinogenic risk. In the case of Cr^{6+}, the highest TR values was recorded precisely for Słopnice and the lowest for Cło. It is important to note that Cr^{6+} is a highly carcinogenic and mutagenic metal. Chromium compounds damage the respiratory system and gastrointestinal tract, they cause skin lesions and have carcinogenic, mutagenic, embryogenic, and teratogenic effects. The International Agency for Research on Cancer (IARC) has classified Cr^{6+} compounds as Group 1, i.e. compounds epidemiologically proven to have carcinogenic effects. In turn, the presence of Pb in soil and its absorption through various exposure pathways may have contributed to the development of cardio-vascular diseases in the population studied. Depending on its form, Pb has been classified by the IARC as possibly or probably carcinogenic. In all the locations analyzed, cardio-vascular diseases and cancer have the highest share in the total disease incidence. Nevertheless, it is important to note that disease incidence is determined by numerous factors. Mortality rate, on the other hand, can be significantly affected by public awareness, the right approach toward one's health and disease symptoms, adequate, balanced diet, and regular medical check-ups (EC 2020).

Conclusions

In many regions of the world, people value healthy eating and deliberately include increasing amounts of vegetables into their diets. Therefore, one of the challenges faced by modern science is to determine safe levels of macro and microelements in vegetables so that they offer the best quality and health value. Thus, crop safety and knowledge about the origin of vegetables, as well as the place and method of their cultivation are gaining in importance. Individuals growing vegetables in allotment gardens and backyard vegetable gardens as a pastime are particularly exposed to the harmful effects of microelements (including PTEs). They are not always aware of the amount of contaminants present in soil in their farmland and subsequently on their plate. Sometimes they mistakenly believe that produce grown by themselves is healthier and of higher quality.

Based on the health risk analysis conducted, we found that:

1. The share of different exposure pathways in the total health risk decreases in the following order: intake of contaminated vegetables > accidental soil ingestion > dermal contact > inhalation of contaminated soil particles.
2. Children are more susceptible to toxic effects of PTEs than seniors and economically active adults. This stems from a higher soil ingestion rate, a higher rate of dermal contaminant absorption and a lower body weight.
3. In the areas analyzed, it is not necessary to take immediate preventive and protective actions, as the TR and HQ values calculated for the con-

Table 6 Comparison of estimated daily intake (EDI) and hazard quotient (HQ) estimated for adult and child exposuring to intake with contaminated leaves lettuce, observed in this study with those found in other heavy-metal-lettuce studies

References	Receptor	Cr		Fe		Mn		Ni		Pb		Zn	
		EDI*	HQ	EDI	HQ	EDI*	HQ	EDI	HQ	EDI	HQ	EDI	HQ
own study	A	3.1E-04–5.5E-04	2.1E-04–3.7E-04	1.4E-02–3.4E02	1.5E-02–4.9E-02	2.9E-03–9.0E-03	2.1E-02–6.5E-02	2.3E-04–3.9E-04	1.1E-02–2.0E-02	7.9E-05–6.8E-04	2.2E-02–1.9E-01	4.7E-03–2.9E-02	1.6E-02–1.7E-01
	C	7.3E-04–1.3E-03	4.9E-04–8.6E-04	2.5E-02–7.9E-02	3.5E-02–1.1E-01	6.8E-03–2.1E-02	4.9E-02–1.5E-01	5.4E-04–9.3E-04	2.8E-02–4.6E-02	1.8E-04–1.6E-03	5.2E-02–4.5E-01	1.1E-02–6.8E-02	3.6E-02–2.3E-01
Edogboa et al. (2020)	A	1.4E-01	1.0E-03	na	na	na	na	na	na	1.0E-02	4.0E-02	4.8E-01	2.0E-02
	C	5.0E-01	4.0E-03	na	na	na	na	na	na	5.0E-02	1.5E-01	1.7E+00	6.0E-02
Manea et al. (2020)	A	na	na	1.0E+01	2.3E-01	1.3E+00	1.5E-01	7.0E-02	5.0E-02	1.7E-01	7.4E-01	2.0E+00	1.0E-01
		na	na	9.3E+00	2.1E-01	1.3E+00	1.4E-01	1.2E-01	1.0E-01	5.0E-02	2.2E-01	1.3E+00	7.0E-02
		na	na	5.3E+00	1.2E-01	6.6E-01	7.0E-02	3.0E-02	2.0E-02	2.0E-02	9.0E-02	8.6E-01	4.0E-02
Chang et al. (2014)	A	na	2.1E-02	na	na	na	na	na	na	na	2.3E-02	na	na
	C	na	3.3E-02	na	na	na	na	na	na	na	3.8E-02	na	na
Qureshi et al. (2016)	A	6.2E-04	1.5E+00	4.6E-02	1.2E+01	na	na	na	na	na	na	1.7E-03	3.1E-02
	C	7.2E-04	na	5.3E-02	na	na	na	na	na	na	na	2.0E-03	
Zhou et al (2016)	A	na	na	na	na	na	na	na	na	na	1.0E+00	na	2.7E-01
	C	na	na	na	na	na	na	na	na	na	1.4E+00	na	3.6E-01
Liu et al (2021)	A	na	8.4E-01	na	na	na	na	na	7.0E-02	na	4.2E-01	na	9.0E-02
	C	na	1.4E+00	na	na	na	na	na	1.2E-01	na	3.1E-01	na	1.6E-01
Nkosi et al. (2022)	A	na	na	2.9E-03	4.1E-03	na	na	na	na	na	na	6.0E-04	1.9E-03
	C	na	na	4.3E-02	6.1E-02	na	na	na	na	na	na	8.9E-03	3.0E-02
	A	na	na	1.4E-03	2.0E-03	na	na	na	na	na	na	3.0E-04	1.1E-03
	C	na	na	2.1E-02	3.0E-02	na	na	na	na	na	na	4.7E-03	1.6E-02
Jiang et al. (2017*)	A	na	1.7E+00	na	na	na	na	na	1.1E-01	na	1.16E-01	na	1.15E-01

* home grown produce

Table 7 Reference doses (RfD), cancer slope factor (CSF) and upper tolerable daily intakes (UL) values for investigated metals

Element	RfD_{oral} (mg/kg•day^{-1})	RfD_{derm} (mg/kg•day^{-1})	RfD_{inh} (mg/kg•day^{-1})	CSF_{oral} (mg/kg•day^{-1})	CSF_{derm} (mg/kg•day^{-1})	CSF_{inh} (mg/kg•day^{-1})	UL (mg•day^{-1})
Cr^{3+}	1.50E+00[1),2),3)]	1.95E-02	1.43E-03	–	–	–	–
Fe	7.00E-01[1),2)]	7.00E-01	–	–	–	–	4.50E+01[1)]
Mn	1.40E-01[2)]	1.40E-01	1.43E-05	–	–	–	1.10E+01[1)]
Ni	2.00E-02 [1),2),4)]	8.00E-04	2.57E-05	–	-	9.10E-01	1.00E+00[1)]
Pb	3.50E-03[1),2),3),10)]	5.25E-04[8),9),10)]	3.52E-03	8.50E-03[5),6)]	8.50E-03	4.20E-02	2.40E-01[1)]
Zn	3.00E-01[1),2),3),10)]	6.00E-02[10)]	3.00E-01[11),12)]	–	–	–	4.00E+01[1)]
Cr^{6+}	3.00E-03[1),2)]	7.50E-05	2.86E-05	5.00E-01[2),7)]	2.00E+01	2.94E+02	–

Harmanescu et al. (2011)
US EPA (2023b)
Islam et al. (2016a, b)
Latif et al. (2018)
Islam et al. (2014)
Islam et al. (2018)
OEHHA (2023)
Trojanowska and Świetlik (2017)
Zheng et al. (2010)
Sawut et al. (2018)
Yu et al. (2021)
Gong et al. (2022)

taminants studied did not exceed the 1.0E-03 and 1.00E+00 thresholds, respectively.

4. The obtained HI values for individual elements contaminating the industrial areas studied descend in the following order:
- in the region of Zn-Pb ore mining and processing: Pb > Fe > Zn > Mn > Cr^{6+} > Ni > Cr^{3+},
- in the region of hard coal mining and steel processing: Pb > Fe > Cr^{6+} > Zn > Ni > Mn > Cr^{3+},
- in the metropolitan area and metalworking conglomerate: Fe > Pb > Cr^{6+} > Mn > Ni > Zn > Cr^{3+},
- in rural-agricultural areas: Fe > Cr^{6+} > Pb > Ni > Mn > Zn > Cr^{3+}.
5. The EDI values estimated for individual metals did not exceed UL—a parameter indicating the highest tolerable intake level.
6. We observed that the share of different exposure pathways in the total EDI decreased in the following order: intake of contaminated vegetables > accidental soil ingestion > dermal contact > inhalation of soil particles.
7. The EDI level was higher in children than in adults (senior > economically active individual).

Post-industrial and industrial areas associated with metal ore mining and processing should be constantly monitored not only for inorganic and organic contaminants present in various environmental segments, but also for health risk stemming from the exposure of inhabitants to these xenobiotics via different pathways. We sincerely hope that the results of our analyses will contribute to a better understanding of the need to take necessary actions by the administration and agencies responsible for the state of the environment and population health as regards tightening the law and extensive education. Every initiative constitutes important support for activities related to improving living conditions of people who live in areas subject to a strong, century-long anthropogenic impact.

Author contributions A.K authored the project and designed the study; A.K planned and supervised experimental work which was done by J.W.; A.K. contributed to the study design and discussed the data; A.K. performed the statistical analysis; A.K. revised the data; A.K. & J.W. wrote the original draft of the paper. All authors contributed to the manuscript final form and approved the version to be submitted. All authors have read and agreed to the published version of the manuscript. A.K – 60%, J.W. – 40%.

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Data Availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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