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ORIGINAL PAPER

Heavy metal(loid)s contaminations in soils of Pakistan: a review for the evaluation of human and ecological risks assessment and spatial distribution

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Abstract Heavy metal(loid)s (HM) contaminations in the soil poses threats to the human and ecological community due to their bioaccumulation, toxicity, and persistent nature in the ecosystem. This review was designed to know about the HM contamination in soils, ecological risk, distribution, and potential health risks. Soil HM concentrations published in the last 30 years were collected from Springer, Science Direct, Willey, Mendeley, ResearchGate, Google Scholar, etc. HM concentrations were used for the geo-accumulation index (Igeo), contamination factor, as well as integrated indices such as spatial distribution of ecological risk index. Similarly, the Igeo pattern was observed in Sindh > Baluchistan > Punjab > Khyber Pakhtunkhwa > Gilgit-Baltistan > Islamabad. Moreover, the high ecological risk mean values ranged (160 < ERI < 320) due to cadmium (Cd) was exhibited in the Punjab and Khyber Pakhtunkhwa provinces and Islamabad. Non-carcinogenic risk like hazard quotient was found higher for children (1.59) of Punjab due to arsenic (As) ingestion, whereas the lower risk was observed due to Zn (2.5E−08) for adults of Punjab province via inhalation pathway. Similarly, the health index (HI) from exposure to As (1.61) in soil was higher than the rest of the HM. Moreover, cancerous risk was determined and found in the tolerable range (10^{-4}–10^{-6}). This study recommended that HM contaminants in the soil need to be monitored on regular basis, especially in Baluchistan, Gilgit-Baltistan, and Sindh provinces.

Keywords Contamination factor · Enrichment factor · Ecological risk index · Cancer and non-cancer risks

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Introduction

Heavy metal(loid)s (HM) are hazardous contaminants owing to their persistent, bio-accumulative, and toxic behavior in the environment (Dhandhayuthapani, 2022; Ustaoğlu et al., 2022). Among HM, certain metals like copper (Cu), iron (Fe), and zinc (Zn) in a specific amount are necessary for the health of human beings (Assunção et al., 2022; Weyh et al., 2022). However, their higher concentration may cause toxicity in humans and other living beings. HM including cadmium (Cd), cobalt (Co), chromium (Cr), lead (Pb), mercury (Hg), and arsenic (As) are toxic even in tiny quantities and cause various health problems (Gu et al., 2022; Jayamurali et al., 2021). For example, hypertension, headache, nausea, fever, renal failure, and bone fractures are all symptoms of Cd poisoning (Baghaie

& Fereydoni, 2019; Rehman et al., 2018; Yu et al., 2021), while Cr poisoning causes stomach pain, vomiting, nausea, prostration, liver, and kidney disorders (Doabi et al., 2018). Polycythemia, abnormal thyroid arteries, respiratory problems, and overproduction of red blood cells are all adverse symptoms of Co (Doabi et al., 2018; Packer, 2016).

Soil is an important component of the environment for agriculture production and human survival (Drobnik et al., 2018, Rajendran et al., 2022, Tokatli & Islam, 2022). The HM enters the soil via natural sources such as disintegrating as well as erosions of ore deposits and bed-rocks (Muhammad & Ullah, 2022, Ullah & Muhammad, 2020) and anthropogenic including mining, metallurgy, wastewater irrigation, traffic, industrial emission, and agrochemical application (Bakht et al., 2022; Cruzado-Tafur et al., 2021; Guadie et al., 2021; Rajendran et al., 2022). These HM are neutralized to a specific level by the soil via its buffering capacity (Kicińska et al., 2022; Stigliani, 1996); however, if that level exceeded the critical load, then the soil becomes a source rather than a sink (Batjes & Bridges, 1993, Fontes & Gomes, 2003). These HM accumulate in the growing food, contaminate the food chain and cause threats to ecological and human life (Bawwab et al., 2022; Rubio-Gracia et al., 2022; Tokatli, 2019).

Heavy metal(loid)s had threatened the ecological environment and human life via their high mobility, poor degradation ability, and toxicity in the environment (Yanez et al., 2002). Recently, the pollution quantification factors (Hao et al., 2022), geospatial distribution (Mandal et al., 2022), ecological (Ren et al., 2022; Varol et al., 2022; Yüksel et al., 2022), and health risks assessment (Aguilera et al., 2021) techniques have been used for the formulation of environmental protection policies. HM contaminations and potential risks of soil have been sporadically studied in Pakistan (Jadoon et al., 2020a; Saddique et al., 2018). However, there is a lack of comprehensive study of HM contaminations in soil, pollution factors, and risk assessments. Therefore, it is imperative to investigate HM contamination levels at a national level for pollution factors, associated risks, and distribution patterns. HM concentrations published in the last three decades were collected and evaluated for the pollution factors using single and integrated indices to present a comprehensive environmental picture.

Study area description

Pakistan is located in the South Asian subcontinent (23° to 37.5° N of latitudes & 61° to 78° E of longitudes). It shares a border with China in the north, in the south with the Arabian Sea, India in the east, and in the west with Iran and Afghanistan (Fig. 1). The country holds a diverse type of topography varying prominently from region to region (Shahzad et al., 2021). The series of Himalaya-Karakoram-Hindu Kush is acknowledged as the natural water reservoir and vital for life sustenance of South Asia having an enormous number of glaciers, lakes, rivers, and the resultant tributaries (Archer & Fowler, 2004). Toward its North and North-West, mountains with highest altitudes are located which remain too cold during winter, while in summer (April–September), they remain very pleasant. Moreover, the plain areas (of the Indus-Valley) remain very hot during summer and persist cold during winter. The coastal areas mostly remain temperate (Karim et al., 2021). The annual average rainfall fluctuates from 13 cm in the lower parts of the Indus plains to 89 cm in the Himalayan areas.

Tectonics and geology of Pakistan

The Pakistan-tectonic has comprised two convergent boundaries: an active collision zone (continent–continent collision) and a lithospheric subduction zone (oceanic) in the northeast and southwest, respectively. These collision boundaries are associated with the Chaman Transform zone, a huge north–south displacement, i.e., strike-slip faults (Kazmi & Jan, 1997). Geologically, Pakistan is comprised of two major basins (sedimentary in origin), namely Indus Basin and Baluchistan Basin which developed across distinct geological periods. These two basins were combined jointly during Cretaceous and Paleocene time along the Chaman fault (Kazmi & Abbasi, 2008; Malkani, 2015). The Indus Basin occupies the eastern part of the country and is situated on the western side of the Indian Plate. The Indus Basin consists of the Precambrian to Cenozoic sediments, whereas Baluchistan occupies the western part of the country and is located on the southern margin of the Eurasian Plate. The active continental margin of Baluchistan represents an arc-trench system west of the Chaman Ornach Transform Fault zone. The exposed rocks

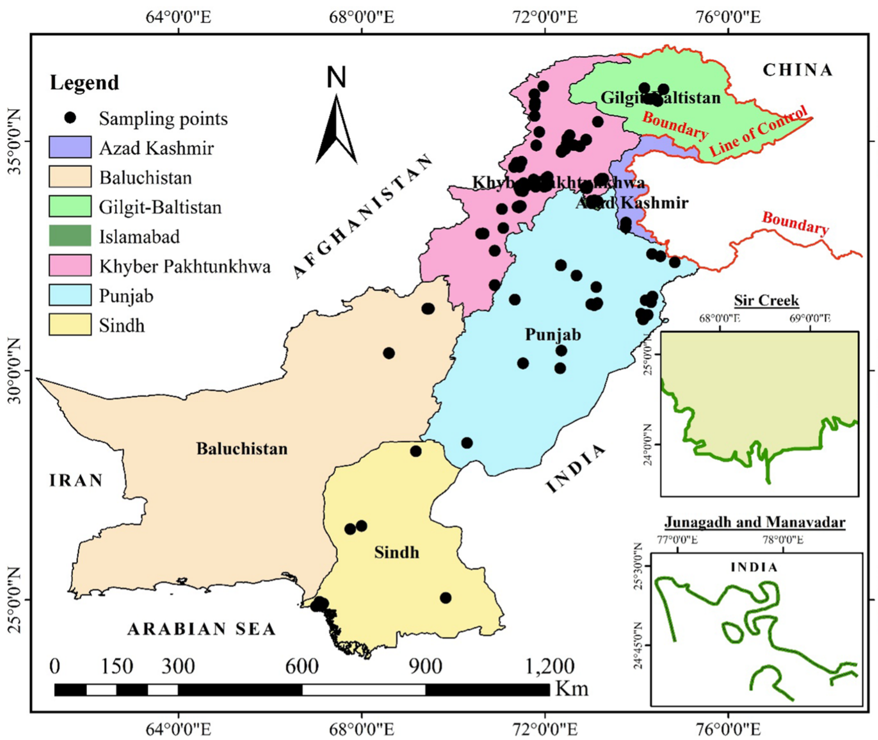

Fig. 1 Location of the studied sites in the study area (modified after Soil Survery of Pakistan)

(sedimentary) in the Baluchistan basin are of the Cretaceous-Quaternary period (Kadri, 1995; Kazmi & Jan, 1997).

Data management

For this study, scientific publications published over the last 30 years focusing on HM concentrations in the soil of Pakistan were collected (Table 1). The research articles were searched over different search media like Springer, Science Direct, Willey, Mendeley, ResearchGate, Google Scholar, etc. The data were compiled by means of range and average of HM as described in the literature.

Pollution quantification factors

Contamination factor

The contamination factor (CF) values of the selected HM were calculated using Hakanson (1980) Eq. (1), which is the ratio of the concentration of HM to its reference or background values. The background values are 1 mg/kg for (Cd), 29 (Co), 90 (Cr), 50 (Cu), 35,900 (Fe), 750 (Mn), 68 (Ni), 70 (Pb), 175 (Zn), 1.5 (Mo) and 15 (As) (Hakanson, 1980; Ma et al., 2016; Raju et al., 2012) and are classified by Jiao et al. (2015) into five classes (Table 2).

$$\text{CF} = \text{Soil concentration in studies/Background} \quad (1)$$

Geo-accumulation index

Geo-accumulation index (Igeo) is also calculated individually for HM and can be obtained by using Eq. (2). It gives valuable information about the severity and range and abundance of HM contents in the soils of studied sites (Muller, 1969) and their classification is given in Table 2.

$$\text{Igeo} = \log 2\left[\text{Cn}/1.5x\ \text{Bn}\right] \quad (2)$$

Here, Cn represents the calculated concentration of HM and Bn represents their background concentration (Nazeer et al., 2014):

Table 1 Heavy metal(loid)s concentrations (mg/kg) in soils of previously reported studies in Pakistan

Provinces	Location	Latitudes	Longitudes	Pb	Cd	Fe	Mn	Ni	Co	Zn	Cu	Mo	Cr	As	References
Baluchistan	Loralai Valley	30.381	68.596	20.2	0.5	24,826	339	541	1.2		16.2		34.8		Ullah and Muhammad (2020)
	Zhob Valley	31.3496	69.4665	61.4	3.2	36,000	1285	1025	9		54.3		1330		Ullah and Muhammad (2020)
	Loralai Valley	30.38272	68.59197	19.6	1.3	24,520	385.2	686	29.1		15.1		13.6		Muhammad et al. (2019)
	Zhob Valley	31.35177	69.43275	79.7	3.8	48,870	860	880	62.1		53		88.2		Muhammad et al. (2019)
Gilgit-Baltistan	Himalaya	36.13794	74.59182	47	1.9	1241	343			35.5	18.1		32.6		Shah et al. (2013)
	Dainyor (Gilgit)	35.94196	74.38806	36	0.9			31		1190	99		1		Khan et al. (2010)
	Jageer Baseen (Gilgit)	35.92889	74.25467	29	0.8			57		210	72				Khan et al. (2010)
	Konadas (Gilgit)	35.92842	74.31081	35	1			52		590	147				Khan et al. (2010)
	Nagirl (Gilgit)	35.88191	74.46428	43	0.3			36		172	55				Khan et al. (2010)
	Nalter (Gilgit)	36.16335	74.17161	138	2.3			24		460	71				Khan et al. (2010)
Islamabad (Capital)	Islamabad	33.70658	73.01783	209	3.4	40,700		90.8	16.3	1658	17.4				Ali and Malik (2011)
	Islamabad (Summer)	33.70017	73.10875	1	0.05	7.1	0.1		0.2	0.2	0.1		0.2		Iqbal and Shah (2011)
	Islamabad (Winter)	33.69592	73.14303	0.9	0.1	0.6	0.03		0.3	0.1	0.1		0.1		Iqbal and Shah (2011)
	Islamabad	33.71427	73.07828	62.5	6			32		91.1	25				Faiz et al. (2009)
	Islamabad	33.66747	73.04034	32.7			1407	31		86	11.7		42		Abbas et al. (2021)
	Islamabad	33.65	73.01667	67.1	11.9			27.2		197	9.5		0.9		Ali et al. (2014)
	Islamabad (Summer)	33.7026	73.1260	38.3	1.6	12,784	394			20.8	10.3		21		Iqbal and Shah (2011)
	Islamabad (Winter)	33.7026	73.1260	27.4	2.1	3958	454			45.3	17.8		25.7		Iqbal and Shah (2011)
Khyber Pakhtunkhwa	Abbottabad (Waste dump)	34.146402	73.232728	3.5	0.1	211	10.4	7.9	0.4	6.1	0.6				Jadoon et al. (2020b)
	Abbottabad (Agriculture)	34.16596	73.255177	0.8	0.2	348	23.3	8.3	0.5	6.2	0.1				Jadoon et al. (2020b)
	Abbottabad (Road side)	34.185519	73.232728	1.1	0.1	132	15.6	7.5	1	4.8	0.2				Jadoon et al. (2020b)
	Abbottabad (Residential)	34.146402	73.187829	1.1	0.1	335	9.8	8.7	0.5	6.9	0.8				Jadoon et al. (2020b)
	Abbottabad (Playground)	34.185519	73.277627	1.3	0.02	239	13.2	7.1	0.6	4.4	0.1				Jadoon et al. (2020b)
	Bannu	32.98947	70.66224				285	39.3		122	16.8		42.8		Rehman et al. (2018)
	Bannu	32.98613	70.60416											3.9	Rehman et al. (2016)
	Bannu	32.99093	70.64548	40.5	7.9			102					44.9		Khan, Muhammad, et al. (2016)
	Besham area, Kohistan (Pazang)	34.89891	72.76103	117	2	25,080	2437	99	117	361	193		146		Muhammad et al. (2011)
	Besham area, Kohistan (Lahor)	35.43088	73.15638	1750	20	26,960	5779	172	105	5123	205		439		Muhammad et al. (2011)
	Bucha Area (Muhammad Agency)	34.43948	71.32282	38	3	20,322	1306	629	24	46	32		1410		Shah et al. (2013)
	Charsadda	34.16818	71.75039	0.7		197	28.8	0.4	0.5	5.4	0.8		2.3		Khan et al., 2008
	Chitral (Ashriat)	36.20306	71.69827	12	3.7			39.7	35.9	67.6	66.5		66.2		Ali et al. (2019)
	Chitral (City)	35.852	71.785											0.1	Rehman et al. (2020b)
	Chitral City	35.76923	71.77229	14.8	2	45.8	490	17.8	23.5	86	20.1	16.6	6		Rehman et al. (2020a)
	Chitral (Drosh)	35.55454	71.77304	20.7	3.9			37.6	29.2	60.7	50.1		67.9		Ali et al. (2019)
	Chitral (Sewakht)	36.03	71.77											0.7	Rehman et al. (2020b)
	Chitral (Sewakht Mines)	35.84190	71.78190	4.7		5.9	0.1	26.6	36.8	102	35.3	3	29.9		Rehman et al. (2018)

Table 1 (continued)

Provinces	Location	Latitudes	Longitudes	Pb	Cd	Fe	Mn	Ni	Co	Zn	Cu	Mo	Cr	As	References
	D I Khan, Ridge Gourds (Yousaf Raza Gillani Town)	31.817416	70.888519	2.3	0.02	65.4		1.5	0.7		0.6		0.2		Iqbal et al. (2020)
	D I Khan, Sponge Gourds (Yousaf Raza Gillani Town)	31.817416	70.888519	2.3	0.02	65.4		1.5	0.7		0.6		0.2		Iqbal et al. (2020)
	D I Khan	31.87065	70.90295				270	26.7		134	15.6		27		Rehman et al. (2018)
	D I Khan	31.86263	70.90241											3.6	Rehman et al. (2016)
	Dir (Lower)	34.91641	71.80953		0.1						4.7		0.2		Jan et al. (2010)
	Dir (Upper)	35.20793	71.8747	0.4	0.2	84.1	10.6	0.7	0.7	1.5	0.6		0.7		Mohammad et al. (2015)
	Hangu	33.52508	71.05859				265	22.8		119	11.9		25.7		Rehman et al. (2018)
	Hangu	33.52232	71.06166											3.1	Rehman et al. (2016)
	Haripur	33.99413	72.88262	93.5	85.7			232		78.6	66		168		Gul et al. (2016)
	Haripur (Rain Water Irrigated Soil)	34.02515	72.91867	14.4	4.9			13.7	4.5	29.9	77.6		16.3		Jehan et al. (2020)
	Haripur (Water Irrigated Soil)	34.00409	72.92485	12.3	4.6			18.2	7	33.5	85		19.8		Jehan et al. (2020)
	Haripur (Canal Water Irrigated Soil)	33.9779	72.9173	13.3	5.4			29.1	7.7	41.4	108		25.3		Jehan et al. (2020)
	Haripur (Wastewater Irrigated Soil)	34.02117	72.93069	21.1	7			46	12.5	68.5	156		39		Jehan et al. (2020)
	Karak														Ali et al. (2020)
	Karak	33.11047	71.09137	10.5	0.1	307	193	18.5		48.5	25.3		18		Shah et al. (2013)
	Kohat	33.56146	71.43012				258	21.2		109	11.1		18.1		Rehman et al. (2018)
	Kohat	33.58974	71.47011	80.4	5		234	80.4	17.1	9.9	12		25.2		Sattar et al. (2021)
	Kohat	33.58886	71.44293											3.7	Rehman et al. (2016)
	Kohat (Tanda Dam)	33.57025	71.39802	0.4	0.1	1.8		0.01		0.2	0.4		2.1		Nazir et al. (2015)
	Kohistan (Alpuri)	34.92013	72.63341	62	2	13,200	485	1262	142	105	63		731		Muhammad et al. (2013)
	Kohistan (Dubair)	35.03697	72.89834	81	2	12,042	405	1185	112	94	68		716		Muhammad et al. (2013)
	Kohistan (Jilal)	35.04172	72.8948	17	2	11,426	453	1420	138	88	61		853		Muhammad et al. (2013)
	Lakki Marwat	32.6168	70.90195				266	30.4		107	13.4		32.4		Rehman et al. (2018)
	Lakki Marwat	32.61244	70.90381											3	Rehman et al. (2016)
	Mardan (Water Irrigated Soil)	34.15342	72.03612	0.2		2.6	1.3	0.1	0.1	1	0.2		0.12		Amin et al. (2013)
	Mardan (Wastewater Irrigated Soil)	34.22367	72.06121	0.9		3.5	4.8	0.6	0.1	1.9	0.9		0.5		Amin et al. (2013)
	Mardan	34.19856	72.02406	27	2.3	25	1.4	49		96	28		60	5.1	Gul et al. (2014)
	Mohmand Agency, Bucha	34.51779	71.25572	50.9			276			99	158		602		Khan et al. (2020)
	Mohmand Agency, Bucha	34.58749	71.31337	28.7			238			68	73.2		174		Khan et al. (2020)
	Mohmand Agency, Bucha	34.53005	71.40186	32			331			55	56.5		597		Khan et al. (2020)
	Mohmand Agency, Heroshah	34.531051	71.152118			35,322	953	713	244	105	107		830		Nawab et al., (2016)
	Nowshera	34.01046	71.98755	0.7		202	24.3	0.5	0.4	6.5	0.9		1.8		Khan et al., (2008)
	Nowshera (Pabbi)	34.00766	71.79495	0.5		180	23.5	0.4	0.2	3.5	0.7		2.2		Khan et al., (2008)
	Peshawar (Baghe Naran Park)	33.97797	71.44476	17.2	6			41.8		59.6	8.5		27.5		Khan, Munir, et al. (2016)
	Peshawar (Chacha Younas Park)	34.01525	71.57805	25.8	5.6			52.5		103	17.9		40.3		Khan, Munir, et al. (2016)

Table 1 (continued)

Provinces	Location	Latitudes	Longitudes	Pb	Cd	Fe	Mn	Ni	Co	Zn	Cu	Mo	Cr	As	References
	Peshawar (Summer)	34.03593	71.45372	11.9	4		387	54	41.1	100	33		31		Naz et al. (2020)
	Peshawar (Winter)	34.04205	71.5922	11	3.7		341	50	40.5	98	31		29.6		Naz et al. (2020)
	Peshawar (Jinnah Park)	34.01519	71.57078	25.6	6.3			52.7		79.6	21.2		38.4		Khan et al. (2016)
	Peshawar (Khyber Park)	33.98299	71.4381	12.7	4.9			49.2		69.9	10		33.5		Khan et al. (2016)
	Peshawar (Parda Bagh)	34.01845	71.57552	37.2	5.8			49.2		158	57.4		35.6		Khan et al. (2016)
	Peshawar (Shahi Bagh)	34.01916	71.57685	34.3	5.8			225		118	40.6		42.1		Khan et al. (2016)
	Peshawar (Sher Khan Shaheed Stadium)	34.01674	71.5505	0.9	5.5			40.6		51.2	9.9		23		Khan et al. (2016)
	Peshawar (Tatara Park)	33.98153	71.44463	26.2	6.9			57.8		83.4	16.4		45		Khan et al. (2016)
	Peshawar (Cricket Ground)	34.02154	71.57834	20.7	7.2			51.5		54.5	13.2		41.1		Khan et al. (2016)
	Peshawar (Hockey Ground)	33.99916	71.47724	25.2	7.6			53		57.4	13.8		41.7		Khan et al. (2016)
	Peshawar (Volley Ball Ground)	34.04892	71.52272	11.7	5.2			30.1		26.6	5.7		13.9		Khan et al. (2016)
	Peshawar	34.01513	71.52491	43.5	8.5			37.1		51.3	43.3		28.2		Ullah and Khan (2015)
	Peshawar (Urban)	34.0172	71.57739	17.2	0.3	21.4	17.6	0.7		2.1	5.1		0.4		Khan et al. (2015)
	Peshawar (Soil from Primary Road)	34.01796	71.52286	97.4	10										Khan et al. (2011)
	Peshawar (Soil from Secondary Road)	33.97128	71.50089	50	7.2										Khan et al. (2011)
	Peshawar (Soil from Tertiary Road)	34.08851	71.53384	45.1	7										Khan et al. (2011)
	Peshawar	34.04983	71.59427	0.4	0.1			10.5		40.9	20.8		1.7		Jan et al. (2010)
	Peshawar	33.9166	71.52149	0.3	0.9			3.5		10.1	13		1.3		Jan et al. (2010)
	Peshawar	34.05666	71.64371	0.7		190	26.1	0.4	0.5	5.9	0.8		3		Khan et al. (2008)
	Peshawar (Bara)	33.92205	71.46259	0.5		166	25.4	0.3	0.4	4.1	0.6		2.4		Khan et al. (2008)
	Peshawar	34.06803	71.5462	4.7	0.6	18	5.3	4.5	5	2.4			29.9		Tariq et al. (2006)
	Peshawar (Sardar Ahmad Jan Colony)	34.030609	71.582731	39.9	0.4	28.9	12.3	0.2		3.6	6.6		0.2		Khan et al. (2015)
	Peshawar (Ring Road Chowk)	33.976538	71.551551	28.7	0.4	22.8	17	0.8		3.5	4.8		0.2		Khan et al. (2015)
	Peshawar (Sardar Colony)	34.0399912	71.586040	6.3	0.1	11.6	16.6	0.5		0.8	5.5		0.5		Khan et al. (2015)
	Peshawar (Ganda Wear End)			2.8	0.03	19.5	13.6	0.5		0.9	3.2		0.2		Khan et al. (2015)
	Peshawar (Budni Drain)	34.061279	71.608430	3.5	0.1	19	17.7	0.8		1	3.6		0.1		Khan et al. (2015)
	Pirsabak Effluent Irrigated Soil (Summer, 2000)	34.03146	72.041098	6.6	0.1			7.2					0.4		Haq et al. (2005)
	Pirsabak Effluent Irrigated Soil (Winter, 2000)	34.03146	72.041098	4.3	0.1			1.1					0.1		Haq et al. (2005)
	Pirsabak Effluent Irrigated Soil (Summer, 2001)	34.03146	72.041098	8	0.1			8.3					0.4		Haq et al. (2005)
	Pirsabak Effluent Irrigated Soil (Winter, 2001)	34.03146	72.041098	6.3	0.1			6					0.2		Haq et al. (2005)
	Pirsabak Tubewell Irrigated Soil	34.03146	72.041098	2.1	0.1			1					0.1		Haq et al. (2005)
	Shangla (Alpuri)	34.8971	72.7513			21,440	640	445	160	78	84		659		Nawab et al., 2016
	Swat	34.81325	72.38171	55	3			637		48	63		863		Shah et al. (2010)
	Swat (Charbagh)	34.83575	72.44357		0.1		5	0.5		0.5	0.4		0.5		Khan, Lu, et al. (2013)

Table 1 (continued)

Provinces	Location	Latitudes	Longitudes	Pb	Cd	Fe	Mn	Ni	Co	Zn	Cu	Mo	Cr	As	References
	Swat (Fatehpur)	35.06784	72.48646		0.1		6.9	0.6		0.4	0.5		0.4		Khan, Lu, et al. (2013)
	Swat (Khwazakhela)	34.93706	72.46871		0.1		4.4	0.5		0.4	0.4		0.5		Khan, Lu, et al. (2013)
	Swat (Madyan)	35.14041	72.53527		0.1		6.4	0.6		0.4	0.5		0.5		Khan, Lu, et al. (2013)
	Swat (Mingora)	34.77174	72.36015		0.1		4.5	0.5		0.4	0.3		0.5		Khan, Lu, et al. (2013)
Punjab	Chenab	31.82265	73.1195	18.1	1.7		494		8	33.7	8.2				Hanif et al. (2016)
	Faisalabad	31.47329	73.1456	64.4	31.7	322	62.8	58.1	24.6	59.3			21.9		Turan et al. (2018)
	Faisalabad	31.45048	73.13482	24.3											Saifullah et al. (2010)
	Faisalabad (Soil before Irrigation)	31.42776	73.07580						8.5						Ashfaq et al. (2009)
	Jhanjar	25.0411	69.83302	14.8				31.9		97.5			34.3		Arain et al., 2009
	Kasur	31.10696	74.42477										724		Riaz et al. (2019)
	Kasur	31.13885	74.44588										30.5		Maqbool et al. (2015)
	Kasur	31.1178	74.4408	1.1	0.1	14.2	0.7	0.6	2.8	0.6			10.6		Tariq et al. (2009)
	Khushab	32.2955	72.3488	29		38.1		7.2		2.4	3.4			43.9	Khan et al., 2017
	Khushab City (Soil Teated with Canal Water)	32.29541	72.34954	26.5		38.6		7		2.3	3.7	5		42.8	Khan et al., 2017
	Khushab City (Soil Treated with Groundwater)	32.29433	72.34663	24.8		33		6.3		1.7	2.6	4.7		40.5	Khan et al., 2017
	Khushab City (Soil Treated with Sewage Water)	32.30002	72.34572	35.6		42.7		8.3		3.2	3.9	6.8		48.3	Khan et al., 2017
	Lahore	31.47444	74.39615	1330	7.3			2.8	0.7		84.5		1		Tariq and Ashraf (2016)
	Lahore	31.52709	74.30557								79.4				Iram et al. (2009)
	Lahore	31.52034	74.35886	7.4	1.2		21.2	14.5	3.7	34.1	15.3		14		Mahmood and Malik (2014)
	Lahore (Soil of Wastewater)	31.54972	71.34361			1540									Mahmood et al. (2020)
	Lahore (Soil of Tube well Water)	31.54972	71.34361			1340									Mahmood et al. (2020)
	Mangla Lake surrounding (Summer)	33.12629	73.76455	26	1.8	40.4	407			30	14		26		Saleem et al. (2014)
	Mangla Lake surrounding (Winter)	33.22762	73.77127	17	1.3	3673	394			40	15		21		Saleem et al. (2014)
	Mian Channum	30.4390	72.3552	2.1	0.3	5.9	0.2	2	2.8	0.3			0.1		Tariq et al., 2009
	Multan City	30.15890	71.52204		2.9		68.3	5.3		47.3					Abbas et al. (2018)
	Potwar	30.1618	71.52333	6	2.6		258	21.1	8.8	33.2	22		17.7		Sattar et al. (2021)
	Rahim Yar Khan	28.4234	70.30029	36.5	0.8	4	174	8.8		56.7	13				Khan et al., 2011
	Sargodha	32.0739	72.686	5.8	4.4			24.4					0.1		Tahir et al. (2017)
	Shakargarh	32.2572	75.1603	1065	35	4074		85.8	747				37.8		Tariq and Rashid (2013)
	Sialkot	32.49448	74.52289	121	36.8	1792		85.5	35.5	94.2	26.9		155		Malik et al. (2010)
	Sialkot (Wastewater Irrigated Soil)	32.54365	74.33998	36.9	9.2		36.5	42.1					43		Khan, Malik, et al. (2013)
	Sialkot (Water irrigated soil)	32.49366	74.52123	12.8	2.9		19.8	30.7					24.9		Khan, Malik, et al. (2013)
	Uchkera (Faisalabad)	31.44683	73.00613	7.8	2.8	2726	212	4.1		75.1					Rashid et al. (2020)
	Vehari (Multan)	30.050804	72.331040											10.7	Natasha et al. (2021)

Table 1 (continued)

Provinces	Location	Latitudes	Longitudes	Pb	Cd	Fe	Mn	Ni	Co	Zn	Cu	Mo	Cr	As	References
Sindh	Manchar Lake (Irrigated with Lake Water)	26.61036	67.99704											18.4	Arain et al. (2009)
	Manchar Lake (Canal Irrigated)	26.54079	67.74792											2.7	Arain et al. (2009)
	Kandhkot	28.24249	69.18242	74.1	1.8										Shaikh et al. (2019)
	Karachi	24.85893	67.00137	42.1		908.4				99.5	33.3		9.6		Karim and Qureshi (2013)
	Karachi (Pre-monsoon)	24.95609	67.07657	41.5		8960				99.5	26.8		9.3		Karim et al. (2014)
	Karachi (Post-monsoon)	24.95609	67.07657	66.4		10,200				90.8	21.9		9.9		Karim et al. (2014)
	Karachi	24.91963	67.15806	105	0.3	3.2		3.9		113	58.5		0.8		Rafeeq et al. (2020)
	Karachi	24.91963	67.15806											27.5	Arain et al. (2009)

Potential ecological risk index

The potential ecological risk index (PERI) was introduced in studies (Hakanson, 1980; Håkanson et al., 1988) to assess the contamination level in soil, toxicity based on HM, and the environmental response (Wu et al., 2015). The PERI is calculated by the summation of risk values (Eq. 5). Its basic purpose is to recognize the contaminants variety and to assess threats (ecological) triggered by HM (Soliman et al., 2015) in the studied sites.

$$\text{PERI} = \sum_{i=1}^{n} \text{ERI} \tag{3}$$

$$\text{ERI} = \text{Tr} \times \text{CF} \tag{4}$$

whereas ERI is the monomial-ecological risk value.

It characterizes the toxicity of particular metals and calculates the potential threats of HM in the studied sites and the environmental sensitivity to the contaminants/pollutants. Hakanson (1980) estimated the toxic response (Tr) values for Cd, Cr, Pb, Zn, Ni, Cu, and As as 30, 2, 5, 1, 5, 5, and 10, respectively. The Tr factor values for Mo, Co, and Mn are 15, 5, and 1, respectively (Lu et al., 2015). The categorization of PERI and ERI is shown in Table 2.

Human health risk assessment

The non-cancerous and cancerous risks (CR) of HM in soil exposure have been calculated for humans of various age groups, i.e., adults and children, using equations, adopted from the studies (Li et al., 2014; Li et al., 2013a; Sun et al., 2013; USEPA, 1989a; Zheng et al., 2013).

The average daily dose (ADD) for exposure measurement was determined for each HM in studied soils. The ADD via ingestion, inhalation, as well as dermal absorption was calculated by the USEPA (1989b) Eqs. (7–9):

$$\text{ADD}_{\text{ing}} = \frac{C * IngRx\text{EF}x\text{ED}xCF}{\text{BW}x\text{AT}} \tag{5}$$

$$\text{ADD}_{\text{inh}} = \frac{C * InhRxEFxED}{BWxATxPEF} \tag{6}$$

$$ADD_{derm} = \frac{C * SAxAFxEVxABSxEFxEDxCF}{BWxAT} \quad (7)$$

All the limits and other estimated parameters used in the computation are based on the USEPA issued data and other relevant literature (Izhar et al., 2016; Li et al., 2013b; Verla et al., 2020).

Non-carcinogenic risk

The non-carcinogenic risk such as hazard quotient (HQ) was calculated by Eq. 10, i.e., dividing the quotient of ADD by the reference dose (RfD) of respective HM (USEPA, 1989b).

$$HQi = \Sigma ADDi / RfDi \quad (8)$$

The hazard index (HI) is the summation of HQ (Zheng et al., 2010); for all the sites, it was calculated using Eq. (11) (USEPA, 1989b).

$$HI = \Sigma HQi \quad (9)$$

According to Zheng et al. (2010), if HI is less than 1, it is considered safe (no significant effects), while if HI is greater than 1, there is a greater probability of non-cancerous effects to exist.

Carcinogenic risk

The carcinogenic risk or CR was calculated by Eq. 12 (USEPA, 1989b).

$$CR = \Sigma ADDi\,x\,CSF \quad (10)$$

Here CSF is the carcinogenicity-slope factor value (Table 2).

Statistical analyses

The graphical presentation of published HM concentration data in soil was accomplished utilizing sigma plot ver. 12.5 (San Jose, California, USA), and spatial distribution maps were produced using ArcMap (Version 10.3).

Results and discussion

The HM is the Earth-crust's natural constituent and is unable to be destroyed/degraded (Komijani et al., 2021). HM encounter their path to human beings through ingestion or inhalation or consumption of contaminated food. Long-time exposure to HM may cause both cellular and neurological problems/disorders and can also cause several kinds of cancers in humans (Khalid et al., 2020; Rehman et al., 2020a).

Heavy metal(loid)s

Average HM concentrations in various provinces and federal areas are summarized in Fig. 2a. Among HM concentrations, the highest mean was observed for Fe in Baluchistan province and the lowest for Cd in Sindh province. Results revealed that the Baluchistan province also showed maximum concentrations of Cr, Mn and Ni compared to other provinces. A higher level of HM contaminations in the Baluchistan province soil may be due to the exposed ore deposits in a mineralized zone (Arif, 2000; Bilgrami, 1969). It mostly consists of ophiolites, dunites, serpentinites, chromites, peridotites, and harzburgites cut dolerites as well as redingote dikes (Bilgrami, 1969, Bilgrami & Howie, 1960). Soil originating from mafic/ultramafic rocks may have a higher amount of HM (Muhammad et al., 2019).

Contamination factor and geo-accumulation index

Among the single indices, the maximum CF was determined for Ni in Baluchistan and the lowest for Fe in Gilgit-Baltistan (Fig. 2b). At an average, soil CF values were in the order as: Baluchistan (2.8) > Punjab (1.95) > Khyber Pakhtunkhwa (1.64) > Gilgit-Baltistan (0.92) > Islamabad (0.89) > Sindh (0.56) (Fig. 2b). Very high CF values were exhibited by Ni (12.1) and Cr (4.07) in Baluchistan; Zn (2.53) and Cu (1.54), in Gilgit-Baltistan; Mo (6.55) and Cd (4.28) in Khyber Pakhtunkhwa; Cd (8.38) and Co (2.91) in Punjab whereas; As (1.08) and Pb (0.94) in Sindh province (Fig. 2b). Very high CF was observed for Ni, Mo, and Cd in Baluchistan, Khyber Pakhtunkhwa, and Punjab provinces, respectively. Similarly, "considerable CF" values are due to Cr in Baluchistan, Islamabad, Khyber Pakhtunkhwa, and Punjab, respectively. While moderate CF values were contributed by Zn and Cu in Gilgit-Baltistan, Islamabad, and Sindh as per the classification described by Jiao et al. (2015) (Table 2). Higher contamination of HM in the soil of the Baluchistan and Khyber Pakhtunkhwa provinces were characterized by the natural enrichment of these metals in the bedrock hosting mafic–ultramafic ore deposits and mining activities (Muhammad et al., 2019; Saddique et al., 2018). However, those of Sindh and Punjab provinces were mainly attributed to anthropogenic activities such as wastewater irrigation (Jamali et al., 2007; Khan et al., 2017).

As for as Igeo is concerned, Ni showed heavy pollution in Sindh, whereas moderate-heavy pollution in Baluchistan, followed by moderate pollution due to Mo in Khyber Pakhtunkhwa and Cd in Punjab (Fig. 2c) as categorized by Sakan et al. (2009). Similarly, mean Igeo values were in the order as: Baluchistan (0.55) > Gilgit-Baltistan (0.18) > Islamabad (0.18) > Sindh (0.61) > Punjab (0.39) > Khyber Pakhtunkhwa (0.33) (Fig. 2c). Higher contamination of HM in study area may be attributed to the human sources and local geology (mafic/ultramafic rocks hosting ophiolites) (Arif & Jan, 1993; Saddique et al., 2018).

Potential ecological risk index

The highest mean ERI values were investigated for Cd and the minimum for Cr (Fig. 2d). Results revealed that average Cd risk values ($160 < ERI \leq 320$) pose high risk in the Punjab province only as categorized by Hakanson (1980) (Table 2). The spatial distribution of ERI values showed high and very high risks due to Cd contamination in the Islamabad, Khyber Pakhtunkhwa and Punjab provinces for about 12% of studied sites, while high risk of Mo in the Khyber Pakhtunkhwa only for 2% sites (Fig. 3). High ERI values in soil were assigned to the HM contaminations as a result of the local geology and anthropogenic activities, and their Tr values (Muhammad et al., 2019; Nawab et al., 2016). The ERI values determined were recorded as slightly higher than those by Pan et al. (2016) in populated agricultural soil in China and lower than described by Bai and Zhao (2020).

Human health risk assessment

Non-carcinogenic

The contaminants HM in soil are toxic to living beings and may cause adverse effects (Saddique et al., 2018). Exposure to HM from soil may occur through multiple routes namely inhalation, ingestion, and dermal pathways (Mama et al., 2020, Rehman et al., 2018). Among HM exposure, the Fe was found the highest, while Cd was the lowest via all the three exposure routes (Fig. 4a–f). It was found that through the ingestion pathway, the intake of HM was the highest (Fig. 4a, b), followed by dermal absorption (Fig. 4e, f), and lowest in the inhalation pathway (Fig. 4c, d). It is obvious from the results that the exposures were higher in Baluchistan province compared to the rest of the provinces. The reason for this may be due to bedrock geology and mining activities (Muhammad et al., 2019; Umar et al., 2013). The intake of HM was used for the potential health risk assessment by HI and CR (Chen et al., 2015; Man et al., 2010).

The HQ was computed for the selected HM for adults as well as children via various routes (Fig. 5a–f). Among these routes, ingestion and dermal contact are the major exposure routes for adults and children. Results showed the highest HQ value for children (1.59) due to As in Punjab province via ingestion (Fig. 5b), while the lowest for Zn (2.5E−08) in Punjab adults through inhalation pathway (Fig. 5c). It is obvious from the findings that the highest risk was via ingestion (Fig. 5a, b), followed by dermal (Fig. 5e, f) and the lowest via inhalation (Fig. 5c, d). The HQ values beyond the threshold limit may cause different chronic health problems (Rehman et al., 2018).

Hazard index values in various provinces and federal areas of Pakistan were summarized in Fig. 6a, b. On average, the highest HI (1.61) value was found for the As in Punjab for children and the lowermost of Zn (0.0003) for adults. Furthermore, As (0.02–1.61) was followed by Cr (0.01–1.11), Ni (0.001–0.59), Pb (0.03–0.51), Fe (0.01–0.26), Cd (0.004–0.13), Co (0.001–0.06), Mo (0.002–0.03), Cu (0.0003–0.01), and Zn (0.0003–0.01). The higher HI values found in Punjab Province compared to the rest of the provinces may be attributed to higher contamination from various industrial and agricultural activities, mining, weathering, and erosion of parent material, i.e., sedimentary as well as mafic and ultramafic rocks (Shahid et al., 2018). It (higher HI) may also be attributed to the increased level of HM intake, their severity of toxicity, and their lower values of RfD (Khan et al., 2013). Higher HI values of As and Cr may result in chronic/long-lasting health issues. Non-cancerous exposure to Cr and As may cause diabetes, cancer,

Table 2 Parameters along with abbreviations, values, and symbols used for risk assessment

Parameters	Symbol	units	Values / Categories	References
Average daily dose	ADD	mg/kg-day		
Average time cancer	ATc	days	70 × 365	USEPA (2002b)
Average time chronic or non-cancer	ATnc	days	30 × 365	USEPA (2002b)
Body weight	BW	kg	70[a], 6[b]	Efe et al., (2014; USEPA, (2002b)
Carcinogenicity slope factor	CSF	–	Inhalation SF: 6.3 (Cd), 9.8 (Co), Ni (0.84), Cr (42), 0.0085 (Pb), 1.51 (As)	Ferreira-Baptista & De Miguel (2005); Lu et al. (2014); USDOE (2011)
Chronic reference dose	RfD	mg/kg-day	Oral RfD: 3.5E-03 (Pb), 0.001 (Cd), 0.7 (Fe), 4.6E-02 (Mn), 2.0E-02 (Ni), 2.0E-02 (Co), 0.3 (Zn), 3.7E-02 (Cu), 5.0E-3 (Mo), 5.0E-03 (Cr), 3.0E-04 (As) Dermal RfD: 5.25E-04 (Pb), 5.0E-05 (Cd), 7.0E-03 (Fe), 1.43E-05 (Mn), 1.0E-03 (Ni), 1.6E-02 (Co), 6.0E-02 (Zn), 1.9E-03 (Cu), 2.0E-3 (Mo), 2.5E-04 (Cr), 2.85E-04 (As) Inhalation RfD: 3.5E-03 (Pb), 0.001 (Cd), 7.0E-03 (Fe), 1.43E-05 (Mn), 2.06E-02 (Ni), 5.7E-06 (Co), 0.3 (Zn), 4.0E-02 (Cu), 2.0E-3 (Mo), 2.86E-05 (Cr), 4.29E-06 (As)	Efe et al. (2014); Ferreira-Baptista & De Miguel (2005)
Contamination factor	CF	Unitless	CF < 1 low concentration 1 < CF < 3 moderate concentration 3 < CF < 6 considerable concentrations CF > 6 very high concentration	Jiao et al. (2015)
Dermal absorption factor	DAF	Unitless	0.03	Chen et al. (2015); HC (2004); Kelepertzis (2014)
Ecological risk index	ERI		ERI < 40 low ecological risk 40 < ERI < 80 moderate ecological risk 80 < ERI < 160 considerable ecological risk 160 < ERI < 320 high ecological risk ERI > 320 very serious ecological risk	Hakanson (1980)
Exposed skin exposed surface area	SA	m^2	5000 [a], 1800 [b]	Efe et al. (2014)
Exposure frequency	EF	Day/year	350	USEPA (2002b)
Exposure duration	ED	Year	24 [a], 6 [b]	USEPA (2002b)
Geo-accumulation index	I_{geo}	Unitless	Igeo ≤ 0 unpolluted 0 < Igeo ≤ 1 unpolluted to moderately polluted 1 < Igeo ≤ 2 moderately polluted 2 < Igeo ≤ 3 moderately to heavily polluted 3 < Igeo ≤ 4 heavily polluted 4 < Igeo ≤ 5 heavily to extremely heavily polluted Igeo > 5 extremely polluted	Muller (1969)

Table 2 (continued)

Parameters	Symbol	units	Values / Categories	References
Inhalation rate	InhR	m^3/day	16 [a], 10 [b]	USEPA (2002b), Zheng et al. (2010)
Ingestion rate	IngR	mg/d	100 [a], 200 [b]	USEPA (2002b)
Particular emission factor	PEF	(m^3/kg)	1.32E-09	USEPA (2002b)
Potential ecological risk index	PERI		PERI < 95 low ecological risk 95 < PERI < 190 moderate ecological risk 190 < PERI < 380 considerable ecological risk PERI > 380 very high ecological risk	Hakanson, (1980)
Skin adherence factor	SAF	mg/cm^2	1[a], 1[b]	USEPA (2002b)

[a]Adult

[b]Children

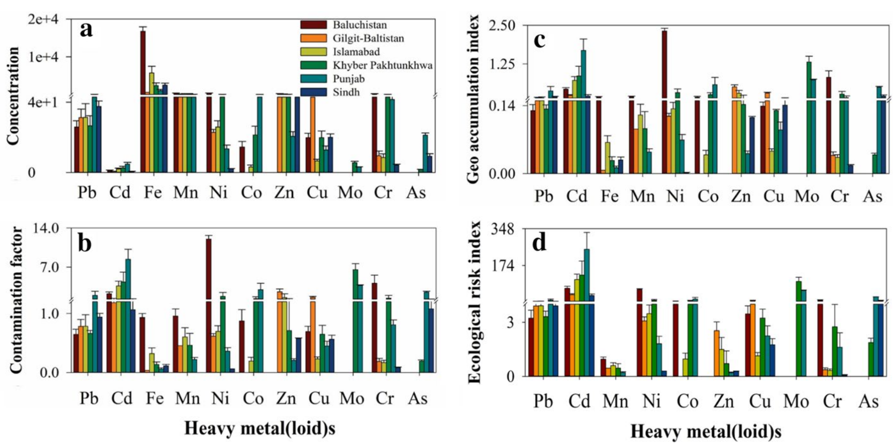

Fig. 2 Soil average heavy metal(loid)s, **a** concentrations (mg/kg), **b** contamination factor, and **c** geo-accumulation index values, **d** ecologicl risk index values

tumor of respiratory and kidney problems (Rehman et al., 2018). Similarly, if the concentration of Ni and Pb further increased, chronic risks due to these two may also be probable in the population.

Cancerous risk

The carcinogenic elements like Cd, Co, Cr, Ni, As, and Pb may produce CR in the exposed population. Moreover, these HM are known to cause CR through multiple exposure routes like ingestion, inhalation, and dermal absorption of soil particles (Hamad et al., 2014; Nickens et al., 2010). The highest (4.04E−07) CR was observed due to Co for children in Punjab (Fig. 7b), while the lowest (2.74E−11) via Pb in Baluchistan for adults (Fig. 7a). The rest of the HM were found between these two extremes (2.74E−11 to 4.04E−07) as exhibited in Fig. 7a, b. Results showed that Co in Punjab, Ni in Baluchistan, and Gilgit-Baltistan Provinces were found to cause higher CR. Results revealed that CR values for the children were higher as compared to adults in all the provinces and for studied HM. This higher CR in children than adults may be ascribed to more exposure due to their hand-to-mouth activities and passing more time outdoor during playing and carelessness during other similar activities (Wang et al., 2010). From the literature, it was found that CR results were determined higher than those recorded by

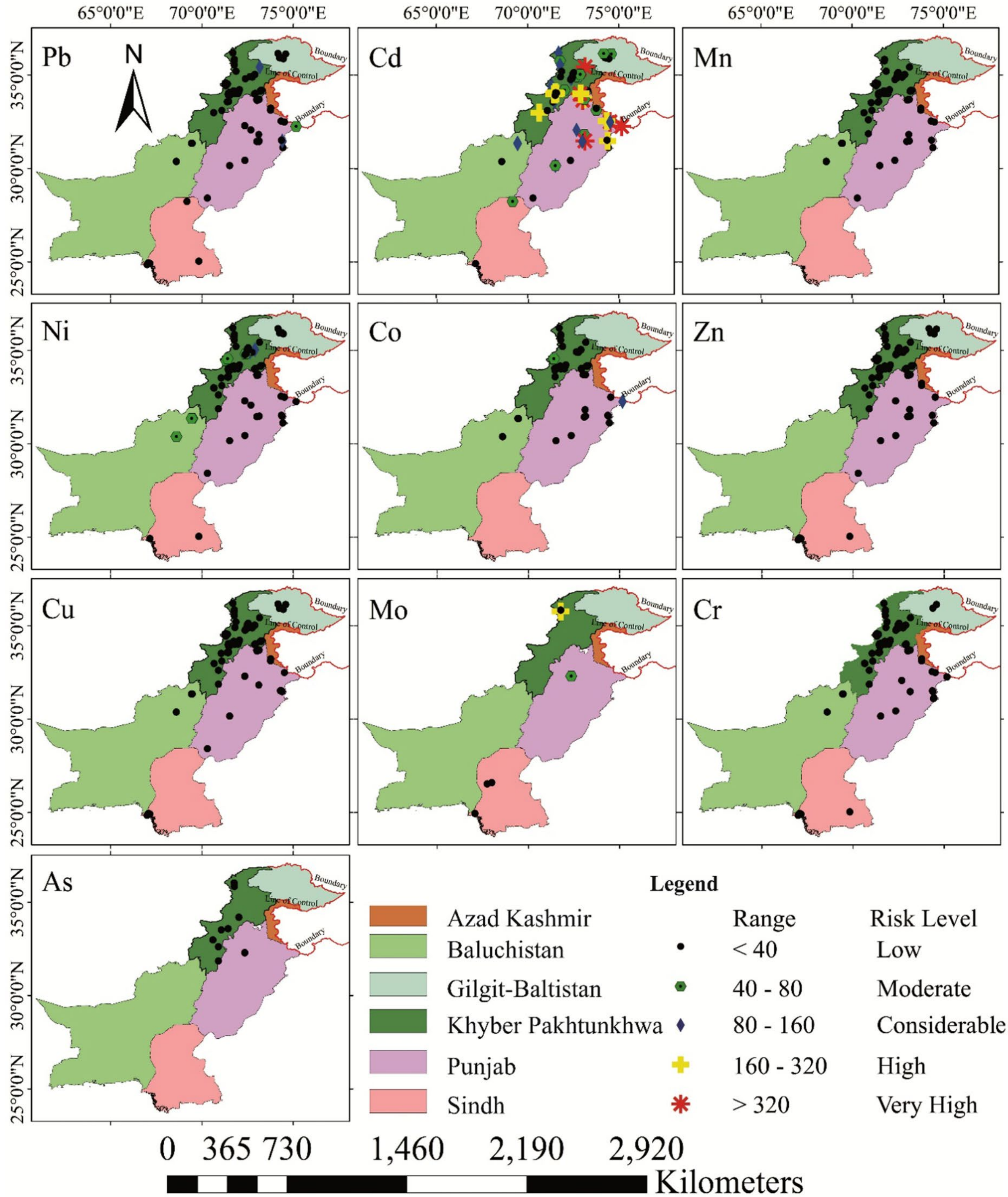

Fig. 3 Ecological risk index values of soil heavy metal(loid)s in the study area

Ferreira-Baptista and De Miguel (2005). CR values for adults and children in all the provinces were found within the tolerable range (10^{-4}–10^{-6}) according to USEPA (2002a) and Hu et al. (2012).

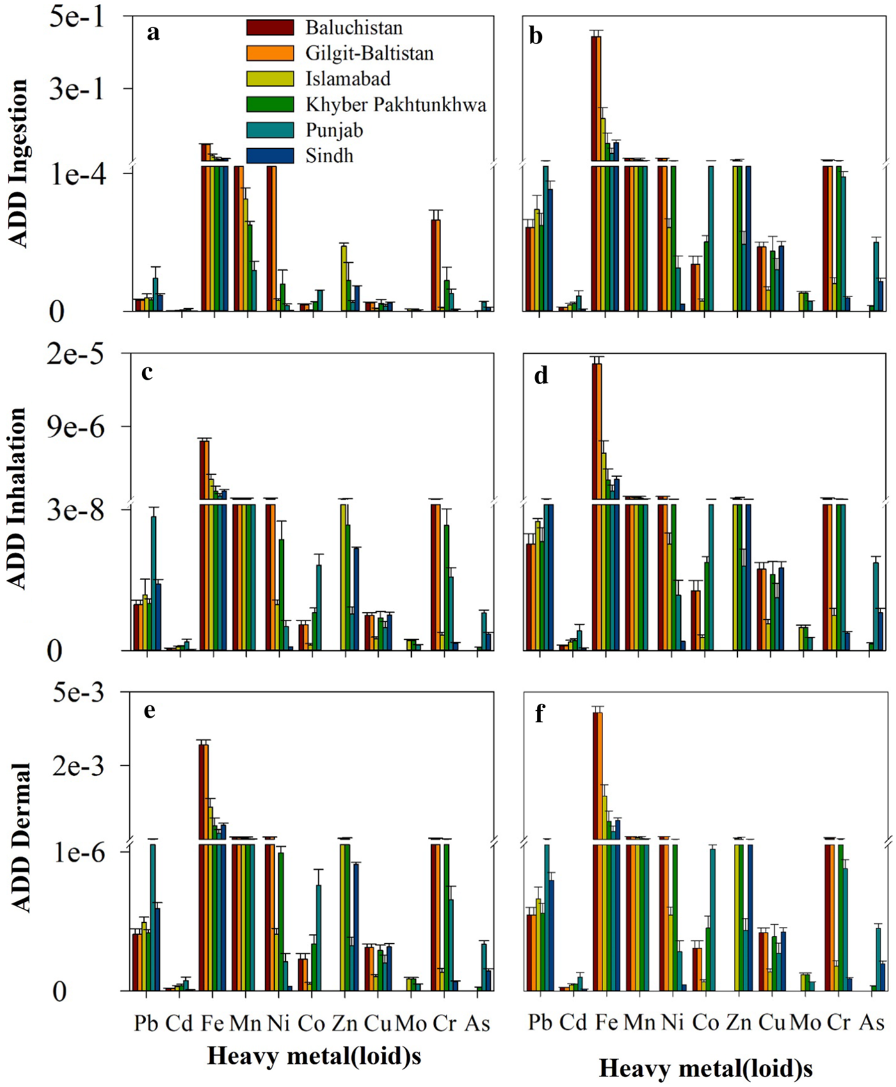

Fig. 4 Human exposure to soil heavy metal(loid)s through various routes in the study area**: a, c and e** ADD adults (mg/kg-day); **b, d and f** ADD children (mg/kg-day)

Although the CR values in the aforesaid areas were found close to the limits. If these issues are not specifically addressed in the future, they will produce adverse effects on the human population.

Conclusion

The current study described the HM distribution, ecological as well as human health risk assessment via soil exposure in all the provinces of Pakistan. It was found that the Baluchistan soil showed higher HM pollution that was attributed by higher CF, Igeo, and ERI. Among the single indices, moderate CF in soils was found for As and Co in Punjab, Zn in Gilgit-Baltistan, Cd in Baluchistan, and Ni in Khyber Pakhtunkhwa; the Igeo pattern was observed in the sequence of Sindh > Baluchistan > Punjab > Khyber Pakhtunkhwa > Gilgit-Baltistan > Islamabad. Whereas, integrated index such as ERI ascribed high ecological average risk in the Punjab province due to Cd. Higher HM contaminations in the soil of the Baluchistan province may be attributed to local geological input and anthropogenic activities. The HQ was found maximum (1.59) for children due to As via ingestion, whereas the minimum risk was due to Zn through the inhalation pathway in the Punjab province. This study concluded that a higher

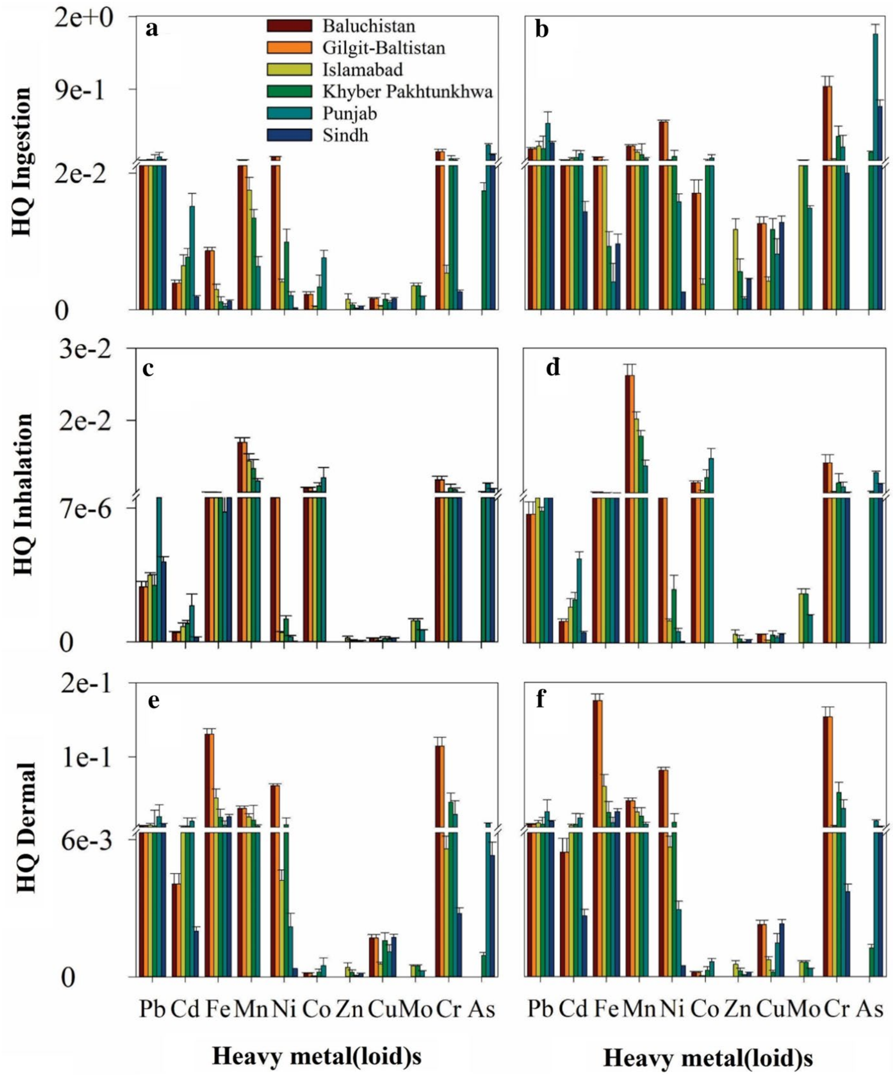

Fig. 5 Non-carcinogenic such as hazard quotient (HQ) of heavy metal(loid)s in the soil to human age groups: **a**, **c** and **e** HQ adults (unitless); **b**, **d** and **f** HQ children (unitless)

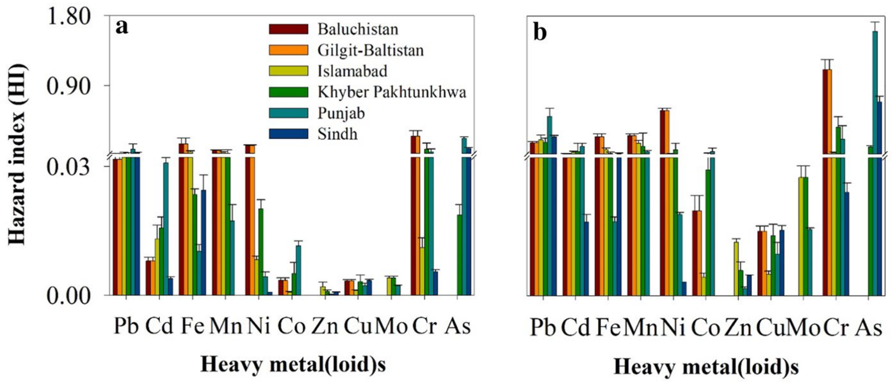

Fig. 6 Hazard index from soil heavy metal(loid)s to human age groups: **a** adults; **b** children

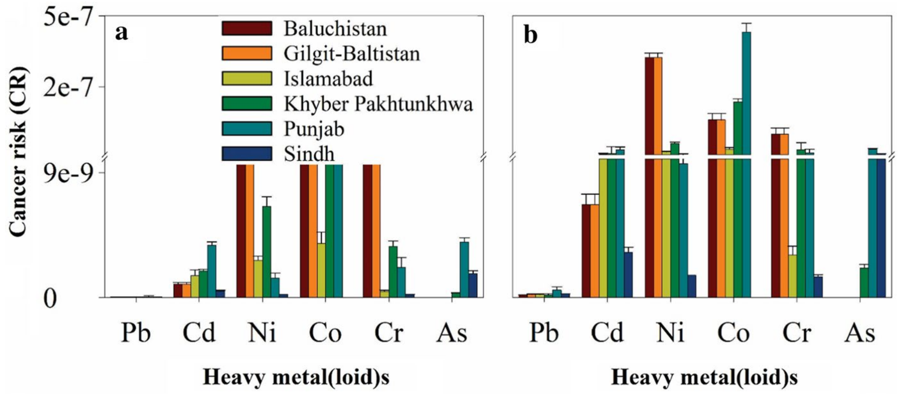

Fig. 7 Cancer or carcinogenic risk via consumption of carcinogenic heavy metal(loid)s to human age groups: **a** adults; **b** children

concentration of HM may produce cancerous and non-cancerous health problems in humans. In comparison with adults, the children group is more prone to HM intake; thus, they may easily be affected adversely. The non-cancerous risk from exposure to As (1.61) in soil was higher than other HM for both adults and children. Similarly, CR values (both for adults as well as children) were determined within the threshold limit and may produce chronic health risks in the future if not monitored and regularized properly. Therefore, the current study recommends the periodic evaluation of HM in the soil of Pakistan generally and that of Baluchistan, Gilgit-Baltistan, and Sindh provinces particularly, where anthropogenic activities are frequently occurring in connection to abundantly available mineral ore deposits (like Fe, chromite, and gold deposits). Further studies are needed to know HM concentrations and to prioritize the strategies for remediation of toxic pollutants to be undergone that will contribute to ecological and environmental sustainability.

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Authors contribution Imran Ud Din was involved in data collection, calculations and writing a draft; Said Muhammad was involved in conceptualization of this study, funding acquisition, project administration, supervision, writing—review & editing of the manuscript; Inayat ur Rehman was involved in resources and software.

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

Code availability Not applicable.

Declarations

Conflict Of Interest The authors declare no competing interests.

Consent to participate All authors reviewed and approved the final manuscript.

Consent for publication All authors are approved for this publication.

Ethics approval Not applicable.

References

Abbas, T., Rizwan, M., Ali, S., Adrees, M., Mahmood, A., Zia-ur-Rehman, M., et al. (2018). Biochar application increased the growth and yield and reduced cadmium in drought stressed wheat grown in an aged contaminated soil. *Ecotoxicology and Environmental Safety*, *148*, 825–833.

Abbas, T., Akmal, M., Aziz, I., Iqbal, M., & Ahmed, H. (2021). Risk assessment and GIS-based mapping of heavy metals in the secondary rock deposits derived soils of Islamabad, Pakistan. *Environmental Earth Sciences, 80*, 1–9.

Aguilera, A., Bautista, F., Gutiérrez-Ruiz, M., Ceniceros-Gómez, A. E., Cejudo, R., & Goguitchaichvili, A. (2021). Heavy metal pollution of street dust in the largest city of Mexico, sources and health risk assessment. *Environmental Monitoring and Assessment, 193*, 1–16.

Ali, I., Khan, I. U., Khan, M. J., Sardar, T., Deeba, F., Hussain, H., Ullah, K., Khan, Q. U., Khan, M., & Khan, M. D. (2020). Exploring geochemical assessment and spatial distribution of heavy metals in soils of Southern KP, Pakistan: Employing multivariate analysis. *International Journal of Environmental Analytical Chemistry*. https://doi.org/10.1080/03067319.2020.1804894

Ali, L., Rashid, A., Khattak, S. A., Zeb, M., & Jehan, S. (2019). Geochemical control of potential toxic elements

(PTEs), associated risk exposure and source apportionment of agricultural soil in Southern Chitral, Pakistan. *Microchemical Journal, 147*, 516–523.
Ali, S. M., & Malik, R. N. (2011). Spatial distribution of metals in top soils of Islamabad City, Pakistan. *Environmental Monitoring and Assessment, 172*, 1–16.
Ali, S. M., Pervaiz, A., Afzal, B., Hamid, N., & Yasmin, A. (2014). Open dumping of municipal solid waste and its hazardous impacts on soil and vegetation diversity at waste dumping sites of Islamabad city. *Journal of King Saud University-Science, 26*, 59–65.
Amin, Nu., Hussain, A., Alamzeb, S., & Begum, S. (2013). Accumulation of heavy metals in edible parts of vegetables irrigated with waste water and their daily intake to adults and children, District Mardan, Pakistan. *Food Chemistry, 136*, 1515–1523.
Arain, M., Kazi, T., Baig, J., Jamali, M., Afridi, H., Shah, A., Jalbani, N., & Sarfraz, R. (2009). Determination of arsenic levels in lake water, sediment, and foodstuff from selected area of Sindh, Pakistan: Estimation of daily dietary intake. *Food and Chemical Toxicology, 47*, 242–248.
Archer, D. R., & Fowler, H. J. (2004). Spatial and temporal variations in precipitation in the Upper Indus Basin, global teleconnections and hydrological implications. *Hydrology and Earth System Sciences, 8*, 47–61.
Arif, M. (2000). Zincian, manganiferous chrome spinel from the Swat valley ophiolite, NW Pakistan. *Geological Bulletin University of Peshawar, 33*, 103–110.
Arif, M., & Jan, M. Q. (1993). Chemistry of chromite and associated phases from the Shangla ultramafic body in the Indus suture zone of Pakistan. *Geological Society, London, Special Publications, 74*, 101–112.
Ashfaq, M., Ali, S., & Hanif, M. A. (2009). Bioaccumulation of cobalt in silkworm (Bombyx mori L.) in relation to mulberry, soil and wastewater metal concentrations. *Process Biochemistry*, *44*(10), 1179–1184.
Assunção, A. G. L., Cakmak, I., Clemens, S., González-Guerrero, M., Nawrocki, A., & Thomine, S. (2022). Micronutrient homeostasis in plants for more sustainable agriculture and healthier human nutrition. *Journal of Experimental Botany, 73*(6), 1789–1799.
Baghaie, A. H., & Fereydoni, M. (2019). The potential risk of heavy metals on human health due to the daily consumption of vegetables. *Environmental Health Engineering and Management Journal, 6*, 11–16.
Bai, J., & Zhao, X. (2020). Ecological and human health risks of heavy metals in shooting range soils: A meta assessment from China. *Toxics, 8*, 32.
Bakht, F., Khan, S., Muhammad, S., & Khan, M. A. (2022). Heavy metal bioavailability in the earthworm-assisted soils of different land types of Pakistan. *Arabian Journal of Geosciences, 15*, 1–8.
Batjes, N. H., & Bridges, E. M. (1993). Soil vulnerability to pollution in Europe. *Soil Use and Management, 9*, 25–29.
Bawwab, M., Qutob, A., Al Khatib, M., Malassa, H., Shawahna, A., & Qutob, M. (2022). Evaluation of heavy metal concentrations in soil and edible vegetables grown in compost from unknown sources in Al-Jiftlik, Palestine. *Journal of Environmental Protection, 13*, 112–125.
Bilgrami, S. (1969). Geology and chemical mineralogy of the Zhob valley chromite deposits, West Pakistan. *American Mineralogist: Journal of Earth and Planetary Materials, 54*, 134–148.
Bilgrami, S., & Howie, R. (1960). The mineralogy and petrology of a rodingite dike, Hindubagh, Pakistan. *American Mineralogist, 45*, 791–801.
Chen, H., Teng, Y., Lu, S., Wang, Y., & Wang, J. (2015). Contamination features and health risk of soil heavy metals in China. *Science of the Total Environment, 512*, 143–153.
Cruzado-Tafur, E., Torró, L., Bierla, K., Szpunar, J., & Tauler, E. (2021). Heavy metal contents in soils and native flora inventory at mining environmental liabilities in the Peruvian Andes. *Journal of South American Earth Sciences, 106*, 103107.
Dhandhayuthapani, O. (2022). An evaluation of chelation therapy for heavy metal toxicity and enhancement of detoxification using natural alternatives with special reference to developing countries. *International Journal of Research in Engineering, Science and Management, 5*, 205–210.
Doabi, S. A., Karami, M., Afyuni, M., & Yeganeh, M. (2018). Pollution and health risk assessment of heavy metals in agricultural soil, atmospheric dust and major food crops in Kermanshah province. *Iran. Ecotoxicology and Environmental Safety, 163*, 153–164.
Drobnik, T., Greiner, L., Keller, A., & Grêt-Regamey, A. (2018). Soil quality indicators–from soil functions to ecosystem services. *Ecological Indicators, 94*, 151–169.
Efe, R., Ozturk, M., Atalay, I., Askarova, M. A., & Mussagaliyeva, A. N. (2014). The ecological situation in contaminated areas of oil and gas exploration in Atyrau Region. Procedia-social and behavioral sciences.In *3rd International Geography Symposium, GEOMED2013*, 10–13 June 2013, Antalya, Turkey 120, 455–459.
Faiz, Y., Tufail, M., Javed, M. T., & Chaudhry, M. (2009). Road dust pollution of Cd, Cu, Ni, Pb and Zn along islamabad expressway, Pakistan. *Microchemical Journal, 92*, 186–192.
Ferreira-Baptista, L., & De Miguel, E. (2005). Geochemistry and risk assessment of street dust in Luanda, Angola: A tropical urban environment. *Atmospheric Environment, 39*, 4501–4512.
Fontes, M. P. F., & Gomes, P. C. (2003). Simultaneous competitive adsorption of heavy metals by the mineral matrix of tropical soils. *Applied Geochemistry, 18*, 795–804.
Gu, W., Guo, J., Bai, J., Dong, B., Hu, J., Zhuang, X., Zhang, C., & Shih, K. (2022). Co-pyrolysis of sewage sludge and Ca (H_2PO_4) 2: Heavy metal stabilization, mechanism, and toxic leaching. *Journal of Environmental Management, 305*, 114292.
Guadie, A., Yesigat, A., Gatew, S., Worku, A., Liu, W., Ajibade, F. O., & Wang, A. (2021). Evaluating the health risks of heavy metals from vegetables grown on soil irrigated with untreated and treated wastewater in Arba Minch. *Ethiopia. Science of the Total Environment, 761*, 143302.
Gul, N., Shah, M. T., Khan, S., & Muhammad, S. (2014). Quantification of the heavy metals in the agricultural soils of Mardan District, Khyber Pakhtunkhwa, Pakistan.

Journal of Global Innovation in Agricultural and Social Sciences, 2, 158–162.

Gul, S., Naz, A., Khan, A., Nisa, S., & Irshad, M. (2016). Phytoavailability and leachability of heavy metals from contaminated soil treated with composted livestock manure. *Soil and Sediment Contamination: An International Journal, 25*, 181–194.

Hakanson, L. (1980). An ecological risk index for aquatic pollution control. *A Sedimentological Approach. Water Research, 14*, 975–1001.

Håkanson, L., Nilsson, Å., & Andersson, T. (1988). Mercury in fish in Swedish lakes. *Environmental Pollution, 49*, 145–162.

Hamad, S. H., Schauer, J. J., Shafer, M. M., Abd Al-Rheem, E., Skaar, P. S., Heo, J., & Tejedor-Tejedor, I. (2014). Risk assessment of total and bioavailable potentially toxic elements (PTEs) in urban soils of Baghdad-Iraq. *Science of the Total Environment, 494*, 39–48.

Hanif, N., Eqani, S. A. M. A. S., Ali, S. M., Cincinelli, A., Ali, N., Katsoyiannis, I. A., Tanveer, Z. I., & Bokhari, H. (2016). Geo-accumulation and enrichment of trace metals in sediments and their associated risks in the Chenab River, Pakistan. *Journal of Geochemical Exploration, 165*, 62–70.

Hao, M., Zuo, Q., Li, J., Shi, S., Li, B., & Zhao, X. (2022). A comprehensive exploration on distribution, risk assessment, and source quantification of heavy metals in the multi-media environment from Shaying River Basin. *China. Ecotoxicology and Environmental Safety, 231*, 113190.

Haq, M. U., Khattak, R. A., Puno, H. K., Saif, M. S., Memon, K. S., & Sial N. B. (2005). Heavy metals accumulation in potentially contaminated soils of NWFP. *Asian Journal of Plant Sciences*, *4*(2), 159–163.

HC. (2004). Federal Contaminated Site Risk Assessment in Canada-Part II: Health Canada Toxicological Reference Values (TRVs) and Chemical-Specific Factors. C. H. Canada. Ottawa - Ontario: Health Canada, Minister of Health: 69.

Hu, X., Zhang, Y., Ding, Z., Wang, T., Lian, H., Sun, Y., & Wu, J. (2012). Bioaccessibility and health risk of arsenic and heavy metals (Cd Co, Cr, Cu, Ni, Pb, Zn and Mn) in TSP and PM2. 5 in Nanjing. *China. Atmospheric Environment, 57*, 146–152.

Iqbal, J., & Shah, M. H. (2011). Distribution, correlation and risk assessment of selected metals in urban soils from Islamabad, Pakistan. *Journal of Hazardous Materials, 192*, 887–898.

Iqbal, M., Ahmed, S., Rehman, W., Menaa, F., & Ullah, A. (2020). Heavy metal levels in vegetables cultivated in pakistan soil irrigated with untreated wastewater: Preliminary results. *Sustainability, 12*, 8891.

Iram, S., Ahmad, I., & Stuben, D. O. R. I. S. (2009). Analysis of mines and contaminated agricultural soil samples for fungal diversity and tolerance to heavy metals. *Pakistan Journal of Botany*, *41*(2), 885–895.

Izhar, S., Goel, A., Chakraborty, A., & Gupta, T. (2016). Annual trends in occurrence of submicron particles in ambient air and health risk posed by particle bound metals. *Chemosphere, 146*, 582–590.

Jadoon, S., Muhammad, S., Hilal, Z., Ali, M., Khan, S., & Khattak, N. U. (2020a). Spatial distribution of potentially toxic elements in urban soils of Abbottabad city, (N Pakistan): Evaluation for potential risk. *Microchemical Journal, 153*, 104489.

Jadoon, S., Muhammad, S., Hilal, Z., Ali, M., Khan, S., & Khattak, N. U. (2020b). Spatial distribution of potentially toxic elements in urban soils of Abbottabad city,(N Pakistan): Evaluation for potential risk. *Microchemical Journal, 153*, 104489.

Jamali, M. K., Kazi, T. G., Arain, M. B., Afridi, H. I., Jalbani, N., & Memon, A. R. (2007). Heavy metal contents of vegetables grown in soil, irrigated with mixtures of wastewater and sewage sludge in Pakistan, using ultrasonic-assisted pseudo-digestion. *Journal of Agronomy and Crop Science, 193*, 218–228.

Jan, F. A., Ishaq, M., Khan, S., Ihsanullah, I., Ahmad, I., & Shakirullah, M. (2010). A comparative study of human health risks via consumption of food crops grown on wastewater irrigated soil (Peshawar) and relatively clean water irrigated soil (lower Dir). *Journal of Hazardous Materials, 179*, 612–621.

Jayamurali, D., Varier, K. M., Liu, W., Raman, J., Ben-David, Y., Shen, X., & Gajendran, B. (2021). An overview of heavy metal toxicity. *Metal, Metal Oxides and Metal Sulphides for Biomedical Applications*, 323–342.

Jehan, S., Khattak, S. A., Muhammad, S., Ahmad, R., Farooq, M., Khan, S., Khan, A., & Ali, L. (2020). Ecological and health risk assessment of heavy metals in the Hattar industrial estate, Pakistan. *Toxin Reviews, 39*, 68–77.

Jiao, X., Teng, Y., Zhan, Y., Wu, J., & Lin, X. (2015). Soil heavy metal pollution and risk assessment in Shenyang industrial district. *Northeast China. Plos One, 10*, e0127736.

Kadri, I. B. (1995). *Petroleum geology of Pakistan*. Pakistan Petroleum Limited.

Karim, R., Tan, G., Ayugi, B., Babaousmail, H., Liu, F., Ngoma, H., & Ongoma, V. (2021). Future changes in seasonal temperature over Pakistan in CMIP6. Preprints 2021, 2021010188. https://doi.org/10.20944/preprints202101.0188.v1

Karim, Z., & Qureshi, B. A. (2013). Health risk assessment of heavy metals in urban soil of Karachi, Pakistan. *Human and Ecological Risk Assessment: An International Journal, 20*, 658–667.

Karim, Z., Qureshi, B. A., & Mumtaz, M. (2014). Geochemical baseline determination and pollution assessment of heavy metals in urban soils of Karachi, Pakistan. *Ecological Indicators, 48*, 358–364.

Kazmi, A. H., & Abbasi, I. A. (2008). *Stratigraphy & historical geology of Pakistan*. Department & National Centre of Excellence in Geology Peshawar.

Kazmi, A. H., & Jan, M. Q. (1997). *Geology and tectonics of Pakistan*. Graphic publishers.

Kelepertzis, E. (2014). Investigating the sources and potential health risks of environmental contaminants in the soils and drinking waters from the rural clusters in Thiva area (Greece). *Ecotoxicology and Environmental Safety, 100*, 258–265.

Khalid, S., Shahid, M., Shah, A. H., Saeed, F., Ali, M., Qaisrani, S. A., & Dumat, C. (2020). Heavy metal contamination and exposure risk assessment via drinking groundwater in Vehari, Pakistan. *Environmental Science and Pollution Research, 27*, 39852–39864.

Khan, K., Lu, Y., Khan, H., Ishtiaq, M., Khan, S., Waqas, M., Wei, L., & Wang, T. (2013). Heavy metals in agricultural soils and crops and their health risks in Swat District, northern Pakistan. *Food and Chemical Toxicology, 58*, 449–458.

Khan, M., Achakzai, A., Iqbal, Y., Ullah, W., Khan, N., Sharif, M., Afzal, M., Bazai, Z., & Ullah, F. (2015). Heavy metals status of the urban and agricultural soils of Peshawar. *Pakistan. Pure and Applied Biology, 4*, 418.

Khan, M. U., Malik, R. N., & Muhammad, S. (2013). Human health risk from Heavy metal via food crops consumption with wastewater irrigation practices in Pakistan. *Chemosphere, 93*, 2230–2238.

Khan, M. U., Muhammad, S., Malik, R. N., Khan, S. A., & Tariq, M. (2016). Heavy metals potential health risk assessment through consumption of wastewater irrigated wild plants: A case study. *Human and Ecological Risk Assessment: An International Journal, 22*, 141–152.

Khan, M. A., Wajid, A., Noor, S., Khattak, F. K., Akhter, S., & Rahman, I. U. (2008). Effect of soil contamination on some heavy metals content of Cannabis sativa. *Journal of the Chemical Society of Pakistan, 30*, 805–809.

Khan, S., Khan, M., & Rehman, S. (2011). Lead and cadmium contamination of different roadside soils and plants in Peshawar City, Pakistan. *Pedosphere, 21*, 351–357.

Khan, S., Munir, S., Sajjad, M., & Li, G. (2016). Urban park soil contamination by potentially harmful elements and human health risk in Peshawar City, Khyber Pakhtunkhwa, Pakistan. *Journal of Geochemical Exploration, 165*, 102–110.

Khan, S., Rehman, S., Khan, A. Z., Khan, M. A., & Shah, M. T. (2010). Soil and vegetables enrichment with heavy metals from geological sources in Gilgit, northern Pakistan. *Ecotoxicology and Environmental Safety, 73*, 1820–1827.

Khan, Z. I., Ahmad, K., Akram, N. A., Mehmood, N., & Yasmeen, S. (2017). Heavy metal contamination in water, soil and a potential vegetable garlic (*Allium sativum* L.) in Punjab Pakistan. *Pakistan Journal of Botany, 49*, 547–552.

Khan, A. Z., Khan, S., Khan, M. A., Alam, M., & Ayaz, T. (2020). Biochar reduced the uptake of toxic heavy metals and their associated health risk via rice (Oryza sativa L.) grown in Cr-Mn mine contaminated soils. *Environmental Technology & Innovation*, *17*, 100590.

Kicińska, A., Pomykała, R., & Izquierdo-Diaz, M. (2022). Changes in soil pH and mobility of heavy metals in contaminated soils. *European Journal of Soil Science, 73*, e13203.

Komijani, M., Shamabadi, N. S., Shahin, K., Eghbalpour, F., Tahsili, M. R., & Bahram, M. (2021). Heavy metal pollution promotes antibiotic resistance potential in the aquatic environment. *Environmental Pollution, 274*, 116569.

Li, H., Qian, X., Hu, W., Wang, Y., & Gao, H. (2013a). Chemical speciation and human health risk of trace metals in urban street dusts from a metropolitan city, Nanjing, SE China. *Science of the Total Environment, 456*, 212–221.

Li, P.-H., Kong, S.-F., Geng, C.-M., Han, B., Lu, B., Sun, R.-F., Zhao, R.-J., & Bai, Z.-P. (2013b). Assessing the hazardous risks of vehicle inspection workers' exposure to particulate heavy metals in their work places. *Aerosol and Air Quality Research, 13*, 255–265.

Li, Z., Ma, Z., van der Kuijp, T. J., Yuan, Z., & Huang, L. (2014). A review of soil heavy metal pollution from mines in China: Pollution and health risk assessment. *Science of the Total Environment, 468*, 843–853.

Lu, S., Teng, Y., Wang, Y., Wu, J., & Wang, J. (2015). Research on the ecological risk of heavy metals in the soil around a Pb–Zn mine in the Huize County, China. *Chinese Journal of Geochemistry, 34*, 540–549.

Lu, X., Zhang, X., Li, L. Y., & Chen, H. (2014). Assessment of metals pollution and health risk in dust from nursery schools in Xi'an, China. *Environmental Research, 128*, 27–34.

Ma, X., Zuo, H., Tian, M., Zhang, L., Meng, J., Zhou, X., Min, N., Chang, X., & Liu, Y. (2016). Assessment of heavy metals contamination in sediments from three adjacent regions of the Yellow River using metal chemical fractions and multivariate analysis techniques. *Chemosphere, 144*, 264–272.

Mahmood, A., Mahmoud, A. H., El-Abedein, A. I. Z., Ashraf, A., & Almunqedhi, B. M. (2020). A comparative study of metals concentration in agricultural soil and vegetables irrigated by wastewater and tube well water. *Journal of King Saud University-Science, 32*, 1861–1864.

Mahmood, A., & Malik, R. N. (2014). Human health risk assessment of heavy metals via consumption of contaminated vegetables collected from different irrigation sources in Lahore, Pakistan. *Arabian Journal of Chemistry, 7*, 91–99.

Malik, R. N., Jadoon, W. A., & Husain, S. Z. (2010). Metal contamination of surface soils of industrial city Sialkot, Pakistan: A multivariate and GIS approach. *Environmental Geochemistry and Health, 32*, 179–191.

Malkani, M. S. (2015). *Stratigraphy, mineral potential, geological history and paleobiogeography of Balochistan Province* (p. 43). Sindh University Research Journal-SURJ (Science Series).

Mama, C., Nnaji, C., Emenike, P., & Chibueze, C. (2020). Potential environmental and human health risk of soil and roadside dust in a rapidly growing urban settlement. *International Journal of Environmental Science and Technology, 17*, 2385–2400.

Man, Y. B., Sun, X. L., Zhao, Y. G., Lopez, B. N., Chung, S. S., Wu, S. C., Cheung, K. C., & Wong, M. H. (2010). Health risk assessment of abandoned agricultural soils based on heavy metal contents in Hong Kong, the world's most populated city. *Environment International, 36*, 570–576.

Mandal, S., Bhattacharya, S., & Paul, S. (2022). Assessing the level of contamination of metals in surface soils at thermal power area: Evidence from developing country (India). *Environmental Chemistry and Ecotoxicology, 4*, 37–49.

Maqbool, Z., Asghar, H. N., Shahzad, T., Hussain, S., Riaz, M., Ali, S., Arif, M. S., & Maqsood, M. (2015). Isolating, screening and applying chromium reducing bacteria to promote growth and yield of okra (Hibiscus esculentus

L.) in chromium contaminated soils. *Ecotoxicology and Environmental Safety*, *114*, 343–349.
Mohammad, J., Khan, S., Shah, M. T., & Islam-ud-din, A. A. (2015). Essential and nonessential metal concentrations in morel mushroom (Morchella esculenta) in Dir-Kohistan Pakistan. *Pakistan Journal of Botany SI, 47*, 133–138.
Muhammad, S., Shah, M. T., & Khan, S. (2011). Heavy metal concentrations in soil and wild plants growing around Pb–Zn sulfide terrain in the Kohistan region, northern Pakistan. *Microchemical Journal, 99*, 67–75.
Muhammad, S., Shah, M. T., Khan, S., Saddique, U., Gul, N., Khan, M. U., Malik, R. N., Farooq, M., & Naz, A. (2013). Wild plant assessment for heavy metal phytoremediation potential along the mafic and ultramafic terrain in northern Pakistan. *BioMed Research International*. https://doi.org/10.1155/2013/194765
Muhammad, S., & Ullah, R. (2022). Spatial distribution of heavy metals contamination in sediments of alpine lakes and potential risk indices, Northern Pakistan. *International Journal of Environmental Analytical Chemistry*. https://doi.org/10.1080/03067319.2022.2042527
Muhammad, S., Ullah, R., & Jadoon, I. A. (2019). Heavy metals contamination in soil and food and their evaluation for risk assessment in the Zhob and Loralai valleys, Baluchistan province. *Pakistan. Microchemical Journal, 149*, 103971.
Muller, G. (1969). Index of geoaccumulation in sediments of the Rhine River. *GeoJournal, 2*, 108–118.
Natasha, S. M., Khalid, S., Niazi, N. K., Murtaza, B., Ahmad, N., Farooq, A., Zakir, A., Imran, M., & Abbas, G. (2021). Health risks of arsenic buildup in soil and food crops after wastewater irrigation. *Science of the Total Environment, 772*, 145266.
Nawab, J., Khan, S., Shah, M. T., Gul, N., Ali, A., Khan, K., & Huang, Q. (2016). Heavy metal bioaccumulation in native plants in chromite impacted sites: A search for effective remediating plant species. CLEAN–Soil. *Air, Water, 44*, 37–46.
Naz, A., Khan, S., Muhammad, S., Ahmad, R., Khalid, S., Khan, A., Nazir, R., & Alam, S. (2020). Risk assessment of hazardous elements in wastewater irrigated soil and cultivated vegetables in Pakistan. *Arabian Journal of Geosciences*, *13*(22), 1–9.
Nazeer, S., Hashmi, M. Z., & Malik, R. N. (2014). Heavy metals distribution, risk assessment and water quality characterization by water quality index of the River Soan, Pakistan. *Ecological Indicators, 43*, 262–270.
Nazir, R., Khan, M., Masab, M., Rehman, H. U., Rauf, N. U., Shahab, S., Ameer, N., Sajed, M., Ullah, M., & Rafeeq, M. (2015). Accumulation of heavy metals (Ni, Cu, Cd, Cr, Pb, Zn, Fe) in the soil, water and plants and analysis of physico-chemical parameters of soil and water collected from Tanda Dam Kohat. *Journal of Pharmaceutical Sciences and Research, 7*, 89.
Nickens, K. P., Patierno, S. R., & Ceryak, S. (2010). Chromium genotoxicity: A double-edged sword. *Chemico-Biological Interactions, 188*, 276–288.
Packer, M. (2016). Cobalt cardiomyopathy: A critical reappraisal in light of a recent resurgence. *Circulation: Heart Failure, 9*, e003604.
Pan, L., Ma, J., Hu, Y., Su, B., Fang, G., Wang, Y., Wang, Z., Wang, L., & Xiang, B. (2016). Assessments of levels, potential ecological risk, and human health risk of heavy metals in the soils from a typical county in Shanxi Province, China. *Environmental Science and Pollution Research, 23*, 19330–19340.
Rafeeq, A. (2020). Soil Contamination due to heavy metals at electronic waste dumpsites in Karachi, Pakistan. *Pakistan Journal of Analytical & Environmental Chemistry, 21*, 332–341.
Rajendran, S., Priya, T. A. K., Khoo, K. S., Hoang, T. K. A., Ng, H.-S., Munawaroh, H. S. H., Karaman, C., Orooji, Y., & Show, P. L. (2022). A critical review on various remediation approaches for heavy metal contaminants removal from contaminated soils. *Chemosphere, 287*, 132369.
Raju, K. V., Somashekar, R., & Prakash, K. (2012). Heavy metal status of sediment in river Cauvery, Karnataka. *Environmental Monitoring and Assessment, 184*, 361–373.
Rashid, I., Murtaza, G., Dar, A. A., & Wang, Z. (2020). The influence of humic and fulvic acids on Cd bioavailability to wheat cultivars grown on sewage irrigated Cd-contaminated soils. *Ecotoxicology and Environmental Safety*, *205*, 111347.
Rehman, Iu., Ishaq, M., Ali, L., Khan, S., Ahmad, I., Din, I. U., & Ullah, H. (2018). Enrichment, spatial distribution of potential ecological and human health risk assessment via toxic metals in soil and surface water ingestion in the vicinity of Sewakht mines, district Chitral, Northern Pakistan. *Ecotoxicology and Environmental Safety, 154*, 127–136.
Rehman, I., Ishaq, M., Ali, L., Muhammad, S., Din, I. U., Yaseen, M., & Ullah, H. (2020a). Potentially toxic elements' occurrence and risk assessment through water and soil of Chitral urban environment, Pakistan: A case study. *Environmental Geochemistry and Health, 42*(12), 4355–4368.
Rehman, I., Ishaq, M., Muhammad, S., Din, I. U., Khan, S., & Yaseen, M. (2020c). Evaluation of arsenic contamination and potential risks assessment through water, soil and rice consumption. *Environmental Technology & Innovation, 20*, 101155.
Rehman, Z. U., Khan, S., Qin, K., Brusseau, M. L., Shah, M. T., & Din, I. (2016). Quantification of inorganic arsenic exposure and cancer risk via consumption of vegetables in southern selected districts of Pakistan. *Science of the Total Environment, 550*, 321–329.
Ren, Q., Sun, R.-L., Zheng, K.-X., Liu, Y.-D., Ruan, X.-L., & Wang, Y.-Y. (2022). Soil properties, heavy metal accumulation, and ecological risk in vegetable greenhouses of different planting years. *Huan Jing Ke xue-Huanjing Kexue, 43*, 995–1003.
Riaz, M., Yasmeen, T., Arif, M. S., Ashraf, M. A., Hussain, Q., Shahzad, S. M., et al. (2019). Variations in morphological and physiological traits of wheat regulated by chromium species in long-term tannery effluent irrigated soils. *Chemosphere*, *222*, 891–903.
Rubio-Gracia, F., Argudo, M., Zamora, L., Clements, W. H., Vila-Gispert, A., Casals, F., & Guasch, H. (2022). Response of stream ecosystem structure to heavy metal

pollution: Context-dependency of top-down control by fish. *Aquatic Sciences, 84*, 1–17.

Saddique, U., Muhammad, S., Tariq, M., Zhang, H., Arif, M., Jadoon, I. A., & Khattak, N. U. (2018). Potentially toxic elements in soil of the Khyber Pakhtunkhwa province and Tribal areas, Pakistan: Evaluation for human and ecological risk assessment. *Environmental Geochemistry and Health, 40*, 2177–2190.

Saifullah, Ghafoor, A., Zia, M. H., Murtaza, G., Waraich, E. A., Bibi, S., & Srivastava, P. (2010). Comparison of organic and inorganic amendments for enhancing soil lead phyto-extraction by wheat (Triticum aestivum L.). *International Journal of Phytoremediation*, *12*(7), 633–649.

Sakan, S. M., Đorđević, D. S., Manojlović, D. D., & Predrag, P. S. (2009). Assessment of heavy metal pollutants accumulation in the Tisza river sediments. *Journal of Environmental Management, 90*, 3382–3390.

Saleem, M., Iqbal, J., & Shah, M. H. (2014). Non-carcinogenic and carcinogenic health risk assessment of selected metals in soil around a natural water reservoir, Pakistan. *Ecotoxicology and Environmental Safety, 108*, 42–51.

Sattar, S., Jehan, S., & Siddiqui, S. (2021). Potentially toxic metals in the petroleum waste contaminated soils lead to human and ecological risks in Potwar and Kohat Plateau, Pakistan: Application of multistatistical approaches. *Environmental Technology & Innovation, 22*, 101395.

Shaikh, R., Kazi, T. G., Afridi, H. I., Akhtar, A., Baig, J. A., & Arain, M. B. (2019). Geochemical exposure of heavy metals in environmental samples from the vicinity of old gas mining area in northern part of Sindh Pakistan. Adverse impact on children. *Environmental Pollution*, *255*, 113305.

Shah, M. T., Begum, S., & Khan, S. (2010). Pedo and biogeochemical studies of mafic and ultramfic rocks in the Mingora and Kabal areas, Swat, Pakistan. *Environmental Earth Sciences*, *60*(5), 1091–1102.

Shah, A., Niaz, A., Ullah, N., Rehman, A., Akhlaq, M., Zakir, M., & Khan, M. S. (2013). Comparative study of heavy metals in soil and selected medicinal plants. *Journal of Chemistry, 2013*, 1–5. https://doi.org/10.1155/2013/621265

Shahid, M., Niazi, N. K., Dumat, C., Naidu, R., Khalid, S., Rahman, M. M., & Bibi, I. (2018). A meta-analysis of the distribution, sources and health risks of arsenic-contaminated groundwater in Pakistan. *Environmental Pollution, 242*, 307–319.

Shahzad, A., Ullah, S., Dar, A. A., Sardar, M. F., Mehmood, T., Tufail, M. A., Shakoor, A., & Haris, M. (2021). Nexus on climate change: Agriculture and possible solution to cope future climate change stresses. *Environmental Science and Pollution Research, 28*, 14211–14232.

Soliman, N. F., Nasr, S. M., & Okbah, M. A. (2015). Potential ecological risk of heavy metals in sediments from the Mediterranean coast. *Egypt. Journal of Environmental Health Science and Engineering, 13*, 1–12.

Stigliani, W. M. (1996). Buffering capacity: Its relevance in soil and water pollution. *New Journal of Chemistry, 20*, 205–210.

Sun, G., Li, Z., Bi, X., Chen, Y., Lu, S., & Yuan, X. (2013). Distribution, sources and health risk assessment of mercury in kindergarten dust. *Atmospheric Environment, 73*, 169–176.

Tahir, M., Iqbal, M., Abbas, M., Tahir, M., Nazir, A., Iqbal, D. N., Kanwal, Q., Hassan, F., & Younas, U. (2017). Comparative study of heavy metals distribution in soil, forage, blood and milk. *Acta Ecologica Sinica, 37*, 207–212.

Tariq, S. R., & Rashid, N. (2013). Multivariate analysis of metal levels in paddy soil, rice plants, and rice grains: A case study from Shakargarh, Pakistan. *Journal of Chemistry*. https://doi.org/10.1155/2013/539251

Tariq, S. R., & Ashraf, A. (2016). Comparative evaluation of phytoremediation of metal contaminated soil of firing range by four different plant species. *Arabian Journal of Chemistry*, *9*(6), 806–814.

Tariq, S. R., Shah, M. H., Shaheen, N., Khalique, A., Manzoor, S., & Jaffar, M. (2006). Multivariate analysis of trace metal levels in tannery effluents in relation to soil and water: A case study from Peshawar, Pakistan. *Journal of Environmental Management*, *79*(1), 20–29.

Tariq, S. R., Shah, M. H., & Shaheen, N. (2009). Comparative statistical analysis of chrome and vegetable tanning effluents and their effects on related soil. *Journal of Hazardous Materials, 169*, 285–290.

Tokatli, C. (2019). Sediment quality of Ergene River Basin: Bio–ecological risk assessment of toxic metals. *Environmental Monitoring and Assessment, 191*, 1–12.

Tokatli, C., & Islam, M. S. (2022). Spatiotemporal variations and bio-geo-ecological risk assessment of heavy metals in sediments of a wetland of international importance in Turkey. *Arabian Journal of Geosciences, 15*, 1–14.

Turan, V., Khan, S. A., Iqbal, M., Ramzani, P. M. A., & Fatima, M. (2018). Promoting the productivity and quality of brinjal aligned with heavy metals immobilization in a wastewater irrigated heavy metal polluted soil with biochar and chitosan. *Ecotoxicology and Environmental Safety*, *161*, 409–419.

Ullah, H., & Khan, I. (2015). Effects of sewage water irrigation of cabbage to soil geochemical properties and products safety in peri-urban Peshawar, Pakistan. *Environmental Monitoring and Assessment, 187*, 1–12.

Ullah, R., & Muhammad, S. (2020). Heavy metals contamination in soils and plants along with the mafic–ultramafic complex (Ophiolites), Baluchistan, Pakistan: Evaluation for the risk and phytoremediation potential. *Environmental Technology & Innovation, 19*, 100931.

Umar, M., Waseem, A., Sabir, M. A., Kassi, A. M., & Khan, A. S. (2013). The impact of geology of recharge areas on groundwater quality: A case study of Zhob River Basin, Pakistan. *Clean-Soil, Air, Water, 41*, 119–127.

USDOE. (2011). *The risk assessment information system (RAIS)*. U.S. Department of Energy's Oak Ridge Operations Office (ORO).

USEPA (1989a). Risk assessment guidance for superfund. Vol I Human Health Evaluation Manual (Part A). Office of Emergency and Remedial Response, Washington.

USEPA (1989b). Risk assessment guidance for superfund. volume I: Human health evaluation manual (Part A), 1. EPA/540/1–89/002.

USEPA. (2002a). *Supplemental guidance for developing soil screening levels for superfund sites*. U.S. Environmental

Protection Agency Office of Emergency and Remedial Response.

USEPA. (2002b). *Supplemental guidance for developing soil screening levels for superfund sites*. U.S. Environmental Protection Agency Office of Emergency and Remedial Response.

Ustaoğlu, F., Islam, M. S., & Tokatli, C. (2022). Ecological and probabilistic human health hazard assessment of heavy metals in Sera Lake Nature Park sediments (Trabzon, Turkey). *Arabian Journal of Geosciences, 15*, 597.

Varol, M., Ustaoğlu, F., & Tokatlı, C. (2022). Ecological risks and controlling factors of trace elements in sediments of dam lakes in the Black Sea Region (Turkey). *Environmental Research, 205*, 112478.

Verla, E. N., Verla, A. W., & Enyoh, C. E. (2020). Bioavailability, average daily dose and risk of heavy metals in soils from children playgrounds within Owerri, Imo State, Nigeria. *Chemistry Africa, 3*, 427–438.

Wang, Z., Chai, L., Yang, Z., Wang, Y., & Wang, H. (2010). Identifying sources and assessing potential risk of heavy metals in soils from direct exposure to children in a mine-impacted city, Changsha, China. *Journal of Environmental Quality, 39*, 1616–1623.

Weyh, C., Krüger, K., Peeling, P., & Castell, L. (2022). The Role of Minerals in the Optimal Functioning of the Immune System. *Nutrients, 14*, 644.

Wu, S., Peng, S., Zhang, X., Wu, D., Luo, W., Zhang, T., Zhou, S., Yang, G., Wan, H., & Wu, L. (2015). Levels and health risk assessments of heavy metals in urban soils in Dongguan, China. *Journal of Geochemical Exploration, 148*, 71–78.

Yanez, L., Ortiz, D., Calderon, J., Batres, L., Carrizales, L., Mejia, J., Martinez, L., Garcia-Nieto, E., & Diaz-Barriga, F. (2002). Overview of Human Health and Regulatory Issues on Chemical Mixtures-Overview of Human Health and Chemical Mixtures: Problems Facing Developing Countries. *Environmental Health Perspectives Supplement, 110*, 901–910.

Yu, Y., Liu, L., Chen, X., Xiang, M., Li, Z., Liu, Y., Zeng, Y., Han, Y., & Yu, Z. (2021). Brominated flame retardants and heavy metals in common aquatic products from the pearl river delta, south china: Bioaccessibility assessment and human health implications. *Journal of Hazardous Materials, 403*, 124036.

Yüksel, B., Ustaoğlu, F., Tokatli, C., & Islam, M. S. (2022). Ecotoxicological risk assessment for sediments of Çavuşlu stream in Giresun, Turkey: Association between garbage disposal facility and metallic accumulation. *Environmental Science and Pollution Research, 29*, 17223–17240.

Zheng, J., Chen, K.-h, Yan, X., Chen, S.-J., Hu, G.-C., Peng, X.-W., Yuan, J.-g, Mai, B.-X., & Yang, Z.-Y. (2013). Heavy metals in food, house dust, and water from an e-waste recycling area in South China and the potential risk to human health. *Ecotoxicology and Environmental Safety, 96*, 205–212.

Zheng, N., Liu, J., Wang, Q., & Liang, Z. (2010). Health risk assessment of heavy metal exposure to street dust in the zinc smelting district, Northeast of China. *Science of the Total Environment, 408*, 726–733.