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REVIEW ARTICLE

The uptake and bioaccumulation of heavy metals by food plants, their effects on plants nutrients, and associated health risk: a review

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Abstract Heavy metal contamination is a globally recognized environmental issue, threatening human life very seriously. Increasing population and high demand for food resulted in release of various contaminants into environment that finally contaminate the food chain. Edible plants are the major source of diet, and their contamination with toxic metals may result in catastrophic health hazards. Heavy metals affect the human health directly and/or indirectly; one of the indirect effects is the change in plant nutritional values. Previously, a number of review papers have been published on different aspects of heavy metal contamination. However, no related information is available about the effects of heavy metals on the nutritional status of food plants. This review paper is focused upon heavy metal sources, accumulation, transfer, health risk, and effects on protein, amino acids, carbohydrates, fats, and vitamins in plants. The literature about heavy metals in food plants shows that both leafy and nonleafy vegetables are good accumulators of heavy metals. In nonleafy vegetables, the bioaccumulation pattern was leaf > root ≈ stem > tuber. Heavy metals have strong influence on nutritional values; therefore, plants grown on metal-contaminated soil were nutrient deficient and consumption of such vegetables may lead to nutritional deficiency in the population particularly living in developing countries which are already facing the malnutrition problems.

Keywords Heavy metals · Soil pH · Nutrients · Bioaccumulation · Toxicity · Plant growth

Introduction

Heavy metals have high density and mostly toxic in nature for human, plants, and animals regardless of their concentrations (LWTAP 2004) and have high atomic density five times greater than water or more than 4 g/cm^3 (Hawkes 1997) or more than 5 g/cm^3 (Saxena and Shekhawat 2013; Weast 1984). The nonessential metals are part of earth crust that enters the upper soil horizon and food chain through biogeochemical cycles (Tinsley 1979). Metals and metalloids such as cadmium (Cd), lead (Pb), mercury (Hg), and zinc (Zn) are called heavy metals because of their high densities (Oves et al. 2012), while arsenic (As) is included in this list because of similar properties (Chen et al. 1999). Essential and nonessential trace elements, when exceed the threshold limits, can cause different physiological, morphological, and genetical anomalies including reduced growth, mutagenic effects, and increased mortality (Khan et al. 2010a; Li et al. 2010; Luo et al. 2011).

Food crops are one of the important parts of our diet, and they may contain a number of essential and toxic metals (Yang et al. 2011; Waqas et al. 2015) depending on growing media characteristics. Vegetables are the major source of human exposure to heavy metal and contribute about 90 % of the total metal intake, while the rest 10 % intake occurs through dermal contacts and inhalation of contaminated dust (Martorell et al. 2011; Kim et al. 2009; Ferré-Huguet et al. 2008; Khan et al. 2014). Food safety is a burning issue regarding human health in the recent decades because of the high demand for food. This scenario leads to stimulate researchers and scientists to work on health risk associated with consumption of heavy

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metals, pesticides, and toxin-contaminated food (D'Mello 2003).

Essential and nonessential elements are regularly added to our food chain through excessive use of agrochemicals, municipal wastewater, industrial effluents, and raw sewage for irrigation (Tongesayi et al. 2013). The Agency for Toxic Substances and Diseases Registry (ATSDR 2011) has classified heavy metals and metalloids such as As, Pb, and Cd found in the environment as 1, 2, and 7 on the basis of toxicity.

Some elements like Cu, Cr, Fe, Mn, and Zn are essential for animals and human beings because they play an important role in different metabolic functions, enzymatic activities, sites for receptors, hormonal function, and protein transport at specific concentrations (Apostoli 2002; Antoine et al. 2012). Other elements like As, Cd, and Pb are nonessential and have no beneficial role in plants, animals, and humans (Chang 2000) and have no nutritional function, as they are highly toxic (Goldbold and Huttermann 1985; Nies 1999). It is necessary to characterize the sources and contents of heavy metals in soil in order to establish quality standards and to determine the threats to human health and food safety (Sun et al. 2013). Environmental pollution with heavy metals is unrelenting, covert, and permanent in nature (Wang et al. 2001). Biological organisms are incapable to degrade metals because of their nonbiodegradable nature and long half-life, and they persist in their body parts and environment leading to health hazards (Amaral and Rodrigues 2005; Nabulo et al. 2011). Heavy metals have the capability to move from contaminated soil and water and bioaccumulate in vegetables causing health risks (Stasinos and Zabetakis 2013; Rattan et al. 2005; Khan et al. 2015).

Soil characteristics play an important role in terms of food production, and the contamination of this vital resource with heavy metals and their ultimate uptake and bioaccumulation in food crops posses major environmental and health problems (Fig. 1), particularly in developing countries (Lin et al. 2007). Soil type and plant genotype and their interaction have significant effect on heavy metal concentrations (Ding et al. 2013). Mineral fertilizers have higher heavy metal concentrations as compared to organic manure; therefore, the application of mineral fertilizers results in soil heavy metal pollution (Hu et al. 2013).

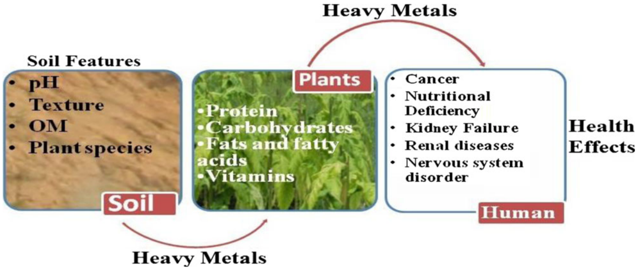

Fig. 1 The diagrammatic presentation of heavy metal sources, plant uptake, and health effects

So far, a number of experiments (pots and field) have been conducted to study the effect of soil parameters and other elements on mobility and bioavailability of heavy metals from soil to crop system (Li et al. 2007; Hart et al. 2006; Khan et al. 2013a, b). The mobility and bioavailability of heavy metals in contaminated soil is affected by a number of biological processes and physiochemical properties like soil pH, organic matter (OM) (Ahmad and Goni 2010; Ernst 1996; Alloway 1995), cation exchange capacity (CEC), soil texture, and soil microbiota. Soil pH has significant effects on availability and accumulation of heavy metals in the edible parts of plants (Hu et al. 2013; Wang et al. 2013a). Similarly, CEC and OM have negative impact on the mobility and bioavailability of heavy metals like Pb (Arshad et al. 2008; Ding et al. 2013; McLaughlin et al. 2011; Khan et al. 2015). Cd toxicity to the soil environment is well known; it is a toxic heavy metal and causes toxicity even at low concentration. The bioaccumulation rate of Cd is higher in the field crops as compared to other elements (Moustakas et al. 2001; Arao and Ae 2003).

For the improvement of nutritional composition of soil, different agricultural strategies like biofortification and proper use of fertilizers have been suggested (Graham et al. 2006; Bonierbale et al. 2007).

In recent years, most of the studies have focused on As contamination of food chain (Gilbert-Diamond et al. 2011; Huang et al. 2012; Kim et al. 2009) along with other heavy metals and metalloids that were found above the recommended limits (Tufuor et al. 2011). Food crop irrigated with industrial effluents and wastewater is the major source of soil and crop contamination with heavy metals and metalloids (Lee et al. 2008; Tiwari et al. 2011; Sipter et al. 2008).

The associated health hazards of toxic metal depend on concentrations of these metals in specific media and exposure time. Long time and chronic exposure can cause health hazards even at low concentrations of toxic metal (Mahalakshmi et al. 2012). Among the abiotic stresses to plants, heavy metal toxicity is one of the major stresses and the toxicity is based on physiochemical properties of heavy metals (Saxena and Shekhawat 2013; Zhuang et al. 2009).

The aims of this paper are to summarize the literature about the heavy metals as a major environmental issue and critically discuss the information about heavy metal (As, Cd, Cr, Cu, Ni, and Pb) contamination in soil and the grown food plants, metal bioaccumulation, soil-to-plant transfer, nutritional effects, and health risks.

Heavy metals in soil

Soil contamination with heavy metals is a serious global environmental problem (Facchinelli et al. 2001; Solgi et al. 2012; Wang et al. 2001) posing risks to human, animals, microbes, and plants and contaminating surface and groundwater. Heavy metals and other pollutants enter to the soil ecosystem through natural processes and anthropogenic activities. Trace element concentrations in soil environment are mainly dependent upon the geology of the area (Carral et al. 1995), while anthropogenic activities like solid waste disposal, wastewater irrigation, sludge application, automobile exhaust, mining and smelting processes, urbanization, agricultural activities, and industrialization also contribute heavy metals into the soil environment (Facchinelli et al. 2001; Lim et al. 2008; Montagne et al. 2007; Wei and Yang 2010; Chen et al. 1999; Tsai et al. 2001; Shi et al. 2005). Similarly, the physiochemical characteristics of soil have substantial effects on heavy metal concentration and its availability to plants (Fig. 1). Heavy metal toxicity is mainly associated with metal speciation in soil (Allen et al. 1980; Liu et al. 1996). The heavy metal concentrations in agriculture soil were in range of 0.1–40, 0.01–0.7, 5–3000, 2–100, 10, and 2–200 mg kg^{-1} for As, Cd, Cr, Cu, Ni, and Pb, respectively (O'Neill 1995; Allaway 1968), while the heavy metal concentrations in garden soil were in range of 3.06–15.89, 0.27–2.86, 14.08–53.97, 18.51–579.84, 10.04–35.60, and 5.11–60.85 mg kg^{-1} for As, Cd, Cr, Cu, Ni, and Pb, respectively (Szolnoki et al. 2013). Similarly, the concentrations of As, Cd, Cr, Cu, Ni, and Pb in sediments were ranged from 0.2–13.8, 0.3–8.4, 2–1000, 4–200, 2–500, and 7–150 mg kg^{-1}, respectively (Cannon et al. 1978). Among toxic elements, As is highly carcinogenic and present in the soil of both developed and developing countries (Fig. 2). Table 1 summarizes the heavy metal concentrations in different soils, while their permissible limits in soil are given in Table 2. The permissible limits of different countries and organizations show variation in concentrations for different heavy metals. These differences may be due to different strategies adopted by these countries and organizations to set permissible limits. The variation in permissible limit may be based on soil characteristics and type. The permissible limits for As were 75, 30, and 20 mg kg^{-1} set by USEPA, State Environmental Protection Administration (SEPA) China, and FAO/WHO, respectively, while the permissible limits for Cu and Ni were similar for almost all countries and organizations. Other heavy metals like Cd, Cr, and Pb show great variations in their respective permissible limits set by different organizations/countries. The concentrations of all the selected heavy metals were observed above the permissible limit set by different countries and international organizations (WHO, USEPA, SEPA, etc.) for heavy metals in soils from different regions of the world (Table 2).

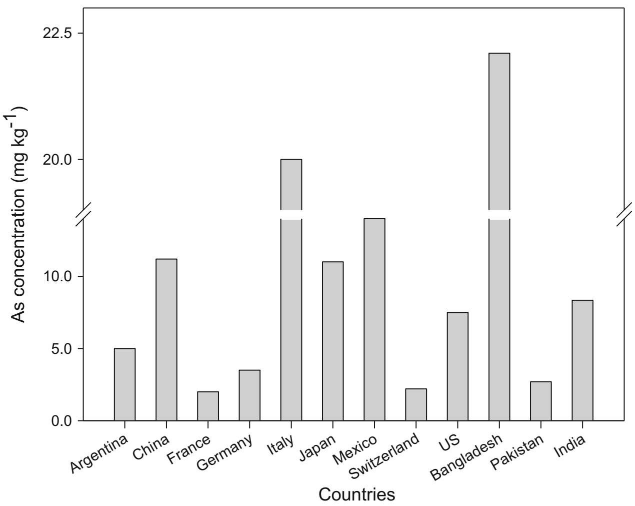

Fig. 2 Concentrations of As in the soils of different regions of the world: sources include Mandal and Suzuki (2002), Arain et al. (2009), and Biswas et al. (2013)

Heavy metal concentrations are greatly affected by soil organic contents (Khan et al. 2015). Soils with high organic waste concentrations are generally confined to heavy metal concentrations of less than 1000 mg kg^{-1} soil, while industrial waste-contaminated soil contains more than 10,000 mg kg^{-1} soil (Bader et al. 1999). Increasing concentrations and variation in distribution of heavy metal in metal-amended soil generally augment the heavy metal concentrations in plants (Castro et al. 2009). Soil is the main source of contamination of food chain with heavy metals because soil is used as an important tool for waste management and waste dumping (Zhuang et al. 2009; Rogival et al. 2007).

The prime route of heavy metal intake into the human body is through soil–crop system in agriculture area (Liu et al. 2007), where the anthropogenic activities are the primary sources of contaminations (Lim et al. 2008; Li et al. 2008; Montagne et al. 2007; Wei and Yang 2010; Yang et al. 2009a). The main route of exposure to heavy metals in urban environment is through ingestion, absorption through skin, and inhalation of dust particles (Ahmed and Ishiga 2006; Lim et al. 2008; De Miguel et al. 2007; Ferreira-Baptista and De Miguel 2005; Sindern et al. 2007), whereas the primary source of pollution in urban soil is anthropogenic one which includes vehicular emission, power plant, tire wear particles, auto repair shops, car wash centers, brake lining, coal combustion, chemical plants, weathering of building, atmospheric deposition, and house hold solid waste (Amato et al. 2009; De Miguel et al. 1997; Duzgoren-Aydin et al. 2006; Han et al. 2006; Kartal et al. 2006; Lu et al. 2009; Madrid et al. 2002; Morton-Bermea et al. 2009; Oliva and Espinosa 2007; Sezgin et al. 2003; Zhou et al. 2008).

Ecotoxicological assessment of contaminated soil is very difficult due to complex nature and diversity of soil microbiology (COM 2006). However, these test methods are considered as a good tool for obtaining information regarding bioavailability of contaminants to some specific organisms (ISO/DIS 2006).

Ecological risk assessment approach is generally applicable for representing metal-contaminated sites (US EPA 2001;

Table 1 Heavy metal concentrations (mg kg^{-1}) in soil

References	Heavy metals				
	Cd	Cr	Cu	Ni	Pb
Waterlot et al. (2013)	16.7[acde]	NA	74.1	NA	1122[acde]
Khan et al. (2010a)	0.99[ce]	NA	88.8	40	54.4
Castro et al. (2009)	NA	8.5	11.0	15.5	<0.2
Noor-ul-Amin et al. (2013)	NA	0.121	0.225	0.123	0.225
Xu et al. (2013b)	1.2[ce]	NA	107[cde]	NA	66
Zhuang et al. (2009)	3[cde]	NA	449[acde]	NA	282[ade]
Luo et al. (2011)	0.90–17.1[acde]	6.41–68.9	72.4–11,140[acde]	8.83–60.1[cde]	52.2–4500[acde]
Khan et al. (2013a, b)	0.09–0.11	0.44–0.51	0.33–0.50	0.46–0.55	NA
Hu et al. (2013)	1.7[cde]	NA	41	NA	83
Khan et al. (2008b)	0.84[ce]	60.9	32.8	24.9	49.4
Piotrowska and Kabata-Pendias (1997)	0.30[e]	NA	NA	NA	NA
Yu et al. (2006)	7.43[adce]	47.07	132.82[cde]	NA	223.22[de]
Gebrekidan et al. (2013)	0.75[ce]	31.02	25.25	26.00	3.27
Khan et al. (2008a)	0.80–2.58[cde]	64.2–77.5	22.8–61.8	22.8–38.5	29.7–97.9
Gichner et al. (2006)	0.14	NA	19	NA	47.6
Singh et al. (2010b)	2.98[cde]	6.41	30.14	8.96	26.48
Kar et al. (2013)	NA	NA	NA	NA	NA
Kim et al. (2009)	0.325[e]	35.1	26.25	NA	1448[acde]
Biswas et al. (2013)	NA	NA	NA	NA	NA
Bigdeli and Seilsepour (2008)	0.67[ce]	70	54	32	60
Aremu et al. (2010)	NA	4.31	0.73	0.47	1.21
Meers et al. (2005)	7.61[acde]	204.25[cde]	144.10[cde]	23.15	262.16[ade]
Liu et al. (2011)	0.19	46.98	40.77	53.65[cde]	50.11
Chang et al. (2014)	0.17	46.7	NA	NA	42.5
Shi et al. (2013)	NA	NA	37.7	NA	NA
Yang et al. (2007)	≥0.28	≥48	≥20	≥33	≥35
Mishra et al. (2009)	3.54 [cde]	42.60	57.57	47.10	NA
Kachenko and Singh (2006)	5.54[acde]	NA	78	NA	363[acde]
Bigdeli and Seilsepour (2008)	0.67[ce]	70	54	32	60
Luo et al. (2011)	0.9[ce]	12.3	324[cde]	8.83	95.6
Brahman et al. (2014)	NA	NA	NA	NA	NA

[a] Above the permissible limit of India

[b] Above the permissible limit of USEPA

[c] Above the permissible limit of China EPA

[d] Above the permissible limit of EU

[e] Above the permissible limit of FAO/WHO

Jensen et al. 2006); for this purpose, soil quality values also called guideline values are used (National Environment Protection Council (NEPC) 1999; CCME 2005; US Environmental Protection Agency (EPA) 2005; Niemeyer et al. 2010). These guideline values are based on dose–response data derived from laboratory tests on ecological process or single plant or animal species (Jones 2006). Finally, statistical applications are applied to derive these guideline values (O'Halloran 2006). Soil quality values are established on the basis of total metal concentrations in the soil. However data of total metal concentrations is not sufficient for risk assessment, and other qualities like chemical form, electric potential, and ion activity of metals are to be considered while predicting metal toxicity (Chapman et al. 2003; Stumm and Morgan 1996; Wang et al. 2013b). Soluble metals and free metal ions are more bioavailable and toxic (Lund 1990) than other form of heavy metals.

Table 2 International standards for different heavy metals (mg kg^{-1}) in soil and plants

Heavy metals	Commission Regulation EU (2006)		US EPA (2005)		FAO/WHO (1984, 2001a)		SEPA China (1995, 2005)		Indian standard (Awashthi 2000)	
	Soil	Plants	Soil	Plants	Soil	Plants	Soil	Plants	Soil	Plants
As	NA	NA	75	NA	20[a]	0.1	30	0.5	N/A	1.1
Cd	3	0.2	85	NA	0.3	0.1	0.6	0.1–0.2	3–6	1.5
Cu	100	20	NA	NA	100[a]	73	100	20	135–270	30
Cr	100	1	3000	NA	100[a]	2.3	200	0.5	NA	20
Ni	50	NA	NA	NA	50[a]	66.9	50	10	75–150	1.5
Pb	100	0.30	420	NA	100[a]	0.3	300	9	250–500	2.5

[a] Ewers (1991)

Factors affecting mobility and bioavailability of heavy metals

Heavy metal accumulation in plants is strongly influenced by different soil parameters (Wilson et al. 2014; Wang et al 2013a; Ahmad and Goni 2010) such as soil pH, OM (Fig. 1), redox potential, total metal contents, and CEC (Chlopecka 1996; Imai et al. 2002; Wang et al. 2012a). Heavy metals like Cu and Zn show a significantly negative correlation with pH (García et al. 2009; Wang et al. 2013a), while soil OM effects vary from metal to metal (Wang et al. 2013a; Khan et al. 2015). The aging factor and other soil properties are the main factors affecting the bioavailability of heavy metals (Ahmad and Goni 2010; Smolders et al. 2009). The sensitivity of heavy metals in soil is greatly affected by soil CEC and pH (Lock and Janssen 2001).

The pedotransfer function assessment is now commonly used to understand heavy metal mobility and availability in soil environment. The following regression equations are used to forecast the values of those parameters which are difficult to measure from the easily measured soil properties such as soil particle size, pH, OM, and CEC (Bouma 1989; Martin et al. 2005; Perfect 2003). The Freundlich equation is used as pedotransfer function assessment tool to assess metal availability in soil. The original model was proposed for Cd bioavailability. Springob et al. (2001) used the equation for assessment of Cd bioavailability. However, the modified Freundlich equation can be used for other metal availability in soil environment. The modified Freundlich equation is as under:

$$S = {C_{\mathrm{metal}}}^{M} \tag{1}$$

where S represents the sorbed fraction, C_{metals} represents soil metal concentrations, and M (shape) represents the Freundlich parameters. M has an average value of 0.8 (Springob et al. 2001), while k value can be calculated through multiple regression techniques (Eqs. 2 and 3). For the assessment of k value, Springob et al. (2001) modified the Freundlich function in simple and log domain, respectively.

The modified equations are as under:

$$S = k^{*} x_1^{a} x_2^{b} \ldots\ldots. X_n^{z} {C_{\mathrm{metal}}}^{M} \tag{2}$$

$$S = k^{*} \; + a \log x_1 + b \log x_2 \ldots.. + z \log x_n + M \log C_{\mathrm{metal}} \tag{3}$$

where x_1 to x_n are the soil variables used to predict the value of k, while a, b… z are exponents allowing nonlinear contribution of different variables. Similarly, Eq. 2 can be expressed in log domain by multiple linear regression analysis (Eq. 3). The ability of soil to accumulate metals depends upon soil OM which acts as a main sorbent for metals (Sauvé et al. 2003; Ge and Hendershot 2005).

Soil OM

Soil OM has the capability to bind toxic metals to control heavy metal behavior and alleviate toxicity in soil (Datta et al. 2001). Wu et al. (2014) mentioned that the sequential analysis shows that Pb availability in soil gradually decreased while Cd availability increased. Similarly, the soil OM-bounded fraction of Pb increased, while that of Cd decreased. This shows that Pb has higher affinity and stability toward OM than Cd (Winter et al. 2012). This difference in relative binding affinity of Pb and Cd with soil OM is because of metal chemistry differences (Wu et al. 2014).

The heavy metals binded with dissolved OM are easily available to soil flora (Krishnamurti et al. 2004). Similarly, humic acid is an important part of organic carbon having phenolic and carboxylic functional groups which increases the heavy metal mobility and availability to plants (Fox and Comerfield 1990; Khan et al. 2006; Lagier et al. 2000; Marschner and Kalbitz 2003; Senesia et al. 2003; Evangelou and Marsi 2001; Halim et al. 2003). Therefore, soil with high humic acid concentration is not suitable for agricultural activities.

pH

Soil pH strongly influences the bioavailability of heavy metals in soil and their toxicity on living organisms (Amini et al. 2005; Basta et al. 2005; Li and Shuman 1996; Nigam et al. 2001; Prasad 1999; Seuntjens et al. 2004). At low pH, the mobility and bioavailability of metals are greater as compared to high pH (Kuo et al. 2004; Merry 2001; Tsadilas et al. 2005). The soil pH reduces the metal uptake by plants, and the availability of metals increases when the pH is below the critical value of 4. The geology, distance from roadside, industries, and type of irrigation affect the pH values in soil. Wastewater irrigation brings changes in the pH of soils (Zhuang et al. 2009). Like mobility and bioavailability of metals, the pH plays an important role in the metal speciation in soil (Luo et al. 2011). Along with other physiochemical characteristics, pH can significantly affect the heavy metal removal from contaminated soils (Di Palma et al. 2003). Heavy metal like Cu has the tendency of making Cu–OM complexes (Li et al. 2008) which leads to affect its availability. Cu bioaccumulations in plants are significantly affected by soil pH and negatively correlated with each other (García et al. 2009; Wang et al. 2006a, 2013a). Toxicological effects of free metal ions on ecological resources are the functions of soil pH (Lofts et al. 2004); therefore, it is necessary to have a basic knowledge of soil pH used for cultivation purposes. The soil with low pH should not be used for agriculture purposes due to highly availability of metals in it.

Soil texture

Soil texture along with other factor is one of the important factors that induces metal availability in soil. Clay contents can significantly affect the availability of heavy metals and their subsequent toxicity to living organisms (Beyer and Cromartie 1987). Crops grown on sandy soil are metal deficient, particularly Zn, as compared to loamy texture (Rashid and Ryan 2004; Martens and Reed 1991); this may be due to large pore size and the low retention capacity of sandy soil to retain metals.

Soil-to-plant transfer of heavy metals is strongly influenced by the soil texture. Treder and Cieslinski (2005) stated that plants cultivated on sandy soil have higher concentrations of heavy metals than those grown on clay loamy soil. The high bioaccumulation in plants is linked with higher mobility of metals in sandy soil as compared to clay soil.

Microorganisms and heavy metals have significantly negative correlationship. Effects of high heavy metal concentrations on the microbial community structure, activity, and abundance have been reported (Khan et al. 2010b; Sandaa et al. 1999; Tsezos 2009). Similarly, there is a strong association between soil microbiota and soil texture; most of microorganisms occurs in association with clay content (Alexander 1977; Sessitsch et al. 2001). Furthermore, the heavy metal movement from upper to lower soil horizon is also affected by soil texture. In sandy-textured soil, heavy metals can easily move from one horizon to other as compared to clay soil. Pore size has also effects on the metal mobility and bioavailability.

Plant species

The bioaccumulation of heavy metal is different for different plant species reflected by their growth, reproduction, occurrence, and survival in the metal-contaminated soil. It is notable that different plant species show different toxicity to the same pollutant and in the same environmental condition, because the mechanisms of elemental uptake by plants are not the same for all plant species (Garty 2001; Zechmeister et al. 2003). Heavy metal accumulation in food plants depends on metal concentrations as well as phyto-availability and phyto-variety, as different plants have different uptake rates (Medina et al. 2005: Yang et al. 2009b). The capacity of plants to uptake heavy metals is different for different heavy metals, and the same heavy metal can be accumulated at different ratio in different plant species (Singh et al. 2010b). Metal bioavailability is also affected by the presence of organic compounds of that metal in plants. As species bioavailability is considerably reduced by organo-arsenic compounds present in plant tissues (Juhasz et al. 2006). Generally, the leafy vegetable metal uptake rates are higher and more contaminated than nonleafy vegetables (Yu et al. 2006).

Heavy metals in plants

Vegetables are an important source of human diets, and their contamination can cause serious health problems (Bi et al. 2006; Khan et al. 2008a; Liu et al. 2005a; Lim et al. 2008; Pruvot et al. 2006; Radwan and Salama 2006). Leafy vegetables like lettuce are considered as potential hyperaccumulators of heavy metals (Ramos et al. 2002). One of the properties of green leafy vegetable is the accumulation of heavy metals in their tissues without exhibiting any toxicity symptoms (Intawongse and Dean 2006). Monteiro et al. (2007) reported that with increasing exposure duration, the concentrations of heavy metals in lettuce roots and shoots increased. Heavy metals can cause changes in physiology and growth of tomato at variable concentrations and result in chlorosis and necrotic symptoms on leaves (López-Millán et al. 2009). The plants grown on wastewater-irrigated soil contain high concentrations of metals in their vegetative and nonvegetative parts (Khan et al. 2008b). Garate et al. (1993) described that lettuce has higher capacity to accumulate heavy metal in different tissues. Heavy metal uptake is also affected by different plant species (Fig. 1) and within the same species by different cultivars (John and Van Laerhoven 1976). Like other food crops, potato is an important food crop grown throughout the world. It is rich with energy, dietary fibers, vitamins, carbohydrates, and essential elements such as Fe, Ca, Zn, and K (Finglas and Faulks 1984). Mineral concentrations and photosynthetic activities of plants can also be affected by toxic metals (López-Millán et al. 2009).

According to Swedish National Food Administration (1984), consumption of potato (200 g) provides carbohydrate, protein, energy, Ca, Cu, P, Fe, Mg, and Zn (36.6 g, 3.8 g, 172 kcal, 0.44 mg, 18 mg, 90 mg, 1.2 mg, 48 mg and 0.82 mg, respectively). The soil pH substantially affects the supply of these essential nutrients to plants; low pH means more supply of nutrients (Lutz et al. 1972). Moreover, the nutrient supply to plants is affected by a number of factors including soil type, climate, cultivation practices, and storage condition (Srikumar and Ockerman 1990). Concentrations of heavy metals vary in different organs of the same plant. Xu et al. (2013a) reported the heavy metal accumulation in the order of leaf > root ≈ stem > tuber. However, other scientists conveyed that the root concentrations are higher than shoot (Vanassche and Clijsters 1990).

In fruit plants, like tomato, the translocation rate of heavy metals to the fruit is rather low (Table 3 and Fig. 3), hence characterized as low-rate translocation fruit vegetable (Angelova et al. 2009). Accumulation and distribution of heavy metals like Cd have been found in different parts of tomato (Donma and Donma 2005). Tomato is an important food plant from economical as well as nutritional point of view (FAOSTAT 2007). Tomato is a rich source of minerals, vitamins, and other nutrients (Giovanelli and Paradise 2002) consumed both in raw and processed form (Martinez-Valvercle et al. 2002).

Vegetables are vulnerable to heavy metals at high concentrations, and large-scale irrigation with wastewater and application of fertilizers for commercial production increase the risk of heavy metal contamination (Gil et al. 2004). Heavy metals have significantly negative effects on plant growth (López-Millán et al. 2009); other toxic effects may include root browning, alteration of mineral concentrations, and changes in photosynthesis (López-Millán et al. 2009). At higher concentration, metal moves from roots to shoots of the plant (Rodríguez-Celma et al. 2010). Misra and Mani (1991) have suggested that metal concentrations in plant tissues were in the range of 0.02–7, 0.1–2.4, 0.2–1.0, 4-15, 1.0, and 1–13 mg kg^{-1} for As, Cd, Cr, Cu, Ni, and Pb, respectively.

The heavy metal concentrations in soil are given in Table 1, while their concentrations in plants are shown in Table 3 and Figs. 2 and 3. The Cd concentrations in most of the selected plants were above the permissible limits set by SEPA, EU, India, and FAO. In this review paper, we have selected different vegetables including leafy, ground stem, and fruits. The maximum concentration was found in leafy vegetables such as lettuce. The order of contaminations was leafy>fruit>ground stem vegetables (Table 3 and Fig. 3). Cr concentrations were found above the safe limit of EU (1.0 mg kg^{-1}) and FAO (0.05 mg kg^{-1}). Similarly, the concentrations of Pb were also above the EU (0.3 mg kg^{-1}), FAO (0.3 mg kg^{-1}), Indian standard (2.5 mg kg^{-1}), and SEPA (9.0 mg kg^{-1}) in most of the selected plants. The order of contamination was potato > spinach > cucumber > lettuce > mustard > rice (Table 3). The permissible limits for heavy metals in vegetables are summarized in Table 2. Like soil, the permissible limits set by different countries and organizations for individual metal show great variation in their respective concentrations.

Metal uptake by plants

Vegetables (leafy and nonleafy) grown on contaminated soil are considered as the major source of heavy metals. Based on heavy metal uptake, the plants are classified as accumulator, hyperaccumulator, and excluders. Plant contamination with heavy metals may occur through soil–plant, water–plant, and air–plant interfaces; however, soil–plant interface is the major source of plant metal accumulation. Literature shows that there is a strong relationship between heavy metals in soil and food crops (Bini et al. 2012; Khan et al. 2015). In general, the bioavailability of heavy metals depends on the amount of exchangeable metals in soil. Carbonate-bound and exchangeable metals are more bioavailable than other fractions (Wong et al. 2002). The bioavailability of heavy metals in plant varies for different plant organs, and the absorption and bioaccumulation rate is highest for roots as compared to other parts (Verma and Dubey 2003). Similarly, solubility and soil type also affect the metal uptake by plants (Castro et al. 2009). The mean heavy metal uptake by plants increases as the contents of these metals increase in the soil environment (Chaves et al. 2011). Galal and Shehata (2015) reported that the bioavailability of heavy metals depends upon the distance from the source; they observed that the bioavailability rate was higher in heavy-traffic roadside plants. Sludge- and compost-amended soils reduce availability of metals to plants avoiding food chain contamination (Smith 2009). Liu et al. (2005a) mentioned that the bioavailability of Cd is the highest, while that of As is the lowest for crop cultivated in heavy-metal-contaminated soil. *Amaranthus dubius* have the capability to remove heavy metals from soil through their root system, but shoot absorption is negligible for a number of heavy metals like As, Cr, Cu, Ni, and Pb (Mellem et al. 2009).

Accumulation, distribution, and chemical status of heavy metals in plants

Assessment of heavy metal concentrations in food crops is done through accumulation factor calculation (Table 4), which

Table 3 Heavy metal concentrations (mg kg^{-1}) in plants

Plants	Cd	Cr	Cu	Ni	Pb	References
Lettuce	14.98±0.53[acde]	NA	8.15±0.18	NA	3.64±0.55[ade]	Waterlot et al. (2013)
Mustard	0.62±0.32[cde]	NA	17±9	4±1.3[a]	17±1.7[acde]	Khan et al. (2010a)
Lettuce	0.84±0.02[cde]	NA	17±1.7	24±2.5[a]	15±0.43[acde]	
Spinach	2.10±0.75[acde]	NA	11±1.1	7±5.7[a]	18±10[acde]	
Lettuce	<0.2[e]	<0.2	8.67±2.03	<0.2	<0.2	Castro et al. (2009)
Tomato	NA	6.1[cde]	10.5	1.6[a]	4.45[ade]	Noor-ul-Amin et al. (2013)
Onion	NA	1.05[cd]	6.05	2[a]	2.7[ade]	
Brinjal	NA	7.5[cde]	6.85	3[a]	4.35[ade]	
Lettuce	0.13±0.11[e]	NA	0.84±0.31	NA	0.15±0.09	Xu et al. (2013b)
Garlic	0.02±0.02	NA	0.42±0.13	NA	0.02±0.01	
Cabbage	0.04±0.04	NA	0.6±0.29	NA	0.11±0.08	
Lettuce	0.27±0.02[cde]	NA	0.98±0.10	NA	0.13±0.01	Zhuang et al. (2009)
Carrot	0.14±0.02[e]	NA	0.85±0.16	NA	0.18±0.01	
Mustard	0.08±0.00	NA	0.75±0.06	NA	0.37±0.14[de]	
Lettuce	4.22±0.51[acde]	NA	23.2±2.5[cd]	NA	8.59±0.9[ade]	Luo et al. (2011)
Rice	0.43±0.21[cde]	NA	42.3±5.6[acd]	NA	13.6±2.8[acde]	
Cauliflower	2.74±0.3[acde]	NA	15.8±2.5	NA	8.82±1.5[ade]	
Potato	0.09±0.01	0.11±0.06	0.06±0.04	0.06±0.05	NA	Khan et al. (2013a, b)
Tomato	0.09±0.01	0.12±0.06	0.03±0.02	0.07±0.05	NA	
Rice	0.08±0.04	BDL	0.19±0.02	0.23±0.21	NA	
Tomato	0.03±0.02	NA	0.91±0.15	NA	0.02±0.02	Hu et al. (2013)
Lettuce	0.06±0.01	NA	0.42±0.03	NA	0.04±0.01	
Spinach	0.52[cde]	8.7[cde]	14.3	8.6[a]	4.5[ade]	Khan et al. (2008b)
Lettuce	0.9[cde]	7.5[cde]	14.6	14[ac]	5.5[ade]	
Potato	0.11	NA	NA	NA	NA	Piotrowska and Kabata-Pendias (1997)
Cucumber	0.66[cde]	60.53[acde]	10.3	NA	21.26[acde]	Yu et al. (2006)
Spinach	1.06[cde]	109.44[acde]	15.64	NA	31.95[acde]	
Cabbage	0.71[cde]	55.97[acde]	10.97	13.41[ac]	1.21[de]	
Potato	0.18±0.04[e]	0.39±0.06	2.52±0.13	0.25±0.06	2.58±0.36[ade]	Gebrekidan et al. (2013)
Tomato	0.38±0.02[cde]	0.60±0.06[c]	2.43±0.15	0.73±0.06	2.50±0.24[de]	
Cabbage	0.18±0.01[e]	0.43±0.02	4.10±0.05	0.75±0.09	3.82±0.15[ade]	
Lettuce	0.40–0.91[cde]	3.4–4.0[cde]	NA	12–15[ac]	2.25–5.3[ade]	Khan et al. (2008a)
Rice	0.23[cde]	8.8[cde]	63.3[acd]	NA	8.115[ade]	Kim et al. (2009)
Potato	0.7[cde]	NA	15.0	NA	6.9[ade]	Gichner et al. (2006)
Potato	6.3[acde]	NA	24.4[cd]	NA	51.2[acde]	
Mustard	0.28[cde]	1.25[cd]	9.98	3.02[a]	2.58[ade]	Singh et al. (2010b)
Spinach	0.20[cde]	NA	22.74[cd]	0.00	2.57[ade]	Bigdeli and Seilsepour (2008)
Tomato	0.01	NA	39.99[acd]	0.03	1.94[de]	
Maize	NA	1.36±0.01[cd]	2.05±0.2	1.04±0.5	0.32±0.01	Aremu et al. (2010)
Bean	0.24±0.20[cde]	5.31±1.80[cde]	15.87±4.12	5.65±1.54[a]	1.49±1.09[de]	Meers et al. (2005)
Rice	0.03±0.02	0.97±0.31[c]	4.88±1.70	2.31±0.75[a]	0.22±0.05	Liu et al. (2011)
Lettuce	0.049±0.052	0.13±0.09	NA	NA	0.18±0.20	Chang et al. (2014)
Chinese cabbage	0.027±0.012	0.23±0.10	NA	NA	0.11±0.12	
Wheat	NA	NA	6.68±0.97	NA	NA	Shi et al. (2013)
Vegetables	≥0.20	≥0.13	<1	≥0.20	≥0.10	Yang et al. (2007)
Lettuce	0.08±0.01	0.18±0.02	2.02±1.76	0.38±0.30	NA	Mishra et al. (2009)
Brinjal	0.15±0.07[ce]	0.21±0.01	3.76±0.34	1.03±0.11	NA	
Spinach	0.34±0.13[cde]	0.37±0.20	3.25±2.81	2.32±0.25[a]	NA	
Radish	0.24±0.04[cde]	0.24±0.02	2.57±2.37	1.87±0.33[a]	NA	
Pudina	9.39±1.66[acde]	65.60±2.66[acde]	25.02±1.97[cd]	21.64–30.11[ac]	20.92±2.31[acde]	Gupta et al. (2012)
Cauliflower	12.46±1.03[acde]	86.11±1.44[acde]	15.26±0.80	58.95±2.00[ac]	29.69±1.93[acde]	

Table 3 (continued)

Plants	Cd	Cr	Cu	Ni	Pb	References
Spinach	12.97±0.88[acde]	95.79±1.21[acde]	32.11±2.08[acd]	68.66±1.36[ace]	47.69±3.44[acde]	
Radish	16.16±1.04[acde]	76.26±2.17[acde]	27.00±1.70[cd]	60.12±2.18[ac]	51.78±4.16[acde]	
Lettuce	0.213±0.134[cde]	NA	0.533±0.171	NA	2.49±1.57[de]	Kachenko and Singh (2006)
Spinach	0.361±0.185[cde]	NA	1.01±0.345	NA	4.31±3.08[ade]	
Tomato	0.01	NA	39.99[acde]	0.03	1.94[de]	Bigdeli and Seilsepour (2008)
Spinach	0.2[cde]	NA	22.74[cd]	0	2.57[ade]	
Lettuce	3.11	NA	18.9	NA	4.34	Luo et al. (2011)
Cabbage	2.74	NA	15.8	NA	8.82	
Rice	0.43	NA	42.3	NA	13.6	
Rice	0.013	NA	2.4	NA	NA	Batista et al. (2010)

[a] Above the permissible limit of India

[b] Above the permissible limit of USEPA

[c] Above the permissible limit of China EPA

[d] Above the permissible limit of EU

[e] Above the permissible limit of FAO/WHO

is the expression of metal concentrations in soil in relation with concentrations in plant (Eq. 4) (Khan et al. 2010a; Li et al. 2012). Heavy metals pass through a series of processes including bioaccumulation, transformation, and biomagnification after entering into food chain; therefore, it is very difficult to remove heavy metals from living organisms (Widowati 2012).

Soil-to-plant transfer and accumulation of heavy metals are a matter of concern and have been presented in a number of articles (Table 4) and a key component for health risk assessment (Cui et al. 2004; Fismes et al. 2002; Huq et al. 2001; Rattan et al. 2005; Mapanda et al. 2005; Khan et al. 2008a; Wang et al. 2006b; Liu et al. 2005c) Higher soil-to-plant transfer of heavy metals means strong accumulation of these metals in plant tissues (Khan et al. 2008a). Wang et al. (2006b) and Khan et al. (2008a) described that there is an inverse relationship between soil total metal concentrations and soil-to-plant transfer factor. However, the soil-to-plant transfer is calculated on the basis of total metal concentrations in soil (Hooda et al. 1997). The bioaccumulation factor of heavy metals is measured by the ratio of metal concentrations in plants to metal concentrations in that soil (Eq. 4) (Mattina et al. 2002).

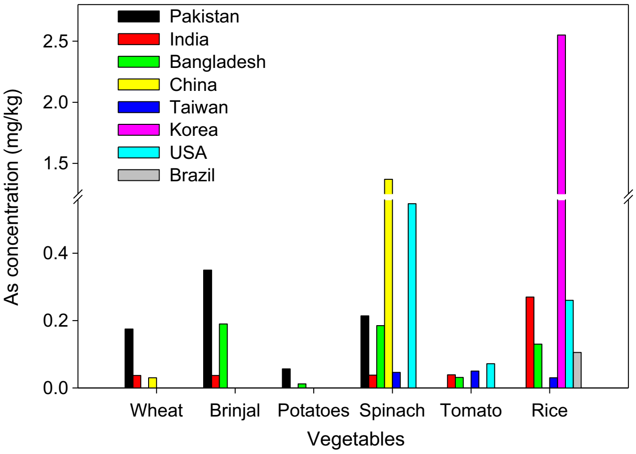

Fig. 3 The concentrations of As in different vegetables grown in different countries. Sources: Arain et al. (2009), Sekhar et al. (2003), Patel et al. (2005), Owens et al. (2004), Alam et al. (2003), Yu et al. (2006), Chang et al. (2014), Shi et al. (2013), Williams et al. (2005), Kar et al. (2013), Ramirez-Andreotta et al. (2013), and Batista et al. (2010)

Food plants have the tendency to accumulate heavy metals in their tissues. Nonessential elements entering our environment may lead to bioaccumulation by plants (Kashif et al. 2009). Trace elements have the capability to interact with roots through absorption in polluted soil environment and increasing risk of toxic effects on plants and animals (Rosselli et al. 2006). Plant analysis, both wild and cultivated plants, for heavy metals is one of the major sources for assessment of contaminated soil (Blaylock et al. 2003; Ernst 1996; Wenzel et al. 1993); these plants act as bioindicators for local- and large-scale soil pollution (Baker et al. 2000; Baker and Brooks 1989; Zupan et al. 2003).

The accumulation factors (Table 4) and daily intake of heavy metals (Table 5) are commonly calculated using the following formulae.

$$\mathrm{PTF} = \frac{C\mathrm{Plant}}{C\mathrm{soil}} \tag{4}$$

where C_{plant} and C_{soil} are the concentrations of heavy metal in plants and soil, respectively (Khan et al. 2010a; Cui et al. 2005; Mohamed et al. 2003). Table 4 summarizes the soil-

Table 4 Soil-to-plant transfer of heavy metals

Plants	As	Cd	Cr	Cu	Ni	Pb	Reference
Tomato	NA	NA	11	22	9	14	Noor-ul-Amin et al. (2013)
Onion	NA	NA	10	15.5	1	12.5	
Tomato	0.0070	NA	NA	NA	NA	NA	Kar et al. (2013)
Spinach	0.0065	NA	NA	NA	NA	NA	
Cabbage	0.0022	NA	NA	NA	NA	NA	
Lettuce	NA	1.5	NA	0.26	NA	0.05	Xu et al. (2013b)
Cabbage	NA	0.4	NA	0.12	NA	0.03	
Lettuce	NA	0.59	NA	0.090	NA	0.002	Waterlot et al. (2013)
Bean	NA	NA	NA	0.07	NA	NA	Ebbs et al. (2006)
Tomato	NA	NA	NA	0.06	NA	NA	
Carrot	NA	NA	NA	0.06	NA	NA	
Rice	NA	0.2		0.013	NA	0.005	Zhuang et al. (2009)
Slender amaranth (Ghinri)	NA	1.135	0.326	0.677	NA	0.399	Abbasi et al. (2013)
Glossy nightshade (Kach mach)	NA	1.776	0.385	0.735	NA	0.573	
Lettuce	NA	0.239	NA	0.004	NA	0.003	Luo et al. (2011)
Brassica oleracea	NA	0.943	NA	0.007	NA	0.011	
Potato	0.46	0.40	0.39	0.40	0.41	0.40	Cheraghi et al. (2013)
Maize	NA	1.14	0.07	0.43	0.56	NA	Khan et al. (2013a, b)
Wheat	NA	1.08	0.04	0.58	0.63	NA	
Rice	NA	0.85	NA	0.45	0.45	NA	
Potato	NA	0.98	0.25	0.08	0.13	NA	
Rice	0.01	0.17	NA	0.1	NA	0.02	Liu et al. (2005a)
Cabbage	NA	0.26	0.01	0.16	0.03	1.27	Gebrekidan et al. (2013)
Tomato	NA	0.23	0.01	0.09	0.01	1.26	
Onion	NA	0.22	0.01	0.09	0.02	1.23	
Potato	NA	0.26	0.01	0.1	0.01	0.78	
Ladies finger	0.001	NA	<1.0	<1.0	<1.0	<1.0	Alam et al. (2003)
Brinjal	0.014	NA	<1.0	<1.0	<1.0	<1.0	
Potato	0.006	NA	<1.0	<1.0	<1.0	<1.0	
Spinach	NA	NA	0.67	0.23	0.14	0.99	Chary et al. (2008)
Brinjal	NA	NA	0.48	0.05	3.1	0.54	
Ladies finger	NA	NA	0.59	0.06	0.02	0.61	
Cabbage	0.02–0.05	0.47–4.69	0.02–0.06	0.23–0.53	NA	0.07–0.29	Wang et al. (2012b)
Lettuce	0.05–0.11	1.76–4.10	0.00–0.07	0.29–0.53	NA	0.09–0.25	
Radish	0.02–0.05	0.30–2.01	0.00–0.02	0.15–0.28	NA	0.00–0.06	

to-plant transfer factor of heavy metals. Results show that tomato, in general, has high bioaccumulation factor among vegetables (Noor-ul-Amin et al. 2013).

$$\mathrm{DIM} = \frac{C\mathrm{metal} \times C\mathrm{factor} \times D\mathrm{food\ intake}}{\mathrm{BWaverage\ weight}} \quad (5)$$

DIM is the daily intake of metals, C_{metal} represents the metal concentrations in plant; C_{factor} is the conversion factor (fresh weight to dry weight); $D_{\mathrm{food\ intake}}$ shows daily vegetable intake, and $\mathrm{BW}_{\mathrm{average\ weight}}$ is the average body weight. According to FAO (2000), average daily intakes of vegetables for adults and children are 0.345 and 0.232 kg person^{-1} day^{-1}, respectively, whereas the average body weights for adults and children were considered as 73 (FAO 2000) and 32.7 kg, respectively (Ge 1992; Khan et al. 2010a; Wang et al. 2005). The daily food intake by a single individual is 55, 105, and 445 g day^{-1} for pulses, vegetables, and cereals, respectively (Tripathi et al. 1997).

Generally, heavy metals have the capability to migrate from polluted soil to plant tissues (Stasinos and Zabetakis 2013). Toxic metals can accumulate in different plant organs; however, the accumulation rate varies from organ to organ (McLaughlin et al. 1999; Wagner 1993), and some organs accumulate more than others. Bioaccumulation and transportation of heavy metals in plants are the major human exposure pathway to soil contamination through food chain (Ryan et al. 1982; Watanabe et al. 2000; Cui et al. 2004; Yu et al. 2006;

Table 5 Daily dietary intake of heavy metals via consumption of contaminated food (mg kg^{-1} day^{-1})

Plants	Individual	As	Cd	Cr	Cu	Ni	Pb	Reference
MAL/RDI	Adults	0.015[e]	0.050[a]	0.02–0.03[b]	0.75–0.90[b]	0.7–1[b]	0.050[a] 0.01–0.02[b]	EC (2006) FNB (2004)
MAL/RDI	Adults	0.58[c]	0.072[d]	NA	1.5–3.0[d]	NA	0.429[d]	Warren et al. (2003) Iyengar and Nair (2000)
RfD (oral reference dose)	Adults+Children	3.0×10^{-4}	1×10^{-3}	3.0×10^{-3}	4.0×10^{-4}	2.0×10^{-2}	NA	USEPA (2012)
Spinach	Adults	NA	8.4×10^{-4}	NA	4.5×10^{-3}	2.8×10^{-3}	7.3×10^{-3}	Khan et al. (2010a)
	Children	NA	1.3×10^{-3}	NA	6.7×10^{-3}	4.2×103	1.1×10^{-2}	
Lettuce	Adults	NA	3.4×10^{-4}	NA	9.6×10^{-3}	4.2×10^{-3}	5.9×10^{-3}	
	Children	NA	5.1×10^{-4}	NA	1.4×10^{-2}	6.3×10^{-3}	8.9×10^{-3}	
Tomato	Adults	NA	NA	3.0	10.0	3.0	6.5	Noor-ul-Amin et al. (2013)
	Children	NA	NA	3.7	12.0	3.4	7.5	
Onion	Adults	NA	NA	2.5	7.0	0.25	5.9	
	Children	NA	NA	3.0	8.0	0.3	6.9	
Rice	Adults	NA	3.16×10^{-3}	NA	NA	NA	NA	Minh et al. (2012)
	Children	NA	2.27×10^{-3}	NA	NA	NA	NA	
Vegetables[f]	Adults	NA	1.9×10^{-2}		3.62×10^{-1}		6.2×10^{-2}	Xu et al. (2013b)
	Children	NA	NA	NA	NA	NA	NA	
Vegetables	Adults	NA	3.8×10^{-4}	1.7×10^{-3}	1.3×10^{-2}	5.5×10^{-3}	1.1×10^{-3}	Hu et al. (2013)
	Children	NA	NA	NA	NA	NA	NA	
Rice	Adults	1.2×10^{-2}	4.0×10^{-3}	6.0×10^{-3}	1.08×10^{-1}	NA	NA	Antoine et al. (2012)
	Children	NA	NA	NA	NA	NA	NA	
Rice	Adults	NA	1.7×10^{-1}	NA	1.72	NA	0.43	Zhuang et al. (2009)
Vegetables	Adults	NA	8.0×10^{-2}	NA	6.3×10^{-1}	NA	1.8×10^{-1}	Luo et al. (2011)
Maize	Adults	NA	4.3×10^{-5}	1.3×10^{-5}	7.5×10^{-5}	1.1×10^{-4}	NA	Khan et al. (2013a, b)
	Children	NA	6.4×10^{-5}	1.9×10^{-5}	1.1×10^{-4}	1.7×10^{-4}	NA	
Wheat	Adults	NA	4.0×10^{-5}	7.4×10^{-6}	1.0×10^{-4}	1.3×10^{-4}	NA	
	Children	NA	6.1×10^{-5}	1.1×10^{-5}	1.5×10^{-4}	1.9×10^{-4}	NA	
Rice	Adults	NA	3.2×10^{-5}	NA	7.8×10^{-5}	9.1×10^{-5}	NA	
	Children	NA	4.8×10^{-5}	NA	1.2×10^{-4}	1.4×10^{-4}	NA	
Potato	Adults	NA	3.7×10^{-5}	4.8×10^{-5}	1.3×10^{-5}	2.7×10^{-5}	NA	
	Children	NA	5.5×10^{-5}	7.1×10^{-5}	2.0×10^{-5}	4.0×10^{-5}	NA	
Vegetables	Adults	0.14	0.10	NA	1.61	NA	0.41	Liu et al. (2005a)
Cereals	Adults	0.21	0.09	NA	146	NA	0.08	
Pulses	Adults	0.02	0.01	NA	0.57	NA	0.01	
Potato	Adults	2.0×10^{-2}	4.5×10^{-4}	8.1×10^{-3}	5.6×10^{-3}	6.8×10^{-3}	2.0×10^{-3}	Cheraghi et al. (2013)
	Children	2.0×10^{-2}	5.3×10^{-4}	9.5×10^{-3}	6.5×10^{-3}	7.9×10^{-3}	2.0×10^{-3}	
Rice	Adults	0.174	NA	NA	2.633	0.488	NA	Roychowdhury et al. (2003)
	Children	0.093	NA	NA	1.404	0.26	NA	
Vegetable	Adults	0.0104	NA	NA	0.795	0.18	NA	
	Children	0.0209	NA	NA	0.475	0.108	NA	
Radish	Adults	NA	5.1×10^{-4}	1.1×10^{-3}	9.4×10^{-3}	1.1×10^{-3}	NA	Khillare et al. (2012)
Spinach	Adults	NA	8.1×10^{-4}	2.3×10^{-3}	1.3×10^{-2}	6.4×10^{-3}	NA	
Potato	Adults	NA	5.0×10^{-5}	NA	2.0×10^{-3}	NA	6.0×10^{-4}	Mansour et al. (2009)
Tomato	Adults	1.7×10^{-4}	NA	NA	NA	NA	NA	Madeira et al. (2012)
	Children	2.12×10^{-4}	NA	NA	NA	NA	NA	
Vegetables	Adults	NA	NA	3.3×10^{-4}	1.12×10^{-3}	8.1×10^{-4}	6.1×10^{-4}	Chary et al. (2008)
Lettuce	Adults	2.70×10^{-4}	2.50×10^{-4}	7.10×10^{-4}	5.40×10^{-3}	NA	4.90×10^{-4}	Wang et al. (2012b)
	Children	2.70×10^{-4}	2.50×10^{-4}	7.10×10^{-4}	5.40×10^{-3}	NA	4.90×10^{-4}	
Cabbage	Adults	1.50×10^{-4}	9.30×10^{-5}	4.70×10^{-4}	4.80×10^{-3}	NA	2.80×10^{-4}	
	Children	1.70×10^{-4}	1.10×10^{-4}	5.40×10^{-4}	5.60×10^{-3}	NA	3.20×10^{-4}	
Radish	Adults	1.10×10^{-4}	7.60×10^{-5}	2.80×10^{-4}	2.40×10^{-3}	NA	1.10×10^{-4}	

Table 5 (continued)

Plants	Individual	As	Cd	Cr	Cu	Ni	Pb	Reference
	Children	1.30×10^{-4}	8.70×10^{-5}	3.30×10^{-4}	2.80×10^{-3}	NA	1.30×10^{-4}	
Vegetables	Adults	NA	1.33×10^{-2}	NA	3.3×10^{-4}	2.31×10^{-5}	2.5×10^{-2}	Elbagermi et al. (2012)
Fruits	Adults	NA	5.54×10^{-3}	NA	2.05×10^{-4}	1.16×10^{-4}	3.7×10^{-2}	
Rice	Adult	9.3×10^{-3}	2.4×10^{-3}	NA	0.2	NA	NA	Batista et al. (2010)
Rice	Adult	20.85×10^{-3}	NA	NA	NA	NA	NA	Batista et al. (2011)

MAL/RDA maximum allowable limit/ recommended dietary allowance

[a] EC (2006)

[b] FNB (2004)

[c] Warren et al. 2003

[d] Iyengar and Nair (2000)

[e] Provisional tolerable weekly intake; Codex (1995)

[f] Value calculated for group of vegetables

Lacatutsu et al. 1996; Khan et al. 2014). Bunzl et al. (1999) reported that information regarding total metal concentrations in polluted soil is insufficient to know about the mobility and availability of heavy metals to living organism.

Heavy metals need some specific media for mobility from soil to plants and within the plants from one organ to another organ; for this purpose, they make bond with metal sulfur legends and organic acids. Grill et al. (1989) and Lugon-Moulin et al. (2004) conveyed that heavy metals have the capability to bind with phytochelatins and glutathione and accumulate in different plant organs.

Metal toxicity and tolerance

Heavy metals have shown toxicological effects on plants and animals, and their degrees of toxicities vary from species to species and from metal to metal. It is known from the literature that metal toxicity is associated with their speciation in soil; however, it is difficult to determine some specific species because of their complex nature, functioning, and distribution in soil environment (Czupyran and Levy 1989). The bioavailability and toxicity of heavy metals to living organism are dependent on soil physiochemical parameters and microbiology (Alam et al. 2003; Islam et al. 2000). Prasad (1999) discussed that the heavy metal toxicity may be influenced by changes in its characteristics such as pH.

Heavy metals interact with essential micronutrients and affect their uptake and transport by plants (Thys et al. 1991; Hernández et al. 1998) affecting plant growth and their physiological functions. Hernández et al. (1995) observed that at high Cd concentrations, plant elicited toxic symptoms and caused growth retardation. Similarly, Cd even at low concentration can exert toxicological effects on seed germination and growth (Li et al. 2005a) and Cu is also toxic to seedling growth (Munzuroglu and Geckil 2002).

The genotoxicity of heavy metals to living organisms involves interaction of heavy metals with genetic material via binding with DNA basis (Hossain and Huq 2002). A number of transgenic and bioassay techniques have been recommended for assessing the genotoxic effects of environmental pollutants on plants including random-amplified polymorphic DNAs (RAPDs), micronucleus (MCN) induction, or Comet assay (Steinkellner et al. 1998; Angelis et al. 2000; Arkhipchuk et al. 2000; DeWolf et al. 2004; Kovalchuk et al. 2001; Liu et al. 2005b).

For heavy metal toxicity assessment, various plant species are recommended depending on soil properties. Lettuce is used for toxicity assessment in moderate pH environment (pH 6–8) (ISO 2005b; Sheppard et al. 1993; Chapman et al. 2010, 2012) because it is not a good acid-tolerant species (Chapman et al. 2012; Environment Canada 2005). Among higher plants, oat is recommended for toxicity tests of heavy metals (Chang et al. 1997; ISO 2005a) under low pH conditions (Loureiro et al. 2006; Small and Jackson 1949; Bilski and Foy 1987), while *Allium cepa* is Pb tolerant in acidic environment (Dang et al. 1990). Heavy metal tolerance capability of plants may be associated with their chemical form (Yang and He 1995). Similarly, metal-induced reactive oxygen species (ROS) are responsible for peroxidation of fatty acid. To avoid the toxic effect of ROS, plants adopt different defense strategies including antioxidant enzymes (Gill and Tuteja 2010). Nitrogen and sulfur are essential nutrients responsible for protein and glutathione synthesis providing defensive mechanisms for heavy metal tolerance (Anjum et al. 2008; Liedschulte et al. 2010; Sarwar et al. 2010; Zechmann and Müller 2010). The recent studies conducted on plant tolerance mechanism to environmental pollutants showed that heavy metals have strong influence on leaf size and structure, and the first toxicity symptoms appear on leaves; thus, measuring length to width ratio can be very effective in evaluating plant tolerance to heavy metals (Zhang et al. 2014).

Plants can evolve an advance and complex detoxification mechanism to avoid metal toxicity which is composed of selective uptake, chelation, compartmentalization, and secretion of toxic metals (Pourrut et al. 2013). Phytochelatins play a key role in metal detoxification (Cobbett 2000). The *Brassica juncea* (BjCdR15) and *Arabidopsis* TGA3 are good tolerants to high metal concentrations because of the mechanisms such as the regulation of synthesis of phytochelatin by BjCdR15/TGA3 (Farinati et al. 2010). Similarly, different genes are involved in metal tolerance by mediating metal–glutathione conjugate transport (Kim et al. 2006). Plant protein is actively involved in heavy metal homeostasis and metal tolerance (Suzuki et al. 2002).

Effects on plant growth

Heavy metals are phytotoxic in nature and have significantly negative impacts on plant growth, and even at lower concentrations, they inhibit plant growth (Li et al. 2005a; Di Salvatore et al. 2008; Fjällborg et al. 2005). Under high concentrations of heavy metals, the plant growth drastically reduces (Chaves et al. 2011; Gopal and Khurana 2011; Kumari et al. 2011; Manivasagaperumal et al. 2011). High concentrations of heavy metals in the soil greatly affect the growth and metabolic processes of cultivated crops (John et al. 2009; Sinha et al. 2005). Heavy metals induced oxidative stresses, affect the photosynthetic process, and cause growth retardation (Le Guédard et al. 2012; Bibi and Hussain 2005; Wani et al. 2006)). Elevated concentrations of heavy metals may result in stunted growth by hampering the photosynthetic machinery and disturbing the coordination mechanism between essential elements (Astolfi et al. 2004; Gill et al. 2012), ultimately causing plant death (Sanita di Toppi and Gabbrielli 1999).

Cu is an essential element that plays an important role in various physiological functions and plant growth; however, at higher concentration, it becomes toxic and affects plant growth and interferes with normal physiological functions (Bouazizi et al. 2010; Hansch and Mendel 2009; Upadhyay and Panda 2009). Excess of heavy metals like Cu may cause root growth inhibition and damage the plasma membrane resulting in ion leakage from the cells (Bouazizi et al. 2010).

Soares et al. (2001) presented that heavy metals greatly affect the plant growth, developmental processes, and cell division. A reduction from 18 to 77 % has been observed in plant height cultivated in metal-contaminated soil (Gopal and Khurana 2011; Chaves et al. 2011). A significant decrease was observed in the leaf area of plants grown on metal-contaminated soil. This is because of changes in protein synthesis, photosynthetic activities, and respiration (Chaves et al. 2011). High concentration of Cd has significantly negative impact on lettuce shoot growth (Monteiro et al. 2007). This decrease may be due to metal-induced chromosomal aberration (Seregin and Kozhevnikova 2006).

Effects on plant structure

The effects of heavy metals on plant structure are well known. Bini et al. (2012) stated that high metal concentrations in plants have strong effect on plant morphology. Plants, under high metal stress, show clear symptoms of structural changes including absence of palisade structure, reduced leaf thickness, and structural changes in mitochondria (Bini et al. 2012). Heavy metals strongly influence the structure of plant components and cause toxicological symptoms (Lindsey and Lineberger 1981). The toxicity on cellular structure and function of organisms varies according to toxic potential of heavy metal (Saraf and Samant 2013). Trace elements elicit toxicity symptoms on plants root, shoot, and leaf structure (Mangabeira et al. 2001; Vasquez et al. 1991).

Plant cellular metabolism disruption due to heavy metals may cause structural changes in cell membrane (Prasad 1995) and chloroplast and results in reduced photosynthesis (Ramos et al. 2002; Li et al. 2005b; Mahmood et al. 2010). Similarly, high concentration of Fe produces free radicals which may damage cell membrane, protein, and DNA and alter cellular structure (Arora et al. 2002; de Dorlodot et al. 2005).

Metal exposure and human effects

Toxicological effects to human beings from consumption of metal-contaminated food are based on various factors including chemical forms of heavy metals, dose, exposure route, time, frequency, age, gender, nutritional source, and biological species (Caussy et al. 2003; Tchounwou et al. 2004). Figure 1 shows the heavy metal interaction with human health effects. Similarly, personal and environmental hygiene also plays important roles in subsequent exposure to metal toxicity. Human health and soil quality are strongly related with each other especially to the degree of pollution (Velea et al. 2009). The tendency of food plants to accumulate heavy metals in their tissues is a public health concern, because they are toxic to human health and plant tissues. Some metals are required by human body, while others (As, Cd, Pb, etc.) are toxic in nature even at trace concentrations (Yargholi and Azimi 2008; Khan et al. 2010a; Mitra et al. 2009; Gebrekidan et al. 2013) and associated with carcinogenic health risks (Abbasi et al. 2013). Similarly, consumption of As-contaminated vegetables can cause serious health risks (Batista et al. 2011). Many heavy metals are potential carcinogens (Kim et al. 2009; Lee et al.

2006; Lim et al. 2008) and can cause organ dysfunction and damage. US Department of Health and Human Services (2011), World Health Organization, International Agency for Cancer Research (2012), USEPA /IRIS (2012), and California EPA (2011) have declared As, Cd, Cr, Ni, and Pb as human carcinogens.

Food plant contamination with heavy metals and their potential impacts on plant nutritional values are an emerging health issue because of their strong links with each other (Sharma et al. 2009; Zaidi et al. 2005). Toxicological effects of metal-contaminated vegetables are mainly associated with mineral contents due to their toxicological and nutritional characteristics (Fig. 1) (Chary et al. 2008; Weldegebriel et al. 2012; Yang et al. 2011).

The common route of entrance of heavy metals to human body is through ingestion, inhalation, and dermal contacts (Kim et al. 2009), which results in minor to major health problems including diarrhea, nausea, lung diseases, anemia, kidney disorders, stomach problems, skin diseases, neurological disorders, and cancer (ATSDR 2007; NLM/HSDB 2012). Some of the disorders are caused by acute toxicity, while others through chronic exposure.

Heavy metals have the capability to accumulate in different body parts and cause adverse health impact regardless of their concentrations (Ikeda et al. 2000; Duruibe et al. 2007). The toxicological effects of toxic metals may vary from person to person. Higher concentrations of nonessential elements have effects on the reproductive capability of living organisms (Oetken et al. 2004). For health risk assessment associated with heavy metal contamination of soil, a mathematical model should be established to predict the bioaccumulation and transformation of these toxic metals (Hough et al. 2003).

Health risk is the associated health hazard of some specific chemicals and/or phenomenon in a specific environment and/or environmental conditions depending upon exposure duration and availability of receptors (Alexander 1995). Human health risk assessment is generally done through evaluating the health risk index (HRI), daily intake of metal, reference dose, and general body weight of children and adults (Eq. 6) (Cui et al. 2004; Li et al. 2012; Pandey et al. 2012; Luo et al. 2011; Singh et al. 2010a). Other techniques used for assessing carcinogenic and noncarcinogenic health risks associated with heavy metals are target cancer risk (TCR) (Eq. 9), hazard index (HI) (Eq. 8), and target hazard quotient (THQ) (Eq. 7), respectively (USEPA 2006, 2010; Yang et al. 2011). The different equations used for calculating the health risks are given as under:

$$\mathrm{HRI} = \frac{\sum n(Cn\ \times Dn)}{\mathrm{RfD}{-}Bw} \tag{6}$$

$$\mathrm{THQ} = \frac{(\mathrm{MC} \times \mathrm{FI} \times \mathrm{EFr} \times \mathrm{ED}}{\mathrm{RfDo} \times \mathrm{BW} \times \mathrm{AT}} \times 10{-}3 \tag{7}$$

$$\mathrm{HI} = \mathrm{THQ}_1 + \mathrm{THQ}_2 + \ldots\ldots + \mathrm{THQ}_n \tag{8}$$

$$\mathrm{TCR} = \frac{(\mathrm{Cb} \times I \times 10{-}3 \times \mathrm{CPSO} \times \mathrm{EFr} \times \mathrm{EDtot})}{(\mathrm{BWa} \times \mathrm{ATc})} \tag{9}$$

where Eq. 6 C_n represented heavy metal concentrations in vegetables (mg/kg, fresh weight) and D_n daily intake of vegetables per year, RfD means reference oral dose (Table 5), and B_w is the body weight for children and adults (Eq. 5). In Eq. 7, C is the metal concentration in vegetables, I is the ingestion rate (255 g/day/person), EF_r is the exposure frequency (350 days/year), ED is the total exposure duration (70 years), BW is the average body weight, and AT_n is the noncarcinogen's averaging time, (ED×365 day/year) (USEPA 2006; Chien et al. 2002). THQ is the target hazard quotient for heavy metals (Eq. 8). CPSo represents the carcinogenic potency slope, oral $(\mu g/g/day)^{-1}$; ATc represents the carcinogen averaging time (70×365 days) (Eq. 6). The human HRIs for selected heavy metals and vegetables and different age groups are summarized in Table 6.

Studies on health risk assessment show that children are more susceptible to heavy metal pollution than adults because of their physiological and behavioral characteristics (DHAenC, Department of Health and Aging and enHealth Council 2012; Qu et al. 2012; Man et al. 2010; Zota et al. 2011). Health risk assessment is the evaluation of potential health effects to target population exposed to certain toxic media. It is the key procedure for hazardous substance management, designing remediation policies and taking control measures (Khan and Husain 2001; McGraph et al. 2004).

Heavy metal effect on nutritional values

Balance diet is the key requirement of good health. Vegetables are good sources of macro and micro nutrients that meet daily nutrient requirements. However, no single vegetable has all nutrients to fulfill the dietary requirements. Therefore, for a balance diet, a diversified nutritional regime is required to meet daily nutrient requirements (Grusak and Dellapenna 1999). FAO/WHO has set nutritional standards for children and adults at different age groups which are summarized in Table 7. Heavy metals at high concentrations in food chains and their consumption can cause depletion of essential nutrients in the body leading to serious health hazards (Arora et al. 2008; US Department of health and human services 2005).

It is agreed upon that ROS is responsible, in part, for metal contamination of plants resulting in oxidative damages of proteins, lipids, and nucleic acid, which in turn are responsible for various physiological disorders such as growth retardation, nutrient deficiency, reduced transport of nutrients, genotoxicity, and retarded photosynthesis (Le Guédard et al. 2012; Nagajyoti et al. 2010; Upadhyay and Panda 2009). Similarly, along with the above-mentioned disorders, ROS

Table 6 Human health risk index of heavy metals through consumption of vegetables

Plants	Individuals	As	Cd	Cr	Cu	Ni	Pb	Reference
Tomato	Adults	7.97×10^{-2}	NA	NA	NA	NA	NA	Kar et al. (2013)
Spinach	Adults	6.06×10^{-2}	NA	NA	NA	NA	NA	
Cabbage	Adults	3.08×10^{-2}	NA	NA	NA	NA	NA	
Lettuce	Adults	NA	3.4×10^{-1}	NA	2.4×10^{-1}	2.1×10^{-1}	1.7	Khan et al. (2010a)
	Children	NA	5.1×10^{-1}	NA	3.6×10^{-1}	3.2×10^{-1}	2.5	
Spinach	Adults	NA	8.4×10^{-1}	NA	1.1×10^{-1}	1.4×10^{-1}	2.1	
	Children	NA	1.3	NA	1.7×10^{-1}	2.1×10^{-1}	3.1	
Vegetables	Adults	NA	6.33×10^{-1}	NA	1.51×10^{-1}	NA	2.95×10^{-1}	Xu et al. (2013b)
Vegetables	Adults	NA	3.6×10^{-1}	1.1×10^{-3}	3.2×10^{-1}	2.7×10^{-1}	2.9×10^{-1}	Hu et al. (2013)
Rice	Adults	NA	2.5	NA	1.5×10^{-1}	NA	1.0×10^{-1}	Zhuang et al. (2009)
Potato	Adults		4.5×10^{-1}		1.4×10^{-1}	3.4×10^{-2}	5.7×10^{-1}	Cheraghi et al. (2013)
	Children		5.3×10^{-1}		1.6×10^{-1}	3.9×10^{-2}	5.7×10^{-1}	
Glossy nightshade (Kach mach)	Adults	NA	4.6×10^{-2}	2.63×10^{-1}	9.0×10^{-3}	NA	1.78×10^{-1}	Abbasi et al. (2013)
Slender amaranth (Ghinri)	Adults	NA	4.0×10^{-2}	1.76×10^{-1}	7.0×10^{-3}	NA	2.36×10^{-1}	
Vegetables	Adults	NA	2.71	NA	2.6×10^{-1}	NA	8.6×10^{-1}	Luo et al. (2011)
Maize	Adults	NA	8.5×10^{-2}	8.4×10^{-6}	2.0×10^{-3}	5.6×10^{-3}	NA	Khan et al. (2013a, b)
	Children	NA	1.3×10^{-1}	1.3×10^{-5}	3.0×10^{-3}	8.4×10^{-3}	NA	
Wheat	Adults	NA	8.1×10^{-2}	5.0×10^{-6}	2.7×10^{-3}	6.3×10^{-3}	NA	
	Children	NA	1.2×10^{-1}	7.4×10^{-6}	4.1×10^{-3}	9.5×10^{-3}	NA	
Rice	Adults	NA	6.4×10^{-2}	NC	2.1×10^{-3}	4.6×10^{-3}	NA	
	Children	NA	9.5×10^{-2}	NC	3.2×10^{-3}	6.9×10^{-3}	NA	
Potato	Adults	NA	7.3×10^{-2}	3.2×10^{-5}	3.5×10^{-4}	1.3×10^{-3}	NA	
	Children	NA	1.1×10^{-1}	4.8×10^{-5}	5.3×10^{-4}	2.0×10^{-3}	NA	
Radish	Adults	NA	5.1×10^{-1}	7.3×10^{-4}	2.4×10^{-1}	5.5×10^{-2}	NA	Khillare et al. (2012)
Spinach	Adults	NA	8.1×10^{-1}	1.5×10^{-3}	3.3×10^{-1}	3.2×10^{-1}	NA	
Potato	Adults	NA	7.0×10^{-4}	NA	1.0×10^{-4}	NA	1.0×10^{-3}	Mansour et al. (2009)
Tomato	Adults	6.0×10^{-1}	NA	NA	NA	NA	NA	Madeira et al. (2012)
	Children	7.0×10^{-1}	NA	NA	NA	NA	NA	
Rice	Adults	NA	3.16	NA	NA	NA	NA	Minh et al. (2012)
	Children	NA	2.27	NA	NA	NA	NA	
Lettuce	Adults	9.10×10^{-1}	2.50×10^{-1}	4.70×10^{-4}	1.40×10^{-1}	NA	1.40×10^{-1}	Wang et al. (2012b)
	Children	9.10×10^{-1}	2.50×10^{-1}	4.70×10^{-4}	1.40×10^{-1}	NA	1.40×10^{-1}	
Cabbage	Adults	4.80×10^{-1}	9.30×10^{-2}	3.10×10^{-4}	1.20×10^{-1}	NA	7.90×10^{-2}	
	Children	5.60×10^{-1}	1.10×10^{-1}	3.60×10^{-4}	1.40×10^{-1}	NA	9.10×10^{-2}	
Radish	Adults	3.80×10^{-1}	7.60×10^{-2}	1.90×10^{-4}	6.10×10^{-2}	NA	3.30×10^{-2}	
	Children	4.40×10^{-1}	8.70×10^{-2}	2.20×10^{-4}	7.00×10^{-2}	NA	3.80×10^{-2}	

may result in enzyme inactivation and DNA damages (Pourrut et al. 2013; Saxena and Shekhawat 2013). Heavy metals alter the functions of antioxidative enzymes as well as its contents in plant cells and affect the oxidative stresses (Gallego et al. 1999; Sharma and Dietz 2009) that may lead to plant death. Heavy metals are responsible for genetic instability in plants and result in DNA damage (Liu et al. 2005b; Gichner et al. 2004; Steinkellner et al. 1998). Like other physiological disorders, toxic metals strongly influence the genetic characteristics like point mutation and recombination of plants at variable concentrations (Kovalchuk et al. 2001, 2005). It is impossible, to a specific portion of leafy vegetables, for the determination of nutritional components because the serving size varies greatly depending upon people's knowledge, seasons, food tradition and habits, availability of specific vegetables, and economic condition of the community (Stangeland et al. 2009). Consumption of heavy-metal-contaminated food can lead to serious depletion of nutritional components like Fe and vitamins that may cause a number of physiological and pathological disorders (Iyengar and Nair 2000). The influence of heavy metals on plant nutritional components depends on soil environment, type of food crops, exposure time, and plant organs (Gonçalve et al. 2009). Literature shows that metal-contaminated-food-consuming populations were observed to be deficient of macro and micro nutrients including fats, proteins, vitamins, and minerals like Ca, Fe, and Zn (Nordberg

Table 7 Daily nutrient requirements (mg/day, μg/day) for male, female, and different age groups (FAO/WHO 2001b)

Sex/age group	Vitamin A (RE) (μg/day)	Vitamin C (mg/day)	Thiamin (mg/day)	Riboflavin (mg/day)	Folate (μg/day)	Iron (mg/day)	Zn (mg/day)	Ca (mg/day)	Mg (mg/day)
Infant (0–12 months)	375–400	25–30	0.2–0.3	0.3–0.4	80	9.3	6.6–8.4	300–400	26–54
Children (1–9 years)	400–500	30–35	0.5–0.9	0.5–0.9	160–300	5.8–8.9	8.3–11.2	500–700	60–100
Male (10–18 years)	600	40	1.2	1.3	400	14.6–18.8	17.1	1300	230
Female (10–18 years)	600	40	1.1	1.0	400	14–32.7	14.4	1300	220
Male (19–65 years)	600	45	1.2	1.3	400	13.7	14.0	1000	260
Female (19–65 years)	500	45	1.1	1.1	400	29.4	9.8	1000	220
Pregnancy	800	55	1.4	1.4	600	NA	11–20	1200	NA
Lactation	850	70	1.5	1.6	500	15	14.4–19	1000	NA

1996; Fox 1988). Similarly, heavy metals like Cd and micronutrients have strong interaction in gastrointestinal absorption. Fe and Zn are the most important micronutrients involved in these interactions. This absorption involves intestinal Fe transporters (Park et al. 2002; Ryu et al. 2004). Women and children have higher body Cd than men because their Fe requirements are greater than men (Nishijo et al. 2004). Therefore, adequate nutrition is vital for young children and pregnant women in the earlier stages to have optimal development and growth conditions (Christian 2010).

Effects on contents of carbohydrates

Heavy metals have strong influence on carbohydrate contents of vegetables. Excessive accumulation of toxic elements may inhibit carbohydrate synthesis by destroying the photosynthetic electron transport chain and production of ROS (Sandalio et al. 2001). High Pb concentration results in a decrease in the sucrose content of vegetables and affects the taste of rooted vegetables (Gawęda 2007). Kratovalieva and Cvetanowska (2001) reported that tomato plants cultivated in heavy-metal-polluted soil showed an increase in the total sugar contents.

Heavy metals affect the carbohydrate metabolism by different ways and produce changes in their contents, which may be due to inactivation and impairment of certain enzymes participating in carbohydrate synthesis (Vikas et al. 2002; Gawęda 2007; Nagor and Vyas 1997). At high Cd concentration, a general decrease occurs in carbohydrate metabolism, while glycolytic pathway observes an upregulation under heavy metal stresses (Rodríguez-Celma et al. 2010). Similarly, elevated Cd concentration significantly alters plant physiology that results in low carbohydrate metabolism (Chaffei et al. 2004). At lower concentration, trace metal interrupts with photosynthetic activities, carbohydrate metabolism, assimilation of essential macronutrient, and enzyme activities (Sanita di Toppi and Gabbrielli 1999; Vanassche and Clijsters 1990). Heavy metals have the capability to replace chlorophyll Mg and alter its function (Kowalewska et al. 1987). From the existing literature, it is clear that heavy metals have strong influence on carbohydrates of both leafy and nonleafy vegetables and consumption of such contaminated food can lead to a decrease in net carbohydrate contents that may result in malnutrition.

Effects on proteins and amino acids

Proteins are the basic dietary and functional component of food plants having various structural, functional, and nutritional properties and considered as essential nutrients for human beings. Nitrogen and sulfur are essential nutrients required for synthesis of proteins and amino acids (Hesse et al. 2004). The deprivation of essential nitrogen and sulfur in plants may affect the metabolic process (Carfagna et al. 2010). The total protein contents may range from 1 to 7 g/100 g of leafy vegetables (Uusiku et al. 2010). The crude protein contents of different leafy vegetables vary greatly from species to species (Odhav et al. 2007; Mosha and Gaga 1999), and the variation may be due to climatic conditions (Odhav et al. 2007) and structural and physiological characteristics. Heavy metals are responsible for low protein in plants grown on metal-contaminated soil (Widowati 2012). Heavy metals can significantly reduce protein synthesis as a result of physiological changes in plants (Chaffei et al. 2004). High metal concentration may hamper protein metabolism by altering physiological functions and synthetic activities (Sandalio et al. 2001). Heavy metals have the capability to interact with proteins and DNA which produces oxidative damages in plant molecules (Leonard et al. 2004). Nonessential toxic elements, due to oxidative stress, can affect the thylakoid and protein complex resulting in a decrease in photosynthesis (Linger et al. 2005). Higher concentrations of toxic metals have effects on the decomposition of protein contents (Wu et al. 2014). Heavy metals induced membrane damage due to changes in functions and composition of membrane lipids and proteins (Meharg 1993; Vanassche and Clijsters 1986). Similarly, high metal concentrations inhibit protein synthesis by altering the pigment–lipoprotein complex accumulation in photosystems I (Wang et al. 2009) II and effect ribulose-1,5-bisphosphate carboxylase/oxygenase enzymes (Krantev et al. 2008).

Reports regarding heavy-metal-induced changes in protein concentrations have been contradictory. A number of proteins (fructokinase, enolase, GADPH, and PGM) show decrease in concentrations in some plant species (*B. juncea* and poplar), while the same proteins show increase in other plants (*Arabidopsis thaliana*) (Alvarez et al. 2009; Sarry et al. 2006; Kieffer et al. 2009; Roth et al. 2006).

Effects on fats and fatty acids

Literature shows that most of the studies regarding adverse impacts of heavy metals on food crop are focused upon bioaccumulation, transfer, and health effects. Little knowledge is available on heavy metal impact on nutritional components, particularly lipids (Upchurch 2008).

Heavy-metal-induced oxidative stress results in chloroplast degradation and lipid peroxidation (Khanna-Chopra 2012), affecting the nutritional status of the contaminated plant. The photosynthetic activities of plants are also greatly affected by the contents of heavy metals (Hermle et al. 2006; He et al. 2011; Velikova et al. 2011; Solti et al. 2008). High Cd concentration results in lipid peroxidation (Monteiro et al. 2004), which is caused by metal-induced lipoxygenase activity resulting in displacement of metal ions and altering the enzymatic activities (Wildner and Henkel 1979).

Le Guédard et al. (2008) reported that the concentrations of tri-unsaturated fatty acids decreased when plant was cultivated in heavy-metal-contaminated soil. In the same experiment, they observed that the percentage of other fatty acids (C18:0, C18:1, and C18:2) was increased to various levels. Thus, they concluded that fatty acids can be used as a bioindicator. Heavy metals show variable effects on different fatty acids as Djebali et al. (2005) and Ben Youssef et al. (2005) have observed that heavy metals have negative impact on C18:3 percentages, while other fatty acids were affected positively.

Effects on vitamins

Green leafy vegetables are considered as a rich source of nutrients like vitamins (Gupta and Bains 2006). Vitamins are the essential nutrients for all living organisms and for plant microorganism association. Vitamin concentrations in soil have significant effects on plant growth (Bergner 1997). The vitamin contents of plants show great variation in food crops provided with organic fertilizers to those with nitrogen fertilizers, and plants grown with commercial fertilizers show significant reduction in vitamin contents (Price 1945) which may be due to the presence of some trace elements.

Environment (physical, chemical, and biological) has a strong influence on vitamin contents, and in extreme environment with high heavy metal concentrations, temperature, and pH, the vitamin contents are drastically reduced (Ipek et al. 2005). Vitamins are essential nutrients that play an important role in maintaining good health and providing protection against infectious diseases, augmenting immune system functions, and providing protection against certain malignancies. However, heavy metals have significantly negative impacts on vitamin contents and functions (Sugawara et al. 1981; Pleasants et al. 1992). Similarly, metals induced lipid peroxidation which may reduce the vitamin contents (Tatli Seven et al. 2012) in the cultivated crops. There is a negative correlation between the heavy metals and vitamins; that is, when heavy metal concentrations increased, the vitamin contents decreased and vice versa (Widowati 2012; Munzuroglu et al. 2005).

Financial implication

Soil contamination with heavy metals is one of the major environmental problems that can cause serious financial implications in the form of redevelopment issues, remediation, and reestablishment cost along with severe ecological and health concerns (Semenzin et al. 2007). Based on literature, we come to the conclusion that the major financial implications, direct and indirect, associated with heavy metals may include the following:

- Reduction in crop production
- Financial loss in terms of health cost
- Loss of jobs and unemployment
- Heavy-metal-contaminated foods are nutrient deficient that results in abnormal growth and development
- Poverty associated with health effects and low crop yields

Conclusion

Food plants especially green leafy vegetables are the major dietary source being consumed all over the world. They play a significant role in nutritional contribution to the consumers. Green plants are the rich sources of essential nutrients; however, they are strong accumulators of heavy metals and pose great risk to human health. Similarly, nonleafy vegetables are also a good source of nutritional elements and are an important part of balance diet. But, on exposure to environmental contaminants, they accumulate heavy metals in their edible parts. The health effects of heavy metals are direct as well as indirect. Direct impacts involve direct consumption through vegetables, ingestion, and dermal contacts, while indirect impacts include reduction in nutritional components in contaminated food crops. Similarly, vegetables are the major sources of heavy metals resulting in both carcinogenic and noncarcinogenic health risks. Our findings showed that concentrations of heavy metals in food crops are much higher than their background values. The concentrations of Cd, Pb, and Cu were found above the permissible limits set by SEPA China, FAO/WHO, EU, and Indian standards that significantly affect the nutritional components of cultivated crops. Moreover, the heavy metal concentrations in plants and their nutritional composition have inverse relationship. Heavy metals have significantly negative impacts on protein, fat, and carbohydrate contents of contaminated vegetables. Therefore, it is suggested that more intensive studies are required on different aspects of heavy metal contamination on plant nutritional components and highly contaminated land should not be used for agriculture purposes prior to protective and rehabilitative measures.

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