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Review Article

Potentially Toxic Metals: Their Effects on the Soil-Human Health Continuum

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Abstract
As the foundation of nutritious foods lies in the soil, the consumption of crops grown in contaminated soils may pose an elevated risk of health issues through the soil-plant-human pathway. The impact of heavy metals (HMs) and metalloids on the physiological and biochemical responses of plants can have adverse effects on both growth and yield. The excessive accumulation of these substances in plant tissues poses a significant challenge to public health. HMs possess the capability not only to function as carcinogens but also to act as co-carcinogens, thereby activating specific chemical compounds. According to the World Health Organization (WHO) reports, the target values, representing the desirable maximum concentrations of HMs in the soil, follow the order: Cr > Pb > Zn > Cu > Ni > Cd. This implies that Cd poses the highest potential risk, given its target value of 0.8 mg/kg, while Cr carries the lowest potential risk, with a target value of 100 mg/kg. Various agricultural management practices are recognized as significant pathways that induce the accumulation of metals in the soil and the surrounding environment. Hence, understanding the origin and status of HMs in the environment, along with assessing their potential risks and developing strategies to mitigate these risks, becomes crucial. This study aims to evaluate different facets of the soil-human health continuum concerning potentially toxic metals.
Keywords: Toxic metals, Soil, Bioavailability, Toxicity, Human health

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Introduction

Soil has a key role in the production and recovery cycle. Therefore, soil contamination induces disorder in the production and recovery process of material in nature and disorder in the biological process of soil organisms and plants. Soil contamination with heavy metals (HMs) is an environmental problem on a global scale which tends to be more serious with the rapid growth of industrialization, urbanization, and population, and usage of different organic and inorganic fertilizers without paying attention to their deleterious effects on the nature.[1,2] Anthropogenic activities, such as industrial and traffic emissions and various land-use practices may increase HMs loading into different ecosystems.[3] Because soil and water are the first links of any food chain, depletion of HMs in agricultural soils (through the application of different inputs and wastewater irrigation) not only contaminates soil and water but also affects the quality and safety food. The consumption of polluted foods can lead to various diseases such as upper gastrointestinal cancer.[4] Natural and critical concentrations of HMs in natural water, sediments, and soil are shown in Tables 1 and 2. Due to their non-biodegradable nature, long biological half-lives, and potential to accumulate in different parts of the body, these metals are very harmful.[5] Because they are soluble in water, most of these HMs are very toxic to humans.[6] Even small quantities of HMs have harmful effects on human and animals which is due to the lack of an efficient mechanism for their removal from the body. Nowadays, HMs are omnipresent because of their excessive use in industrial applications (Table 1).

Excessive uptake and chronic exposure to HMs may result in different serious human diseases including cancer which is the most common cause of death in developed countries.[7-9] In fact, HMs can not only act as carcinogens but also as co-carcinogens, which activate certain chemical compounds.[10] Therefore, the current study aims to investigate: (*i*) The potential effects of human activities

Table 1. Concentration of HMs in natural water, sediments and their final limit in unpolluted soil (Prasad 2004)

Metal	Natural Water (µg/g)		Soil (µg/g)		Sediments (µg/g)	
	Sea Water	Fresh Water	Loam	Sand	Lake	Sea
Cd	0.01-0.07	0.07	1	1	0.14-2.5	0.02-0.43
Cr	0.08-0.15	0.5	30	15	7-77	11-90
Co	0.04-0.1	1.8	15	5	-	0.1-74
Hg	0.2	<5	0.15	0.15	0.004-0.2	0.001-0.4
Ni	0.001-0.015	0.2	1	1	34-55	2-225
Pb	0.01-0.62	10	50	50	14-40	7-80

Table 2. The concentration (mg/kg) of some HMs in agricultural soils of different regions/countries

Location	As	Cr	Pb	Ni	Zn	Cd	Cu	Ref.
Austria	-	54	30	35	100	0.4	35	11
Czech Republic	-	70	50	30	80	0.2	25	12
NE Morocco	5.3	-	24.4	-	26.8	0.3	15.9	13
Colombia	-	-	0.012	14.1	107	0.008	118.1	14
Mongolia	3.33-14.17	13.04-60	15-46.66	12.73-18.60	52.3-114.1			15
Catalonia, US	10.4	21.6	21.7	20.7	56.1	0.261	15.4	16
Jin-Qu Basin, China	-	54.6	25.6	22.3	69			17
China	9.2	54	24	23	67	0.074	-	18
Beijing, China	-	17.9-21.9	1.97-3.1	1.92-25.53	67.8-79.6			19
European Union	5	100	60	50	200	1	100	20
European average value	11.6	94.8	32	37	68.1	0.28	17.3	21
World average value	6.83	59.5	27	29	70	0.41	38.9	21
National background value in soil	0.1-55	1-3000	17	0.2-5000	10-100	0.1-1	2-50	22
The natural limit in soil	-	1-1000 (100)	2-200 (10)	5-500 (40)	10-300 (50)	0.01-0.7 (0.06)	2-100 (30)	23
The natural limit in soil	0.1-40	5-1500	2-300	2-750		0.01-2		24
Target value of soil*	-	100	85	35	50	0.8	36	25

*Target values are specified to indicate desirable maximum levels of elements in unpolluted soils.

on metal loadings in soil; (*ii*) The assessment of potential health risks associated with HMs; (*iii*) The examination of the distribution of HMs in various environments and different foods under diverse agricultural managements; (*iv*) An exploration of the pathways through which these metals enter the human body, as well as an analysis of the diseases or disorders they may cause in humans.

Historical Background of Soil and Human Health

Authors made an attempt to analyze the different areas of soil and human health research published through varied databases including Web of Science, Google Scholar, Springer Link, and Wiley-Blackwell databases using the keywords such as soil health, soil and human interactions, soil-toxic metals-human, and soil health-human health. The results showed that 32 368 documents were published during 1999-2022, represented by 17013 research papers, 6445 review papers, 6267 book chapters, 76 encyclopedias, and 2563 publications in form of other documents. In the dataset analyzed, a substantial majority of 16 232 publications were dedicated to exploring the environmental aspects linking soil health to human health. This was followed by a smaller proportion of 5118 publications focusing on agricultural/biological sciences. The remaining publications covered various other subject areas. These findings underscore a significant emphasis on understanding the potential health risks posed by naturally enriched HMs to populations exposed through soil, drinking water, and products derived from these soils. In alignment with the primary objectives of our review, which centered on elucidating the correlation between soil health and human health, we systematically identified 87 research articles and 14 review papers. This bibliometric analysis enabled the discernment of gaps in soil research, particularly emphasizing the interplay between soil characteristics and human health outcomes, thus contributing to the discourse on public health concerns (Table 3).

Relations Between Soil Health And Human Health

Soil is both a sink and a source of different HMs.[26] It is widely acknowledged that mineral elements present in soils can exert either positive or negative effects on human health, either directly or indirectly.[27,28] According to Brevik and Slaughter,[28] human health is influenced by soil chemical pollution, micro-and macro-organisms of soil, and soil nutrient supply. The level of the known essential elements in humans can be deficient, adequate, or toxic,

Table 3. Bibliometric Analysis of Soil Health - Human Health Research (Period: 1999-2022)

Year	Distribution			Subject Areas		
	Research Papers	Review Papers	Others[a]	Agricultural And Biological Sciences	Environmental Science	Others[b]
2022	1931	889	982	517	2087	1198
2021	2927	1450	1247	814	2960	1850
2020	2137	777	890	495	1989	1320
2019	1685	562	842	464	1588	1037
2018	1304	479	591	369	1292	713
2017	1117	400	499	390	931	291
2016	915	307	390	292	792	528
2015	699	255	399	262	552	539
2014	622	192	396	203	586	421
2013	513	143	390	195	486	365
2012	443	136	308	125	426	336
2011	397	125	228	141	374	235
2010	334	98	211	115	331	197
2009	328	122	231	126	308	247
2008	288	90	168	116	276	154
2007	240	105	209	73	229	252
2006	198	46	110	52	173	129
2005	177	58	171	66	184	156
2004	175	40	141	80	166	110
2003	154	50	154	64	164	130
2002	123	43	111	51	123	103
2001	90	36	97	42	75	106
2000	117	23	73	30	77	106
1999	99	19	72	40	63	96
Total	17013	6445	8910	5122	16232	10619

[a] Mini reviews, Encyclopedia, Book chapters, Conference abstracts, Case reports.
[b] Chemical Engineering, Energy, Earth and Planetary Sciences, Biochemistry, Genetics and Molecular Biology.

depending upon the concentrations of these elements in the soil and the matter of dose or exposure.[27] Additionally, certain elements such as lead (Pb), mercury (Hg), arsenic (As), and cadmium (Cd) lack any known biological benefit for human health. Instead, they are toxic even at minimal concentrations.[27,29,30] Essential elements such as zinc (Zn), manganese (Mn), copper (Cu), nickel (Ni), and cobalt (Co) are vital for human health, but they can become toxic at elevated concentrations.[31]

Cd, Cr, Pb, and As have been identified as substances capable of inducing carcinogenic health risks, as classified by the International Agency for Research on Cancer (IARC 2012). Additionally, Pb, Cu, Zn, Iron (Fe), As, Cd, Cr, Al, and Co are recognized as HMs associated with the estimation of non-carcinogenic risks.[32]

Concern over soil pollution by HMs has escalated in recent decades due to their persistent nature, toxicity, propensity for bioaccumulation, and resistance to biodegradation.[33,34] Furthermore, there is currently no known homeostasis mechanism for HMs. According to reports, human health experiences significant setbacks when soils contain excessive levels of these toxic metals.[35]

The concentration of HMs in various soils around the world varies widely and is closely associated with the differing strengths of lithologic and anthropogenic sources. These sources include urban development, mine tailings, areas of oil and gas extraction, sites of high metal waste disposal, and other locations where anthropogenic contamination is more prevalent.[26,27,31,33,34,36-39]

There are two pathways through which humans can be exposed to HMs (Figure 1): (i) the soil–human pathway, also known as the direct pathway, and (ii) the soil–food crop–human pathway, commonly referred to as the indirect pathway.[31] The direct pathway encompasses dermal contact (skin absorption or penetration), ingestion of soil, and inhalation of dust (respiration).[27,28,31,40,41] This pathway is influenced by factors such as the rates of soil and dust intake, concentrations of HMs in soil and dust, body weight, duration of exposure, and the bioavailability factor within the human body.[42,43] Given that nutritious food originates from the soil, consuming vegetables grown in contaminated soil (soil-plant–human pathway)[44,45] can potentially elevate the risk of health issues. The rapid growth in population and the consequent rise in

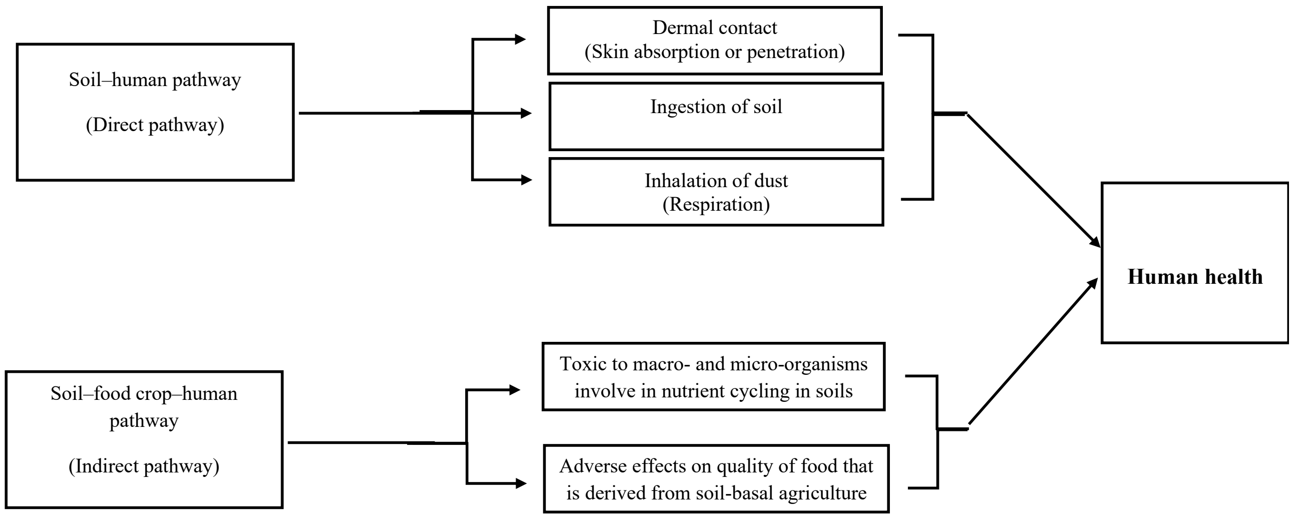

Figure 1. Pathways by Which HMs in Soil Particles Move Into the Body

food demand over the years have led to the cultivation of crops on polluted or contaminated lands, including areas near industries and mining sites.[46-52] Moreover, the indiscriminate use of agrochemicals such as pesticides, fertilizers, and insecticides, along with the utilization of sewage sludge and untreated industrial wastewater, further exacerbates this issue.[19,53-56] Increasing evidence shows that the cultivation of crops on contaminated land can potentially result in the transfer of HMs from soil to the edible parts of a food crop.[57] Moreover, another indirect way by which HMs can adversely affect human health through the food web is toxic to macro-and micro-organisms (fungi and bacteria), which are beneficial for plants and involve nutrient cycling in soils.[58,59] Soil organisms have both direct and indirect effects on the sustainability, quality, and security of food systems that subsequently influence human health and nutrition.[28] Hence, HMs can threaten the health of wildlife and humans through the food chain. Several systems including the blood, liver, brain, kidneys, and lungs can be influenced by HM accumulation in the body.[30,35] Recently, reviews by Alengebawy et al,[30] Aliasgharpour,[29] and Rai et al[57] summarize the impact of HMs on human health and the mechanism of absorption of HMs by humans. The HMs and the methods by which they enter the body of living creatures has been presented in Table 4.

In the direct pathway, several indices are used to provide information on the amount of soil contamination and its potential effect on human and environmental health risks.[69,70] For example, HMs pollution degree in soils can be investigated in terms of the "enrichment factor (EF)"; the "geo-accumulation index," the contamination factor (CF), and the potential ecological risk index (PERI).[56] The conventional approach in risk assessment of metal contamination involves comparing current concentrations with critical thresholds at which adverse effects are anticipated. The permissible concentrations for heavy HMs vary significantly depending on land use and can differ markedly between countries.[71] If the control level is exceeded, further measures must be implemented to identify and manage potential risks. Additionally, several indices have been developed to provide insights into the potential impact of soil contamination on human health risks. These include the average daily dose (including ingestion [ADDing], inhalation [ADDinh], and dermal contact [ADDderm] in mg/kg/d), the non-carcinogenic hazard quotient (HQ; which is the ratio of the ADD of a heavy metal to the corresponding RfD), the hazard index (HI, which is the sum of the HQs from all three pathways), and carcinogenic risk (CR, which is estimated by the total value of cancer risks for each exposure pathway (ADD) using the carcinogenicity slope factor).[15,32,34,45] The hazard index (HI) less than 1 indicates that the HMs in soil do not pose a risk to human health. The acceptable threshold value of the cancer risk is 1×10^{-4} whilst the tolerable CR for regulatory purposes is in the range of 1×10^{-6} -1×10^{-4} (US Environmental Protection Agency.[43] Also, the World Health Organization (WHO) has set the permissible limits of their concentrations (mg/kg) in soil (Table 2).[25] Metals with high permissible limits are considered as safe.[30] These indices help understanding the status of soil contamination and exposure risks for humans. More details about these indices can be found in literature.[15,32,34,45] Table 5 provides an overview of some studies conducted on the relationship between soil pollution and human health.

In the indirect pathway (soil-food crops-human), analogous to the direct pathway, various indices are employed to offer insights into potential risks to human health arising from the consumption of contaminated food crops. For instance, the non-carcinogenic risk (target hazard; THQ) and target carcinogenic risk (TCR) of HMs from the consumption of food crops[72,73] are estimated similarly to the method used for soil. Additionally, the joint FAO/WHO Expert Committee on Food Additives and the Ministry of Health of the People's Republic of China have established the maximum permissible levels of HMs (mg/kg) in various food crops for human consumption. Table 6 presents a review of research

Table 4. HMs and the Methods by Which They Enter the Body of Living Creatures

Type of HMs	The Source or Method of Entry	Reference(s)
Pb, Cd, Ni, Cr, As, Cu, Zn	Organic fertilizers (MSW, SS, etc)*	60-63
Hg, Pb, Cd, Ni, Cr, Co, Cu, Zn	Wastewater	3, 64
Cd, As, Pb, Ni, Cr	Chemical fertilizers (especially phosphorus fertilizers)	1, 65
Cr, Pb, As, Ni, Cu, Zn, Hg, Fe, Mn	Weathering, erosion of bedrocks, volcanic activities and atmospheric deposition	7,66
Cu, Zn, Fe, Mn, Cd, Pb, Co, Ni, As	Herbicides, insecticides and pesticides	30,64
As, Cd, Cr, Ni, Co, Cu, Hg, Pb, and Zn	Industrial activities, coal and fuel combustion, vehicle emissions, metal plating, fertilizer production, mining metallurgy, battery manufacturing and textile dyeing	67
Cr, As, Pb, Hg, Ni and in particular Cd	Cigarette and tobacco smoking, chronic alcohol consumption	9,68

* Municipal solid waste compost and sewage sludge.

investigating the impact of soil pollution on human health through food consumption. Indeed, according to Sir Albert Howard, past president of the Soil Science Society of America, "declining soil fertility, due to a lack of organic material, major elements, and trace minerals, is responsible for poor crops and in turn for poor people. In addition to the adverse effects of high levels of HMs in soil on human health, eutrophic reservoirs may directly and indirectly expose humans to toxins.[74,75] The eutrophication of water is a complex process that occurred by stimulating the growth and flowering of certain types of algae, distributing the quality and condition of natural waters. The primary cause of eutrophication is the enrichment of the water body with nutrients originating from agriculture or sewage treatment.[74] In addition to the deleterious impact of water eutrophication on water quality, this phenomenon may be a threat to the health of the exposed animal and human populations[74] and contribute to the spread of gastrointestinal and dermatological diseases. In recent decades, this has become a global environmental problem.[75,76] Harmful algal blooms represent one of the major ecological health risks associated with eutrophication.[76] Some cyanobacteria have the capacity to produce harmful materials, such as toxins[77,78] and flavor substances,[79,80] which are potential hazards for both human and wildlife health.[78,81] People may be exposed to toxins through the consumption of drinking water from a eutrophic reservoir, direct contact with this reservoir, or the inhalation of evaporation from a mentioned reservoir.[74,75]

Status of HMs in Different Food Diets and Health Risks

Due to their non-biodegradable nature, HMs exhibit high persistence, leading to their easy accumulation in the environment at toxic levels, thereby posing significant risks to human health.[5] Several factors can influence the accumulation of HMs in plants, subsequently impacting food chains. These factors include the type of plant/vegetable, soil pH, soil particle size, organic carbon content, cation exchange capacity of the soil, root exudation, and other physicochemical parameters.[1] The type of HMs, their molecular form, interconversion of valences, and other factors determine how deleterious they can be.[6] Oral intake,[100] inhalation of volatiles and fugitive particulates,[101] and dermal contact[102] are the most important ways of human exposure to HMs.

Water and food are two main sources from which we uptake essential nutrients. Water is considered as a vital substance in the environment,[5] and its contamination with HMs is a worldwide environmental problem[6] which has become increasingly important since the 1990s.[92]

Exposure to HMs through water continues to pose a health threat to populations in certain less-developed countries with inadequate water treatment facilities.[103] Plants irrigated with polluted waters may accumulate toxic levels of HMs,[104,105] as illustrated in Figure 2, which demonstrates the influence of water properties on determining the fate of HMs.

Marine organisms inhabiting coastal areas affected by industrial wastewater discharge often exhibit elevated levels of toxic elements.[106] Furthermore, certain foods possess specific chemical structures or matrix properties, such as texture, making them more susceptible to contamination by various elements.[105]

Vegetables, being a dietary staple for many worldwide, have the capacity to uptake and accumulate significant amounts of HMs in their edible parts,[107] posing potential health risks to both animals and humans.[19] Roggeman et al[108] reported that 40% of the livers and 85% of the kidneys examined in cows exceeded the European limit for Cd. They recommended that an individual weighing 70 kg should not consume more than 150 g of cow meat per day due to chromium (Cr) levels in the muscles.

Leung et al[109] evaluated HMs/metalloid concentration in edible fish species tissue in the Pearl River Delta, China. The researchers reported the overall concentrations of these metals (mg/kg, wet weight) in the fish muscles: As ranged from 0.03 to 1.53, Pb ranged from 0.03 to 8.62, Cd ranged from 0.02 to 0.06, Ni ranged from 0.44 to 9.75, and Cr ranged from 0.22 to 0.65. To mitigate human health risks associated with both acute and chronic food intoxication, they recommended regular determination of HM concentrations in various fish species in the future.

Foodstuffs and drinking water consumed by residents in rural areas are usually produced locally, suggesting that residents living in e-waste areas have a great potential for exposure to HMs.[110] Elevated body loadings of HMs have been recorded in children and recycling

Table 5. Literature Review of the Soil Contamination With Toxic Metals and Related Health Risk Assessment

Location	Depth (cm)	Statistics	HMs Concentration in Soils (mg/kg)	The Assessment of Heavy Metal Contamination in Soils	Health Risk Assessment (Adult)		References
				Igeo	HI	CR	
Isfahan, Iran	0-5	Mean	As: 16 Cd: 2.17 Co: 13 Cr: 81 Cu: 93 Ni: 62 Pb: 180 Zn: 470	As: -.08 Cd: 0.32 Co: -0.99 Cr: -1.45 Cu: 0.24 Ni: -1.05 Pb: 1.64 Zn: 1.33	For all metals <1	As: 6.13×10^{-5} Cd: 1.09×10^{-4} Cr: 7.99×10^{-5} Ni: 9.85×10^{-5} Pb: 1.17×10^{-4}	82
Neyshabur, Iran	0-20	Mean	As: 8.84 Cd: 1.9 Cr: 37.66 Ni: 15.77 Pb: 57.33	As: 1 Cd: 0.59 Cr: 3.35 Ni: 3.45 Pb: 2.16	For all metals <1	For all metals $<10^{-6}$	83
Pahang, Malaysia	0-15		Pb: 32-73 Cu: 68-166 Zn: 93-116 Fe: 68200-128550 Cd: 0.063-0.42 Cr: 6.94-9.34 Ni: 1.45—4.36 Co: 30-108 As: 2.05-5	-	For all metals <1	Pb: 1.06×10^{-7} Cd: 4.84×10^{-8} Cr: 4.57×10^{-8} AS:4.42×10^{-7}	84
Hyderabad, India	5-15	Range	As: 4.4-796 Cr: 9.7-599 Cu: 7.9-184 Ni: 10.2-130 Zn: 24-879	As: -2.1 to 0.16 Cr: -0.56 to 0.87 Pb: 0.1 to 1.96 Ni: -0.29 to 0.81 Zn: -0.47 to 1.09	multi-elemental risk: 0.1-0.37	multi-elemental risk: 1.7×10^{-6}-3.1×10^{-4}	85
A peri-urban area in southeast China		Mean	Cr: 62-78 Cd: 1.11-1.68 Hg: 0.26-0.58 As: 17-48 Pb: 134-190		multi-elemental risk dermal: 1.6 ingestion: 0.31	-	86
Liaoning, Northeast China	0-10	Mean	Cr: 69.9, Cd: 0.86, Pb: 45.1, Zn: 213, Cu: 52.3, Ni: 33.	Cr: -0.26 Cd: 2.56 Pb: 0.29 Zn: 0. 69 Cu: 0.39 Ni: -0.12	For all metals <1	Cr: 4.74×10^{-7} Cd: 8.75×10^{-10} Ni: 4.54×10^{-9}	87
urbanized area of Dongguan, China	0-20	Range	As: 1.20-128 CO: 2.1-64.6 V: 22.6-768 Cd: 0.018-1.94 Pb: 3.4-9149	-	for V, Co, As>1	**As** CR_{ing}:2.34×10^{-5}; $CR_{dermal:}$ 2.29×10^{-6} CR_{inh}: 1.51×10^{-6} **V** $CR_{inh}>10^{-6}$ CO $CR_{inh}>10^{-6}$	88
Riyadh and Mahad AD'Dahab, Netherland	0–3		Cd: 0.0-0.395 Cr: 1.49-31.4 Ni: 0.0-23.8 Pb: 1.28-22.2	Cd: 0 Cr: -7 to -2 Ni: -5 to 0 Pb: -5 to 0	For all metals <1	Cr: 6.79×10^{-6}-2.25×10^{-5} Pb: 5.48×10^{-10}-1.81×10^{-7}	89
Pearl River Delta urban agglomeration of China	0-20	Mean	Cd: 0.27 ± 0.39 Cr: 51.78 ± 33.62 Pb: 47.27 ± 30.58 Hg: 0.26 ± 0.40 As: 13.0 ± 14.22	-	For all metals <1	-	73
Mongolia	0-10	Range of Mean	As: 3.33-28 Pb: 18 -43 Cr: 17-66 Ni: 20-29 Zn:67-155	As: -0.67-0.84 Cr: -1.1 to -0.46 Pb: -1.91 to -0.69 Ni: -0.28 to -0.08 Zn: -0.78 to -0.02	For all metals <1	As: $10^{-10}\times(0.125\text{-}2.54)$ Cr: $10^{-10}\times(0.551\text{-}4.58)$ Pb: -	15
Sialkot, Pakistan	5-60		Cr: 65-535 Mn: 260-410 Cu: 30-125 As: 0.5-2.1 Cd: 0.1-1.0 Hg: 0.005-0.045 Pb: 17-55	Cr: 1.14 As: 1.19 Cd: 1.02 Pb: 0.98	For all metals <1	Cr: 7.514×10^{-5} As: 1.717×10^{-6} Cd: 2.006×10^{-7} Pb: 1.914×10^{-7} Mn: 2.075×10^{-3} Cu: 1.317×10^{-3} Hg: 5.981×10^{-5}	34
Jin-Qu Basin, China	0-20		Cd: 0.06-1.68 Pb: 5.0-108.5 Cr:2.8-157.3	-	Cd: 0.918 Pb: 0.394 Cr: 0.001	-	17
Kermanshah, Iran	0-20	Mean	Zn: 75 Cu: 41 Ni: 131 Cr: 79	$<-1<Zn<1$ Cu≈1 $2<Ni<3$ $0<Cr<1$	For all elements<1	Ni: 1.77×10^{-4} Cr: 5.83×10^{-5}	90

I_{geo}: Geo-accumulation index; HI: Hazard index; CR: Cancer risk.

Table 6. A Literature Review on Contamination of some Food Crops With Toxic Metals and Related Health Risk Assessment

Location	Crop	HMs in Soil (mg/Kg)	HMs In Food Crops (mg/kg)	Health Risk Assessment (Adult)*			Interpretation	References
				THQ	TTHQ	TCR		
Zarrinshahr and Mobarakeh, Iran	Wheat grain, rice grain, onion bulbs	Cd: 1.85 Fe: 35894 Ni: 64.5 Pb: 38	Cd: 0.25 Fe: 55.7 Ni: 1.8 Pb: 1.8	Cd: 2.24 Pb: 4.14 Ni: 0.74 Fe: 0.8	-	-	Soil contamination with Cd, Pb, and Ni and high health risks for the population due to the consumption of Pb and Cd contaminated food crops were recorded.	91
peri-urban area in southeast China	Tea, Rice, vegetable	Cr: 62 (tea)-78 (upland) Cd: 1.11 (paddy)-1.68 (upland) Hg: 0.26 (tea)-0.58 (upland) As: 17 (tea)-48 (upland) Pb: 134 (tea)-190(paddy)	Cr: 0.31 (veg.)-2.25 (tea) Cd: 0.14 (veg.)-0.51(tea) Hg: 0.01(veg.)-0.08(tea) As: 0.08(veg.)0.35(rice) Pb: 0.18(rice)-1.12(tea)	-	<0.05 (tea)-10.44 (rice)	-	The health risk was related to food consumption and the order of health risk of different cropping systems was as follows: rice (10.44)>vegetable (2.86)>tea (0.05). As, Cd, and Cr were identified as main contributors to human health risks.	86
Pakistan	food crops	Cr: 31.65 -61.65 Ni: 30.05 -64.3 Mn: 18.33-66.78 Pb: 11.50 – 90 Cd: 7.13 -11.13	Cr: 1.46–6.08 Ni: 3.36–6.40 Mn: 14.89-201.26 Pb: 22.41–40.85 Cd: 1.18–3.81	Cr: 0.0008-.0033 Ni: 0.14-0.26 Mn: 0.086-1.2 Pb: 5.2-9.4 Cd: 0.95-3.1	-	-	Irrigation with wastewater plays a vital role in accumulation HMs (especially Pb, Cd and Mn) in food crops.	92
		Cd: 0.52–0.93, Pb: 13.6–27.3, Cr: 10.0–21.8, Zn: 44.4–88.5, Cu: 11.9–30.3, and Ni: 14.7–34.5	Cd: 0.17 (bean)-0.41 (Cabbage) Pb: 0.26 (bean)-0.54 (Cabbage) Cr: 0.51 (bean)-2.51 (green pepper) Zn: 2.07 (bean)-14.4 (Cabbage) Cu: 1.12 (bean)-2.84 (Cabbage) Ni: 0.28 (bean)-1.09 (Cabbage)	for all HMs <1	0.028(bean)-0.071 (cabbage)	-	The highest and lowest metal pollution index were respectively recorded for cabbage and. The hazard index of the studied vegetables was<1; therefor, their consumption is unlikely to pose health risks to the target population.	
Potosı´, Bolivia	Potato tuber	As: 13-540 Cd: 2-17 Pb: 33-570 Zn: 100-3500	As: 1-9 Cd:0.1-1 Pb: 0.9-4 Zn: 78-170	As: 4.3-34.2 Cd: 1.2-15 Pb: 0.3-1.1 Zn: 0.3-0.8	-	-	THQ were increased for As and Cd among adults in nearly all of the mining-impacted areas. Only one mining-impacted area had a Pb adult HQ for potatoes above 1.	93
Enyigba, southeastern Nigeria	Vegetable, tuber	As: 1.47-5.22 Cd: 0.4-1.57 Pb: 132-2314 Mn: 788-1389 Zn: 134-273	As: 0.2-0.4 Cd: 0.025-0.55 Pb: 0.26-138 Mn: 3.5-450 Zn: 8.46-99.9	As: 0.35-0.7 Cd: 0.01-0.3 Pb: 0.03-18.08 Mn: 0.05-7.15 Zn: 0.01-0.17	-	-	Mn and Pb expose the local consumers to high health risk.	94
Bangladesh	vegetables and fruits	As: 5-31 Cd: 0.14-0.45 Pb: 18-38	As:<0.01 (fruit)-0.77 (root vegetable) Cd:<0.05 (fruit)-1.2 (leafy vegetable) Pb: 0.5 (fruit)-22 (leafy vegetable)	As: 0.01 (banana)-1.3 (radish) Cd: 0.02 (banana)-0.63 (Helencha) Pb: 0.001 (pat shak)-2.85 (Helencha)	-	As: 3×10^{-6} (banana)-6×10^{-4} (Radish) Cd: 1×10^{-4} (banana)-- 4×10^{-3} (Helencha) Pb: 5×10^{-6} (banana)- 3.8×10^{-4} (bottle ground)	Because of the risk of higher intakes of toxic metals, the study area is unsuitable for growing leafy and root vegetables. Cd caused the highest cancer risk.	95
Dabaoshan mine, South China	Rice & vegetable	Cu: 213-703 Zn: 234-1100 Pb: 130-386 Cd: 1.6-5.5	Vegetable Cu: 0.28-3.61 Zn: 2.34-48.1 Pb: 0.01-0.39 Cd: 0.001-0.71 Rice:	Rice: Cu: 0.66–0.89; Zn: 0.48–0.60; Pb: 1.43–1.99; Cd: 2.61–6.25 Vegetable Cu<0.2 Zn<0.2 Pb<0.5 Cd≈1	-	-	THQs for Cd and Pb of rice and vegetables were>1. Contamination of HMs in food crops grown around the mine posed a great health risk to the local population.	96

Table 6. Continued.

Location	Crop	HMs in Soil (mg/Kg)	HMs In Food Crops (mg/kg)	Health Risk Assessment (Adult)*			Interpretation	References
				THQ	TTHQ	TCR		
Punjab, India	Wheat, mustard, rice, maize	Cd: 0.79 (wheat)-1.73 (rice) Co: 13.15 (mustard)-17.31 (rice) Cr: 2.40 (rice)-4.17 (mustard) Cu: 7.33 (mustard)-11.38 (Maize) Pb: (7.15 (V)-13.39 (rice) Zn: (26.52 (maize- 37.21 (mustard)	Cd: 0.99 (rice)-1.09 (maize) Co: 13.46 (mustard)-15.21 (rice) Cr: 2.45 (mustard)-19.98 (rice) Cu: 6.08 (wheat)-69.89 (rice) Pb: 16.34 (mustard)-18.28 (maize) 35.71 (rice)-59.33(mustard)	Cd: 4.07 (wheat)-0.04 (maize) Co: 2.07 (maize)-182.48 (wheat) Cr: 0.03 (maize)-5.92 (wheat) Cu: 0.04 (mustard)-0.59 (wheat) Zn: 0.005 (maize)-0.66 (wheat)	2.20 (mustard)-193.73 (wheat)	Cr: 5.1×10^{-5}(maize)-8.87 $\times10^{-3}$(wheat)	All the soil samples had high Cd and Co contents, whereas, all crop samples had high contents of Co and Pb. Dietary intake of Co via all food crops posed a higher non-cancer health risk to residents in comparison to other HMs. The Cr posed the highest cancer risk through the consumption of wheat grains, being a staple diet in the study area.	97
Pearl River Delta, South China	Vegetable	Hg: 0.038–1.49 Cd: 0.01–0.69 Pb: 3.42–140 Cr: 3.57–1 1 7 As: 0.68–105	Hg: 0.0014-0.0026 Cd: 0.020-0.060 Pb: 0.055-0.26 Cr: 0.095-0.23 As: 0.033-0.063	For all metals <1	0.128 ± 0.077	-	No significant health risk	98
Jiangsu, China		Rice soil Cr: 58-130 Cd: 0.106-0.198 Hg: 0.144-0.399 Pb: 21-38 Cu: 23-41 Zn: 71-148 Vegetable soil Cr: 57-150 Cd: 0.045-0.856 Hg: 0.05-3.7 Pb: 19-153 Cu: 17-220 Zn: 47-215	Rice Cr: ND-2.83 Cd: 0.005-0.032 Hg: 0.001-0.013 Pb: 0.0076-0.12 Cu: 1.36–3.61 Zn: 9.43–15.78 Vegetable Cr: 0.023-4.44 Cd: 0.0006-0.099 Hg: 0.00002-0.007 Pb: 0.0006-0.293 Cu: 0.17–4.18 Zn: 0.65–15.19	Cr: 0.004 Cd: 0.102 Hg: 0.049 Pb: 0.129 Cu: 0.423 Zn: 0.247		-	Cu, Zn and Pb were the top three metals with higher health risks. For the health of local inhabitants, Cu, Zn and Pb emissions from electroplating firms should be controlled.	99
Hamadan, Iran		Pb: 63- 129 Cd: 3.1-7.4 As: 25-51 Hg: 0.26-1.34 Cr: 50-131		Pb: 0.38 Cd:0.18 Hg: 0.03 Cr: 0.0005 As: 0.98		As: $2.644\times10{-}4$ Cd: $5.99\times10{-}4$ Pb: $6.7\times10{-}6$	Average value of THQ for As was far above the THQ threshold. The majority of the CR values for Pb, As, Cd, and Ni in crops were in the acceptable range for adults. High risks exceeding 1×10^{-4} levels were only found for Ni in crop samples for the adult group.	72
Pearl River Delta urban agglomeration of China	Rice, maize, Leaf vegetables, Brassica vegetables, Legume vegetables, Stalk and stem vegetables, Root vegetables, Fruiting vegetables, cucurbits, Solanaceous fruiting vegetables, Fruit	Cd: 0.27 ± 0.39 Cr: 51.78 ± 33.62 Pb: 47.27 ± 30.58 Hg: 0.26 ± 0.40 As: 13.04 ± 14.22	Cd: 0.02 (Brassica vegetable) - 0.17 (rice) Cr: 0.043 (Brassica vegetable) - 0.56 Pb: 0.048 - 0.27 Hg: 0.00038 – 0.0027	Cr: 4.6×10^{-6} - 0.0024 Pb: 0.001 -0.46 Cd: 0.26-1.03 As: 0.0006-0.49 Hg: 0.00062-0.16		-	All THQs was less than 1 (except THQ for Cd), so Cd was the main metal that posed high potential risks for human health when consumed grain and corn in the PRDUA.	73
Kermanshah, Iran		Zn: 75 Cu: 41 Ni: 131 Cr: 79	Wheat & Maize Zn: 34;38 Cu: 7.9; 4.8 Ni: 1.4; 5.6 Cr: 4.9; 3.3	For all metals <1	Wheat Ni: 8.4×10^{-3} Cr: 1.7×10^{-2} Maize Ni: 6.1×10^{-5} Cr: 1.6×10^{-5}		The carcinogenic risk values of Ni and Cr were above the threshold value (1×10^{-6}), suggesting that Wheat in province might pose a serious threat to human health.	90

THQ, target hazard quotients; TTHQ, sum of the THQs; TCR, target cancer risk.

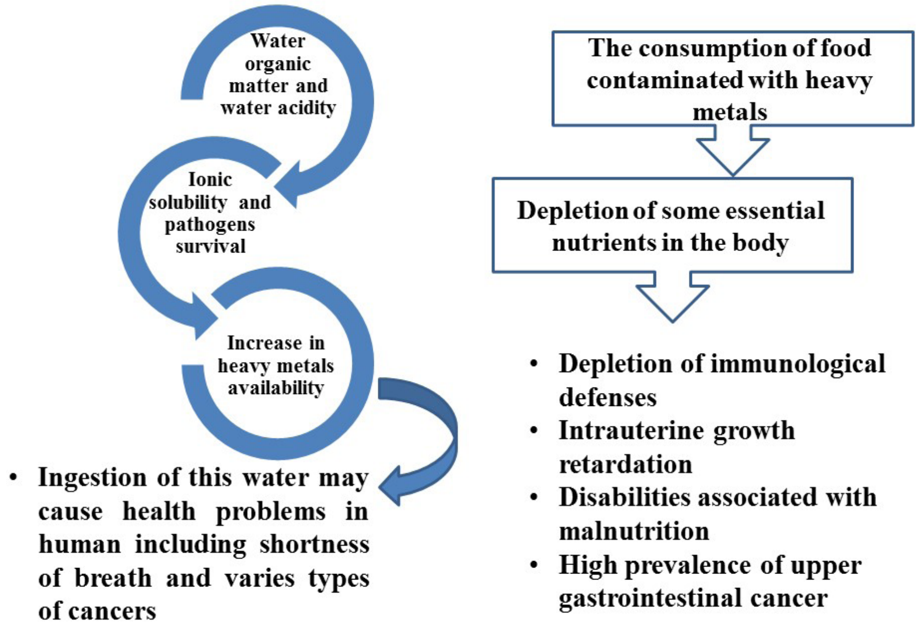

Figure 2. The Properties of the Water, Such as Acidity or the Amount of Organic Matter (left panel)[25,115] and Influence of Entered HMs by Consuming Contaminated Foods on Human Health (right panel).[4]

workers in e-waste areas.[111] Ingestion of house dust may significantly contribute to the exposure of HMs for the general population, given the substantial amount of time spent indoors.[112] This source of exposure is particularly significant for children, who often engage in activities such as playing on the floor and hand-to-mouth contact.

In a study assessing the concentration of HMs in food, house dust, and water from an e-waste recycling area in South China, Zheng and Chen[112] reported elevated concentrations of HMs in the samples, with the exception of drinking water. Furthermore, these researchers highlighted the non-carcinogenic risks associated with rice, vegetables, and house dust for adults, while emphasizing that carcinogenic risks for young children primarily stem from exposure to house dust. Exposure to HMs is a great concern since there are no mechanisms in the human body that can degrade such elements.[5] Malnourishment and diseases such as abdominal pain, anorexia, cardiovascular diseases, immune dysfunction, hypertension, liver, and kidney-related disorders, as well as various kinds of cancers, can arise not only from nutrient deficiency but also from excessive intake of HMs, which they are available in contaminated food and drinking water.[5] As Table 1 indicates, humans are exposed to HMs on a daily basis. Because of the lack of a suitable method for their removal from the body, even small quantities of HMs have adverse effects on public health.[4] The most important method of Cd enters the human body is usually via consuming contaminated foods and smoking cigarettes.[1,113] According to the findings,[114] the concentration of Cd in wheat produced in Iran ranges from < 0.007 to 0.162 mg/kg, with an average of 0.011 mg/kg. This level is considerably lower compared to that of other countries, including many developed nations, indicating the high quality of wheat produced in Iran in terms of Cd content. The measurements also showed that the concentration of Cd in 4% of the samples was further than the maximum allowable concentration of the Iranian national standard (0.03 mg/kg) and based on the standard Codex and EU (0.2 mg/kg), no contamination was observed in any of the wheat samples. Furthermore, the risk assessment of Cd indicated that wheat produced in the country falls within a safe range in terms of Cd concentration, affirming that its consumption does not pose a threat to consumer health.[114]

Julin et al[115] reported that the geometric mean Cd intake via food in the general population in Japan is about 25.5 µg/d, which is higher than that in Sweden (mean, 15 µg/d). The provisional tolerable monthly intake for Cd, aimed at preventing renal tubular dysfunction, is set at 25 µg/kg body weight/month.[25] Studies have also indicated that Cd metal and Cd compounds are associated with an increased risk of various cancers, including lung, breast, pulmonary, prostatic, renal, hepatic, hematopoietic, urinary, stomach cancers, as well as Alzheimer's disease in humans.[116-119] Head and neck cancers (HNC), encompassing a group of similar malignancies affecting the oral cavity (pharynx, ear/nose, and larynx), are among the most prevalent types of cancer worldwide.[120] The incidence of HNC can be influenced by HMs found in tobacco and alcohol, with particular emphasis on Cd concentration, which tends to be higher in tumor tissues compared to normal tissues.[9,68] In humans, high dosages of As ingestion could be fatal and lower levels can cause a variety of systemic effects.[6] As compounds are associated with many forms of skin, head and neck, lung, bladder, kidney, and liver cancers, particularly when high levels enter the human body through drinking water[9] or inhalation and/or ingestion of atmospheric particles.[7] Consumption of fish, shrimp or shellfish, pork, beef, or mutton can contribute to the entrance of high levels of As in maternal blood levels in pregnant women.[121] Arsenic-induced skin cancer is distinguishable from other types of skin cancer because it occurs in sun-protected areas of the body. Increasing documents during the last decades suggest that people exposed to even very low levels of inorganic As for a long time are more amenable to certain cancers, including bladder, lung, and skin cancer. Lower concentrations of the toxic compounds are thought to have different effects on cells and chromosomes compared to higher concentrations, but both may lead to cancer.[122] Causal relationships between long-term exposure to inorganic As and the incidence of human cancers such as skin, lung, and bladder cancers have been approved. Anyone may be exposed to Hg. Eating fish is the principal way by which methyl Hg enters the human body. People may intake other forms of Hg through breathing contaminated workplace air or skin contact, particularly in occupations involving chemical or dental work. Vapors originating from spills, incinerators, and industries utilizing mercury-containing fuels are additional sources contributing to air pollution.[123] The nervous system is highly sensitive to all forms of Hg. Exposure to elevated levels of metallic, inorganic, or organic Hg can lead to permanent damage to the brain, kidneys, and developing fetus. Adverse effects on brain function may manifest as irritability, shyness, tremors, alterations in vision or hearing, and memory impairment.[123] While there are no definitive studies demonstrating that Hg causes cancer in humans or animals. Cr does not accumulate in the body and rapidly becomes excreted into the urine. Cr is a major causative that contaminates round water in several countries. There is increasing evidence showing that Cr can interfere with distinct steps of diverse DNA repair systems[124] as well as oxidative DNA damage. The carcinogenic potential of Cr (VI) is well demonstrated in humans and animals.[8] Some Cr compounds are known to cause lung cancer.[8] However, the role of ingested Cr (VI) in the induction of carcinogenicity still remains controversial.

Pb enters the environment and subsequently the human body through various pathways (see Table 1). In a study conducted on wheat produced in Iran[114], results indicated that the concentration of Pb in the country's wheat ranged from < 0.022 to 0.72 mg/kg, with an average of 0.032 mg/kg. The average Pb concentration in wheat produced in Iran (0.032 mg/kg) is comparatively lower than that of other countries. When evaluated against the Codex standard (0.20 mg/kg), the Pb concentration exceeded the maximum allowable concentration in only 0.70% of the samples. Additionally, the results revealed that Pb concentrations in 1% of the wheat samples exceeded the maximum allowable concentration specified by the national standard of Iran (0.15 mg/kg), while in 99% of the analyzed samples, Pb concentrations were below this threshold. Pb concentrations in rainfed and irrigated wheat were measured at 0.028 and 0.034 mg/kg, respectively. Overall, the risk assessment of Pb indicated that wheat produced in Iran falls within a safe range in terms of Pb concentration, and its consumption poses no threat to consumer health.[114]

Pb enters the body through contaminated food and water, as well as through ingestion and inhalation of atmospheric particles, particularly the ingestion of Pb in fine particulate matter, posing carcinogenic risks.[7] Prolonged exposure to Pb can lead to memory deterioration, prolonged reaction time, and diminished cognitive abilities.[125] Animal studies on kidney and brain tumors have indicated that Pb acetate and Pb phosphate may potentially be carcinogenic. Additionally, environmental exposure to Pb has been associated with an increased risk of brain cancer.[126] Cancer researchers have classified Pb as a possible human carcinogen (group 2B), while its inorganic compounds are considered probable human carcinogens (group 2A).[125] Ni is omnipresent in the air, water, soil, and biological materials (see Table 1), and as a result, it is absorbed through ingestion, inhalation, and skin contact. The toxicity and carcinogenicity of certain Ni compounds have been documented.[127,128]

Selenium (Se) is a key element for the biosynthesis and function of selenoproteins and therefore plays a vital role in the anti-oxidative response, reproduction, metabolism of thyroid hormones, and protection against infection.[129] The initial report suggesting that Se is a cancer-protective trace element emerged in the late 1960s and early 1970s.[130,131] Various mechanisms have been proposed to elucidate the anti-carcinogenic activity of selenium. These mechanisms are thought to be linked to the generation of reactive oxygen species through redox cycling, modification of protein-thiols, and methionine mimicry. However, certain studies suggest that selenium supplementation in a selenium-replete population does not significantly reduce the incidence of certain types of cancers, such as prostate cancer.[132]

Some Strategies to Reduce the Risks Posed by HMs

Soil plays a crucial role in the production and recovery cycles, serving as the foundation of all life on Earth and being one of the indispensable components of biodiversity. Contamination of soil by various organic and inorganic pollutants disrupts production and material recovery processes in nature. Moreover, soil contamination interferes with vital processes of soil-dwelling organisms and can inflict damage upon plants.

HMs hold significance due to their non-degradable nature and their physiological effects on living organisms even at low concentrations.[65,133] These potentially toxic metals originate from both natural and anthropogenic sources. Naturally, HMs derive from various minerals present in the Earth's crust, with their diffusion occurring through processes such as erosion, sedimentation, volcanic activity, forest fires, weathering, acid rain, and surface runoff. Anthropogenic activities contribute to the artificial dissemination of HMs, including mining, combustion of fossil fuels, metallurgical industry operations, and the use of agrochemicals such as organic and inorganic fertilizers, pesticides, and others (see Table 4). Paying attention to these different origins of HMs, and applying suitable and efficient methods and strategies for diminishing these elements' entry into the environment and their dangerous effects on the soil ecosystem and finally living creatures is essential and vital.

Soil contaminants can be remediated through chemical, physical, and biological methods, categorized into two approaches: in-situ and ex-situ methods.[134] In the in-situ method, suitable plants and microorganisms known as hyper-accumulators of HMs are applied (a technique known as bioremediation), along with various amendments such as biochar, organic, and inorganic compounds.[2,63,135,136] Conversely, physical and chemical remediation processes are employed in ex-situ remediation methods.[137,139,140] Preventive measures should be prioritized before resorting to remedial methods, as they are often more cost-effective and easier to implement. Given that soil, as one of nature's most stable and resilient elements, plays a crucial role in mitigating the effects of HMs, it warrants special attention and consideration as a key strategy. Managing soil organic matter through the application of various organic fertilizers, either alone or in combination with chemical fertilizers, ensuring the quality of irrigation water, and carefully regulating the application rates, types, and purity of chemical fertilizers and agrochemicals based on soil and plant analysis results are vital strategies for reducing the entry of HMs into the environment and ultimately the food chain. These measures should be taken seriously and implemented diligently.

Conclusion

HMs enter food chains through various anthropogenic activities, including agricultural and industrial practices, and subsequently find their way into the human body through inhalation, water consumption, and food ingestion. Management of agrochemical applications, quality control of different fuels that are applied as energy sources for houses heating, manufactories, industries, and vehicle operating, management of different agricultural and industrial wastes are the main management strategies for diminishing HMs' entry into the environment. While these strategies are primarily considered preventive measures, once soil and water become contaminated with these potentially toxic elements, the situation changes. Significant costs are often incurred in remediating the soil, water, and the overall environment. Given the hazardous effects of HMs on plants, birds, animals, and ultimately humans, it is crucial to accurately and scientifically identify the various sources of HMs to which living creatures are exposed. This identification is essential for ensuring human health, as HMs are non-biodegradable, possess long biological half-lives, and have a propensity to accumulate in the body, thus posing significant risks to public health. The type and quality of diet and water play a pivotal role in determining the extent to which HMs enter the body. Industrial and agricultural activities stand out as the two primary sources of HMs in the environment, warranting special attention and vigilance. The hazardous effects of HMs on human health have been demonstrated in different studies; however, no efficient methods/ways have been yet proposed to remove the HMs from body habitats in contaminated areas, necessitating the conduction of future research toward solving this problem. Nevertheless, there exist strategies and techniques aimed at reducing the entry of HMs into the soil and subsequently into food chains in contaminated soils, necessitating serious consideration.

Authors' Contribution

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Competing Interests

The authors declare that they have no conflicts of interest.

Consent for Publication

In accordance with the copyright transfer or open access.

Data availability Statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Ethical Approval

Not applicable.

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