Heavy Metals: Definition, Toxicity, and Uptake in Plants

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1 Introduction

The industrialization and urbanization during the last century have resulted in increasing accumulation of heavy metals in soils, water, and air, with subsequent uptake of heavy metals by crops. The consumption of increasing amounts of heavy metals from crops poses an important health risk to animals and humans. While several metals are essential for life, some heavy metals and their compounds are having deleterious health effects.

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2 What Are Heavy Metals?

2.1 Heavy Metal Definition

During the years, the inconsistent use of "heavy metal" terminology has led to confusions about the meaning of this term. Therefore, before using it one should comprehensively define it. Before going into more details on the definition of "heavy metals," let us have a look at the definition of "metals," "metalloids," "essential metals," and "micronutrients."

A ***"metal"*** is a material that conducts electricity, is malleable and ductile, has a metallic luster, and forms cations and oxides (Ali and Khan 2018). Having a look at the periodic table of elements, most of the elements are classified as metals. One should also specify the particular conditions for the existence of an element as a metal, such as room temperature and normal pressure. Otherwise, the category of "metals" would include elements that are nonmetal at normal pressure and room temperature but become metallic at higher pressures or at low temperatures (Buzea and Robbie 2005). In addition, the term "metal" is also used by scientists to refer to both the chemical element and its compounds, sometimes without differentiating between the two (Duffus 2002).

A ***"metalloid"*** or a semimetal is an element with properties intermediate between those of typical metals and nonmetals. Metalloids behave chemically like a nonmetal, being electrical insulators at room temperature, and they acquire metallic behavior either after heating, when in small amounts, or when other atoms are intercalated within their structure. Goldsmith reviews most mentioned metalloids as being B, Si, As, Ge, Sb, and Te (Goldsmith 1982). Vernon's list of metalloids includes B, Si, Ge, As, Se, Sb, Te, Po, and At (Vernon 2013). Vernon defined a metalloid as an element with an electronic band structure of a semiconductor or a semimetal, a medium value of first ionization potential (between 750 and 1000 kJ/mol), and a medium electronegativity value (between 1.9 and 2.2) (Vernon 2013).

An ***"essential metal"*** is a metal necessary for a complete life cycle of a living organism (Duffus 2002). When in insufficient amounts, it results in deficiency symptoms. The term refers to both the metal and its compounds.

Another term, mostly used in life sciences, is ***micronutrient***, which is an element with essential functions in plant cells (Appenroth 2010a). Among these are cobalt, copper, iron, manganese, molybdenum, nickel, and zinc. When the concentration of these micronutrients inside a plant exceeds specific thresholds they become toxic.

The earliest usage of the term" heavy metals" seems to belong to a 1936 book of Niels Bjerrum—Inorganic Chemistry third Danish edition (Bjerrum 1936; Foster 1936; Ali and Khan 2018). Bjerrum defined heavy metals as metals with a density higher than 7 g/cm^3 (Ali and Khan 2018). In the following years Bjerrum's definition was changed by modifying the minimum density of a metal that would qualify as a "heavy metal." This limit varied along the years from 3.5 g/cm^3 up to 6 g/cm^3 (Duffus 2002, 2003). To this day there is no consensus to what the minimum density of a "heavy metal" should be.

As time passed, scientists realized that the density of an element does not dictate its reactivity, and perhaps one needs more criteria for defining a “heavy metal.” Consequently, another criterion was introduced—the ***atomic weight*** of an element (Duffus 2003). While some authors consider “heavy metals” having atomic weights larger than 23 (starting with magnesium), most authors consider atomic weights exceeding 40 (starting with scandium). If scandium is considered a “heavy metal” under the atomic weight criterion, its density of only 3 g/cm^3 does not qualify it as a “heavy metal” under the density criterion.

The ***atomic number*** is another criterion for “heavy metal” classification (Duffus 2002). Within this regard, there is more consistency with various authors agreeing upon the rule of atomic numbers higher than 20 (or higher than Ca). However, metals with atomic number higher than 20 include ***essential metals*** that are necessary for the life cycle of an organism, such as Mg and K (Duffus 2002). Abiding by the atomic number criterion, some authors include within the “heavy metals” category the metalloids As and Te, and the nonmetal Se (Ali and Khan 2018; Duffus 2002).

Currently, the term “**heavy metal**” describes metals and metalloids with a high density, the minimum threshold value differing from author to author (Duffus 2002; Ali and Khan 2018). The elements that are usually considered “heavy metals” are shown in Fig. 1, comprising transition metals (middle), rare earth metals (bottom), and lead-group elements (right side) (Appenroth 2010b). Some authors suggest that “heavy metals” should be defined as naturally occurring metals with an atomic number Z larger than 20 and density above 5 g/cm^3 (Ali and Khan 2018). This definition would encompass 51 elements, as depicted in Fig. 2.

2.2 Negative Connotation Associated with “Heavy Metals”

Broadly speaking, scientific literature uses the terminology “heavy metals” as a negative connotation, in association to environmental contamination and pollution, eco-toxicity, and adverse health effects (Duffus 2002; Ali and Khan 2018; Zaidi et al. 2012; Zhou et al. 2016). The term is often used in ecotoxicology, environmental chemistry, medicine, and legislation publications, sometimes without specifying which elements encompass “heavy metals” (Tchounwou et al. 2012; Mustafa and Komatsu 2016; Zwolak et al. 2019). Occasionally, the generic term of “heavy metals” has been used for toxic elements, such as Cd, Hg, and Pb, and other times for elements that are not necessarily metals nor very heavy or dense, such as As and Se (Duffus 2002). Other times, publications will include light elements as heavy metals, such as Cs, Sr, and Ba (Ali and Khan 2018). For example, Ba is an alkaline earth metal with a density of only 3.62 g/cm^3.

One must emphasize that the general assumption that all “heavy metals” are toxic is not supported by scientific evidence. The elements that are under the umbrella of “heavy metals” terminology have different physicochemical, biological, and toxicological properties (Duffus 2002).

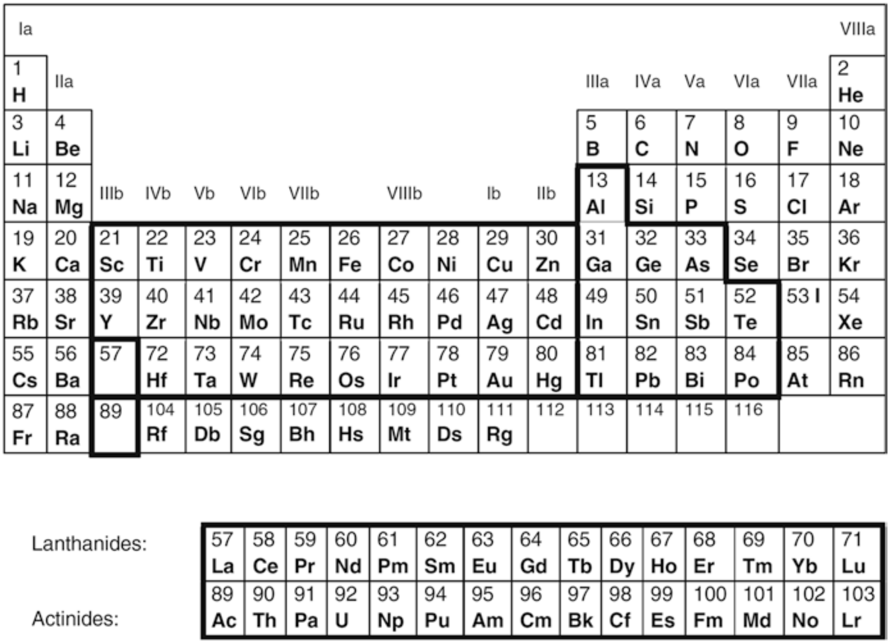

Fig. 1 Schematics showing heavy metals within the periodic table of elements according to Appenroth (reprinted by permission from Springer Nature, Acta Physiologiae Plantarum, "What are heavy metals in Plant Sciences?", vol. 32, pp. 615, Appenroth, K.-J., Copyright (2010) (Appenroth 2010b))

2.3 Controversy Surrounding the Terminology of "Heavy Metals"

Duffus suggests that we should give up the term "heavy metals" in favor of a new classification based on the periodic table that reflects toxic effects and can predict them (Duffus 2002).

One counterargument against this idea is that we cannot possibly group the elements in the periodic table based on their toxic effects, not even based on their physicochemical characteristics. Are we considering the elements of the periodic table in bulk form or ionic form, or as microparticles or nanoparticles? Recent toxicological studies reveal the fact that materials believed to be nontoxic in bulk form have high toxicities when in nanoform (Buzea et al. 2007). Even when talking about the same element in ionic form, or as a nanoparticle, its toxicity depends on the chemical corona and its interaction with the biological fluids within an organism. In addition, the same element but in different oxidation states can be either toxic or beneficial for health, like the example of cerium oxides (Pacheco and Buzea 2018).

Moreover, the physicochemical properties of the same element in bulk form can differ essentially from its counterpart in nanoform (Buzea and Pacheco 2017). For

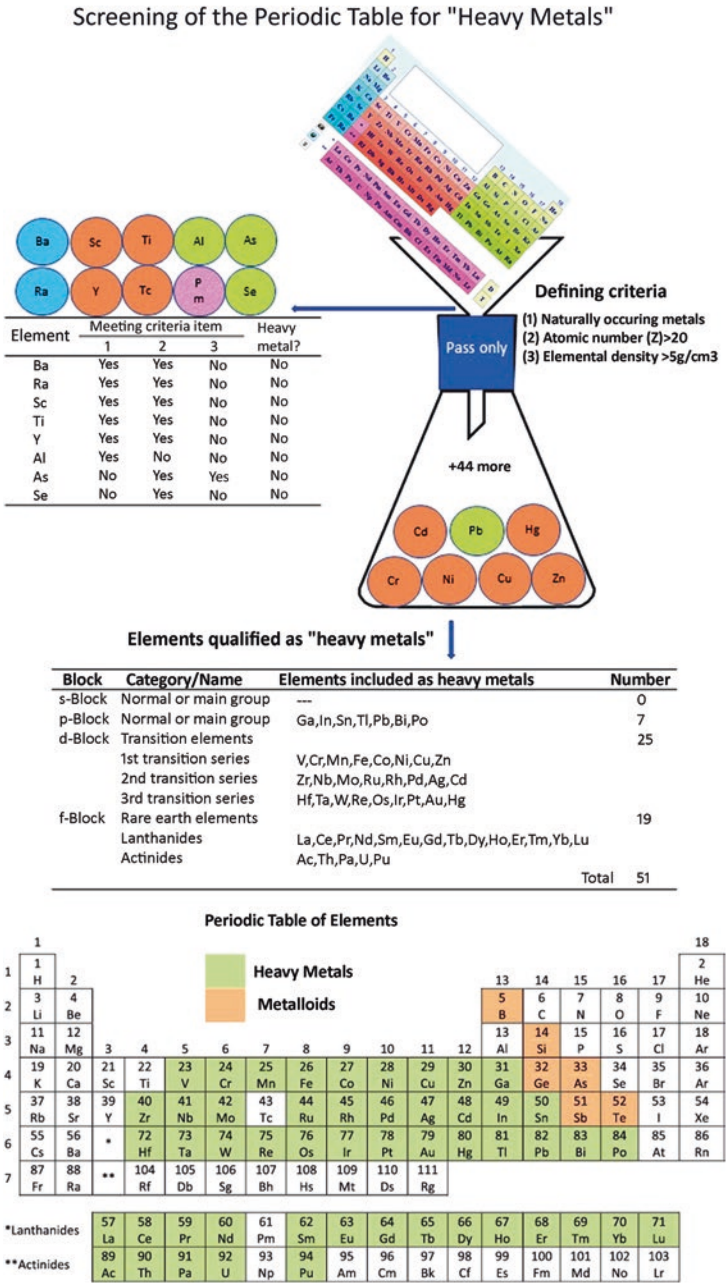

Fig. 2 Image depicting selection of heavy metals and metalloids from the elements of the periodic table as proposed by Ali and Khan (reprinted by permission from Springer Nature: Toxicological & Environmental Chemistry, "What are heavy metals? Long-standing controversy over the scientific use of the term 'heavy metals'—proposal of a comprehensive definition", Ali H. and Khan E., vol. 100, pp. 6–19, Copyright (2018))

example, certain metals nonmagnetic in bulk exhibit magnetic behavior in nanoform, among them being Au, Pt, and Pd (Buzea and Pacheco 2017).

Given the fact that the chemical elements and their compounds under the umbrella term of "heavy metals" have no common toxicity denominator and are selected according to criteria abiding by arbitrary numbers, i.e., the minimum atomic number or elemental density, one should always specify what we call "heavy metals." The meaning of the term "heavy metal" implies that it has a high density; however this physical property is irrelevant in the context of their interaction with plants and organisms (Appenroth 2010a). Moreover, because the term of "heavy metals" includes the metals together with their compounds, one must also underline that as soon as a metal forms a compound, its physical and chemical properties change.

This group of elements termed as heavy metals do not have the same toxicity to organisms, some of them being essential metals necessary for life. There is no correlation between the density of a metal or metal compound and its toxicity to organisms (Appenroth 2010a). The presence in the soil of some metals with a moderate to high atomic number (Cu, Zn, Ni, Pb) can prevent the growth of plants with the exception of a few tolerant species. Hence, the usage of a general term, such as "heavy metals," can be seen as justified for the sake of brevity.

3 Biologically Significant Chemical Properties of Heavy Metals

When speaking about metal toxicity one must take into account their chemical speciation, their biological uptake selectivity, and their biologically significant chemical properties (Duffus 2002). Based on the last electron subshell in the atom to be occupied, metals can be classified as s-block, p-block, d-block, and f-block (Duffus 2002). The s-block metals, such as alkali, form weak complexes acting as electrolytes, while alkaline earth metals are more stable and act as structure promoters and enzyme activators (Duffus 2002). Within the p-block, the higher atomic number metals bind to sulfur, resulting in toxicity. The d-block metals have a wide redox behavior and number of complexes, acting as enzyme catalysts. Within the f-block, comprised of lanthanides and actinides, some metals may act as pollutants.

An important property of a metal ion is its ability to form complexes (Appenroth 2010a). Metals and metalloids are classified in three classes, as class A elements, borderline elements, and class B elements. Hence, the elements that we call "heavy metals" will be divided as:

- Hard acceptors or class A elements: Al^{3+}, Ga^{3+}, Sc^{3+}, Y^{3+}; interact with oxygen-containing ligands.
- Borderline elements: Ga^{3+}, In^{3+}, Sn^{4+}, Pb^{2+}, As^{3+}, Sb^{3+}, Ti^{2+}, V^{2+}, Mn^{2+}, Fe^{2+}, Fe^{3+}, Co^{2+}, Ni^{2+}, Cu^{2+}, Zn^{2+}, Cd^{2+}.

- Soft acceptors or class B elements: Tl^{+}, Tl^{3+}, Pb^{4+}, Bi^{3+}, Pd^{2+}, Pt^{2+}, Cu^{+}, Ag^{+}, Au^{+}, Hg^{2+}. Some of class B ions have high toxicity (Ag^{+}, Tl^{+}, Hg^{2+}, Cd^{2+}) and form bonds with sulfur- and nitrogen-containing ligands.

4 Toxicity of Heavy Metals to Humans and Animals

The most commonly environmentally available heavy metals are As, Cd, Cr, Cu, Pb, Ni, and Zn.

Some heavy metals in low concentrations are essential for biochemical and physiological processes within living organisms; however they may become toxic when in higher concentrations (Jaishankar et al. 2014).

One must emphasize that several heavy metals are extremely toxic even at low levels of exposure (Tchounwou et al. 2012). These systemic toxicants are arsenic, cadmium, chromium, lead, and mercury, and can induce multiple-organ damage.

Below we show toxicity effects associated with some of these elements and their compounds, in alphabetical order. Table 1 summarizes the heavy elements and their compounds, their target organs and manifestation, and carcinogenicity in rats and humans (Borm et al. 2004; Kusaka et al. 2001; Guha et al. 2017).

Arsenic: Arsenic, a very abundant element on earth, actually a semimetal but still considered a heavy metal, is toxic and carcinogenic. It affects cell respiration, cell enzymes, and mitosis (Jaishankar et al. 2014).

Lead: High levels of lead are associated to a myriad of health effects, including reproductive toxicity, developmental effects, neurotoxicity, renal dysfunction, lowered immune response, endocrine dysfunction, and hematological effects (Gidlow 2015). Table 2 shows a list of these health effects in males and females.

Mercury: Mercury in the form of a simple element, inorganic salts, and organic compounds has different levels of toxicity. Mercury compounds can be found as water contaminants. Mercury is neurotoxic and is involved in mitochondrial damage and lipid peroxidation. It can also affect kidneys and muscles.

Cadmium: Cadmium is very toxic among heavy metals, causing hepatotoxicity and nephrotoxicity (Jaishankar et al. 2014).

Chromium: Chromium in both its trivalent Cr+3 and hexavalent Cr+6 states is toxic to organisms, including animals, humans, and plants (Jaishankar et al. 2014). It leads to oxidative stress, DNA, and protein damage.

Iron: Iron, the second most abundant metal in earth's crust, is essential for the existence of all organisms. However, iron can damage DNA, mitochondria, and other organelles as a result of free radical production (Jaishankar et al. 2014).

Table 1 Occupational exposure particles and their carcinogenicity according to several sources: the International Agency for Research on Cancer (IARC) *http://monographs.iarc.fr/ENG/Classification/*, Borm P. J. A. et al., Inhaled particles and lung cancer, part B: Paradigms and risk assessment, International Journal of Cancer, vol. 110 (2004) pp. 3–14, Copyright (2004) with permission from John Wiley & Sons, Inc. (Borm et al. 2004); Kusaka Y. et al., Metal-induced lung disease: lessons from Japan's experience, Journal of Occupational Health vol. 43 (2001) pp. 1–23, under a Creative Commons Attribution (CC-BY) License (Kusaka et al. 2001; Guha et al. 2017)

Material and compounds	Target organs or manifestation	Exposure	Carcinogen in rats	Carcinogen in humans
Air pollution	Lung, bladder cancer	Outdoor air pollution	Yes	Yes
Cd	Cancer of lung, kidney, prostate	Metal industry	Yes	Yes
Cr(VI)	Lung, nose, sinuses, cancer	Metal industry	Yes	Yes
Co	Pulmonary fibrosis, lung cancer, DNA damage	Mining, coloring agents, magnetic alloys, industrial and military application		Possibly
Fe	Cancer of the lung Pneumoconiosis	Steel Pigments, diagnosis	Yes	Yes
Pb	Systemic intoxication (blood and central nervous system)	Mining, leaded gasoline, paints, industry		Probably
Mn	Systemic intoxication, neurological diseases	Welding, metal industry		Yes
Ni	Lung and nasal cancer	Mining, milling, smelting, refining	Yes	Yes
Ti	Pneumoconiosis, lung cancer	Pigments, cosmetics, sunscreen agents	Yes	Possibly
V	Asthmatic bronchitis	Mining, refining, alloys, chemical industry	Yes	Possibly

5 Heavy Metal Availability in Soils

Anthropogenic activities have been identified as sources of heavy metal pollution. These include mining, paper mills, cement factory, and metallurgic activities for soil contamination with metals like copper, zinc, lead, and cadmium (Zhang et al. 2009; Cobb et al. 2000). In addition, studies show that vegetables irrigated with wastewater contain a substantial increase of heavy metals, like manganese, iron, copper, and zinc (Arora et al. 2008; Antisari et al. 2015), and chromium, cadmium, nickel, and lead (Ghosh et al. 2012).

Figure 3 shows a schematic comprising environmental availability of heavy metals within soil, followed by the biological uptake of heavy metals, with subsequent accumulation and toxicity within living systems (Kim et al. 2015), (Harmsen 2007). The amount of heavy metals which is environmentally available within the soil comprises the fraction dissolved in the pore water together with the amount already

Table 2 Possible health effects associated with various lead (Pb) levels in blood in humans (table taken from Gidlow D. A, Lead toxicity. Occupational medicine (Oxford, England), 2015, vol. 65, pp. 348–356, by permission of Oxford University Press (Gidlow 2015))

Blood levels (μg)	Males	Females
<5	Nil	Nil
5–10	Possible hypertension and kidney dysfunction	Possible hypertension and kidney dysfunction Possible spontaneous abortion
11–20	Possible hypertension and kidney dysfunction Possible subclinical neurocognitive deficits	Possible hypertension and kidney dysfunction Possible subclinical neurocognitive deficits Reduced birth weight Possible postnatal developmental delay
21–29	Hypertension and kidney dysfunction Possible subclinical neurocognitive deficits	Hypertension and kidney dysfunction Possible subclinical neurocognitive deficits Possible spontaneous abortion Reduced birth weight Possible postnatal developmental delay
30–39	Hypertension and kidney dysfunction Possible neurocognitive deficits	Hypertension and kidney dysfunction Possible neurocognitive deficits Spontaneous abortion Reduced birth weight Possible postnatal developmental delay
40–79	Hypertension and kidney dysfunction Subclinical peripheral neuropathy Neurocognitive deficits Anemia Sperm abnormalities Colic Possible gout	Hypertension and kidney dysfunction Subclinical peripheral neuropathy Neurocognitive deficits Anemia Colic Possible gout Spontaneous abortion Reduced birth weight Possible postnatal developmental delay
80+	Hypertension Nephropathy Peripheral neuropathy Neurocognitive deficits Anemia Sperm abnormalities Colic Gout Encephalopathy	Hypertension Nephropathy Peripheral neuropathy Neurocognitive deficits Anemia Colic Gout Encephalopathy Spontaneous abortion Reduced birth weight Possible postnatal developmental delay

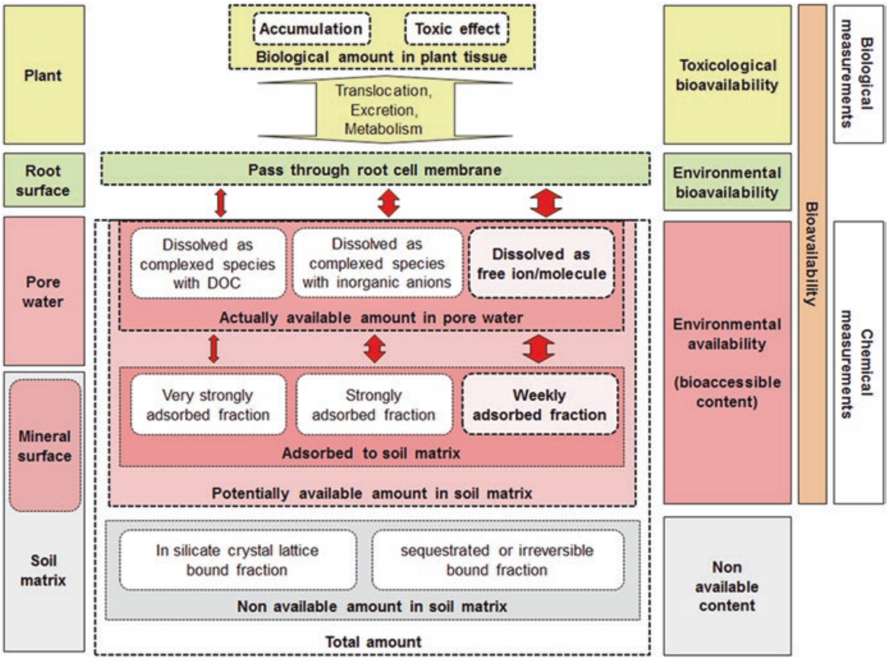

Fig. 3 Schematics depicting the concept of heavy metal bioavailability in plants from soils. The thickness of the arrows correlates with the importance in affecting bioavailability (image reprinted by permission from Springer, Environmental Geochemistry and Health, Bioavailability of heavy metals in soils: definitions and practical implementation—a critical review, Kim et al. (2015))

adsorbed within the soil particles (Kim et al. 2015). The uptake amount of heavy metals from the soil is not a fixed fraction, but should be regarded as a function of the exposure time. The heavy metals potentially available for uptake have various desorption kinetics, depending on their chemistry as well as the soil properties, such as pH and texture.

Table 3 shows the most frequent species of metal ions dissolved within the pore water of agricultural and forest soil. The complexes of heavy metals with inorganic anions like Cl−, OH−, and HCO3− in soils with intermediate to alkaline pH are generally believed to foster bioavailability in plants. The fraction of environmentally bioavailable heavy metals is the fraction that is dissolved in the pore water and can suffer uptake by plant roots. This depends on metal chemistry and plant physiology and can differ among plant species (Kim et al. 2015). High metal ion concentration in pore water can lead to predominantly passive uptake, while lower metal ion concentrations suffer a metabolic active uptake (Kim et al. 2015). The type of metal also dictates the type of uptake: Cd, Cr(III), Ni, and Pb suffer mainly a passive uptake, while the uptake of essential plant nutrients, such as Cu and Zn, may be via an active or both passive and active uptake (Kim et al. 2015).

Table 3 Regular concentrations of heavy metal ions dissolved in the pore water for low or non-contaminated acidic forest soil and agricultural soils

	Pore water concentrations		Species	
	Acidic forest soil (μg/L)	Agricultural soil (μg/L)	Very strong acidic to moderately acidic soils	Slightly acidic to alkaline soils
Cd	1–25	<0.1–3	Cd^{2+}, $CdSO_4^0$, $CdCl^+$	Cd^{2+}, $CdSO_4^0$, $CdCl^+$
Cr	2–20	<1–15	Cr^{3+}, $CrSO_4^+$, Cr-DOC	Cr-DOC, $CrCO_3^+$, $Cr(CO_3)_2^-$, $Cr(CO_3)_3^{3-}$
Ni	5–30	1–30	Ni^{2+}, $NiSO_4^0$, Ni-DOC	$NiCO_3^0$, $NiHCO_3^+$, $NiB(OH)_4^+$
Cu	1–50	3–60	Cu-DOC, Cu^{2+}, $CuSO_4^0$	Cu-DOC, $CuCO_3^0$, $CuB(OH)_4^+$
Pb	2–100	<1–50	Pb^{2+}, Pb-DOC, $PbSO_4^0$	$PbCO_3^0$, $PbHCO_3^+$, $Pb(CO_3)_2^{2-}$
Zn	80–2000	10–400	Zn^{2+}, $ZnSO_4^0$	$ZnHCO_3^+$, Zn^{2+}, $ZnSO_4^0$, $ZnCO_3^0$

DOC dissolved organic carbon

Reprinted by permission from Springer, Environmental Geochemistry and Health, Bioavailability of heavy metals in soils: definitions and practical implementation—a critical review, Kim et al. (2015)

Table 4 Transfer factors of heavy metals from soil to plants in contaminated soils, concentration range in mature leaf tissue, safety limits in foodstuff. *DW* dry weight, *FW* fresh weight (reprinted by permission from Springer, *Environmental Geochemistry and Health,* Bioavailability of heavy metals in soils: definitions and practical implementation—a critical review, Kim et al. (2015))

	Transfer factor	Concentration range (mg/kg DW)			Safety limit (mg/kg FW)		
		Deficient	Normal	Toxic	Leaf vegetables	Stem/root vegetables	Rice
Cd	1–10	–	0.05–0.2	>5–10	0.2	0.1	0.2
Zn	1–10	<10–25	25–150	>150–400	–	–	–
Ni	0.1–1	–	0.1–5	>20–30	–	–	–
Cu	0.1–1	<2–5	5–20	>20–100	–		–
Cr	0.01–0.1	–	0.1–0.5	>1–2	–	–	–
Pb	0.01–0.1	–	1–5	>10–20	0.3	0.1	0.2

The soil physicochemical properties are a decisive factor in the heavy metal concentration in soils available for plant uptake. Metal solubility in soil is dictated by the pH value and the percentage of clay in the soil (Golia et al. 2008).

6 Transfer Factor of Heavy Metals from Soil to Plants

The transfer factor of heavy metals is a measure that predicts the amount of heavy metals accumulated within plants from soils. The transfer factor depends on the type of plant, the type of soil, and the type of heavy metal. For example, leafy vegetables have a higher accumulation of metals compared to root vegetables which have a moderate uptake, while legumes have the lowest accumulation (Alexander et al. 2006). The transfer factor of metals increases from Pb and Cr to Ni and Cu, with the highest being for Cd and Zn (Kim et al. 2015). Table 4 shows usual metal transfer factors from soil to plants, concentration ranges in plant leaves, safety limits, and trigger values for adverse effects for arable soils for a series of metals: Cd, Cu, Cr, Ni, Pb, and Zn (Kim et al. 2015).

7 Genotypic Variations in the Accumulation of Heavy Metals

The uptake concentration of heavy metals in plants is a function of plant species, the variety type within the same species, and the location in plant tissue (Alexander et al. 2006; Zwolak et al. 2019; Pajević et al. 2018; Nikolić et al. 2014; Zhou et al. 2016).

An experiment involving various cultivars of several vegetables grown in control soil and in soil with higher amounts of Cd, Cu, Pb, and Zn shows various uptake of heavy metals for different plant species, and even within the same species for different cultivars (Alexander et al. 2006). The results are summarized in Table 5 (Alexander et al. 2006). Various cultivars of the same vegetable show differences in the amount and type of heavy metals accumulated. For example, Amsterdam carrots accumulate higher concentrations of Cd, Cu, and Zn than Ingot carrots, while the opposite happens for Pb. When comparing one vegetable to another, the legumes have the least accumulation of metals, root vegetables have a moderate accumulation while leafy vegetables have uptake of the highest concentrations of heavy metals (Alexander et al. 2006).

Adults and children might have an increased health risk due to exposure to heavy metals from consumption of vegetables grown on contaminated farmland. Vegetables grown on farmland contaminated with Pb, Cd, Cu, Zn, and As show different uptake of heavy metals (Zhou et al. 2016). The concentration of heavy metals was found to be the highest for leafy vegetables, and decreased for stalk/root/solanaceous vegetables, with the lowest concentrations for legumes/melon vegetables (Zhou et al. 2016). Table 6 shows the concentrations of heavy metals in vegetable edible parts grown in Shizhuyuan area, China, the National Standard value which is the tolerance limit of contaminants in foods in China according to the China National Standards (GB 2762-2012) (Zhou et al. 2016). Data includes mean ± standard error of three replicates.

Table 5 Mean metal concentration in vegetable grown in control and heavy metal-treated soil in the UK. The ES-European Standards values are taken from reference Zwolak et al. (2019)). Table adapted from Environmental Pollution, Vol. 144, Alexander P. D. et al., "Genotypic variations in the accumulation of Cd, Cu, Pb and Zn exhibited by six commonly grown vegetables", pp. 736–745, Copyright (2006), with permission from Elsevier (Alexander et al. 2006)

		Cadmium		Copper		Lead		Zinc	
Vegetable species	Vegetable cultivar	Treated	Control	Treated	Control	Treated	Control	Treated	Control
Carrot	Amsterdam	2.521	0.068	5.77	2.78	6.31	0.34	52.59	19.68
	Nantes	1.812	0.054	4.43	2.42	5.01	0.17	42.54	19.02
	Ingot	2.298	0.074	4.43	2.81	7.23	0.42	33.38	18.43
	European Standards	0.1		–		0.1		–	
Spinach	Bloomsdale	4.24	0.36	9.01	6.29	1.74	0.62	334.9	246.7
	Grodane	6.94	0.45	10.08	6.44	1.78	0.69	380.2	209
	Mediana	6.48	0.33	8.97	7.31	2	0.51	343.2	256
	European Standards	0.3		–		0.3		–	
Pea	Douce P	0.4282	0.1054	5.163	4.117	1.399	0.412	47.49	32.36
	Feltham	0.2615	0.1055	5.727	4.189	0.547	0.322	47.8	36.83
	Fortune	0.3355	0.1441	6.617	4.572	0.731	0.692	54.27	36.68
	European Standards	0.05		–		0.2		–	
Onion	Buffalo	4.0229	0.1928	2.374	2.307	6.486	1.689	50.45	23.75
	Express	3.5566	0.2237	3.078	2.755	8.745	1.216	60.94	32.28
	Keepwell	3.3498	0.1107	2.878	2.342	6.519	1.125	66.97	16.25
	European Standards	0.2		–		0.3		–	
Lettuce	Corsair	9.033	0.144	12.55	5.67	11.73	0.06	160.69	51.24
	Little gem	8.173	0.233	9.97	7.07	19.68	2.9	172.17	70.59
	Lobjoits	9.083	0.084	8.1	5.35	12.95	1.02	163.88	58.15
	European Standards	0.3		–		0.3		–	

Table 6 Concentrations of heavy metals in vegetables grown in China (reproduced from Zhou H. et al. 2016. International Journal of Environmental Research and Public Health, 13, 289 (CC-BY 4.0) (Zhou et al. 2016))

	Vegetable species	Pb (mg/kg)	Cd (mg/kg)	Cu (mg/kg)	Zn (mg/kg)	As (mg/kg)
Root ($n = 3$)	White radish	0.270 ± 0.057	0.011 ± 0.003	0.167 ± 0.073	4.690 ± 1.367	0.099 ± 0.012
	Carrot	0.233 ± 0.001	0.023 ± 0.005	0.227 ± 0.011	1.591 ± 0.092	0.188 ± 0.030
	Sweet potato	0.613 ± 0.162	0.135 ± 0.007	0.015 ± 0.005	4.674 ± 0.790	0.448 ± 0.013
	China National Standards	0.1	0.1	/	/	0.5
Stack ($n = 2$)	White cai tai	0.785 ± 0.239	0.239 ± 0.090	0.456 ± 0.033	24.23 ± 5.541	0.225 ± 0.043
	Red cai tai	0.939 ± 0.327	0.176 ± 0.038	0.478 ± 0.089	20.95 ± 2.993	0.396 ± 0.076
	China National Standards	0.3	0.1	/	/	0.5
Solanaceous ($n = 3$)	Eggplant	0.429 ± 0.001	0.289 ± 0.027	0.937 ± 0.199	2.786 ± 0.588	0.072 ± 0.004
	Red pepper	0.056 ± 0.009	0.047 ± 0.035	0.589 ± 0.124	2.241 ± 0.169	0.016 ± 0.005
	Tomato	0.078 ± 0.023	0.028 ± 0.005	0.468 ± 0.036	1.419 ± 0.185	0.014 ± 0.003
	China National Standards	0.1	0.05	/	/	0.5
Melon ($n = 4$)	Cucumber	0.004 ± 0.001	0.004 ± 0.001	0.284 ± 0.047	1.206 ± 0.107	0.039 ± 0.014
	Pumpkin	0.121 ± 0.031	0.005 ± 0.001	0.647 ± 0.104	2.883 ± 0.749	0.073 ± 0.015
	China National Standards	0.1	0.05	/	/	0.5
Leafy ($n = 2$)	Cabbage	0.671 ± 0.277	0.036 ± 0.022	0.314 ± 0.043	9.926 ± 2.226	0.211 ± 0.014
	Chinese cabbage	0.749 ± 0.129	0.419 ± 0.027	0.155 ± 0.024	14.51 ± 2.811	0.073 ± 0.020
	Spinach	0.971 ± 0.194	0.513 ± 0.055	0.966 ± 0.288	20.81 ± 4.543	0.310 ± 0.064
	Caraway	1.855 ± 0.208	1.031 ± 0.064	0.987 ± 0.037	52.69 ± 6.200	0.739 ± 0.075
	Lettuce	1.162 ± 0.540	0.460 ± 0.207	0.775 ± 0.170	11.79 ± 1.688	0.660 ± 0.086
	China National Standards					
Legume ($n = 2$)	Asparagus bean	0.070 ± 0.014	0.013 ± 0.011	1.999 ± 1.247	6.682 ± 1.550	0.047 ± 0.014
	Kidney bean	0.033 ± 0.036	0.010 ± 0.017	1.310 ± 0.085	5.669 ± 0.236	0.050 ± 0.010
	China National Standards					

8 Relative Toxicity of Heavy Metals in Plants

It is impossible to determine a general scale of heavy metal toxicity to living organisms. Quantitative toxicity measurements of various metals did not show any correlations of their position in the toxicity scale with their physical or chemical properties (Appenroth 2010a). One can only give examples of such measurements in specific plants. For example, quantitative measurements of growth inhibition for the plant *Lemna minor*, including multiplication rate, fresh and dry weight, chlorophyll a and b, and total carotenoid content, showed the following sequence of toxicity (Appenroth 2010a):

$$Ag^{+} > Cd^{2+} > Hg^{2+} > Tl^{+} > Cu^{2+} > Ni^{2+} > Zn^{2+} > Co^{6+} > Cr^{6+} > As^{3+} > As^{5+}$$

Accumulation of heavy metals in plant tissue is associated with decreased root length and plant biomass, negatively affecting seed germination and chlorophyll biosynthesis (Ahmed et al. 2019; Di Salvatore et al. 2008). At a cellular level heavy metals can detrimentally influence photosynthesis and respiration, and other physiological factors, often as a result of an increased production of reactive oxygen species (Ahmed et al. 2019; Shahid et al. 2014; Dimkpa et al. 2012; Pinho and Ladeiro 2012).

Some of the heavy metal ions are required for an optimal growth and development in plants. These include copper, iron, manganese, molybdenum, and zinc (Anjum et al. 2015). However, an inappropriate amount of these metals can lead to phytotoxicity.

9 Conclusions

Heavy metals have a negative connotation, being associated to environmental contamination and pollution, eco-toxicity, and adverse health effects. While some of the metals termed "heavy metals" are essential for living organisms, others are extremely toxic to humans and animals. The accumulation of heavy metals in plants occurs via uptake from soil and wastewater. The highest uptake of heavy metals occurs in leafy vegetables, followed by a moderate level in root vegetables, and the lowest accumulation in legumes. The consumption of plants with high levels of heavy metals can pose deleterious health effects to humans and animals.

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